Heated Catalyst Test Rig for Single-Cylinder Engine

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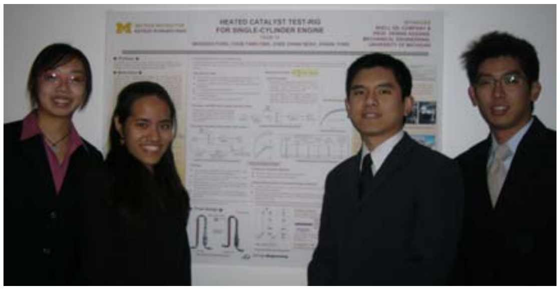
Team BioSoft



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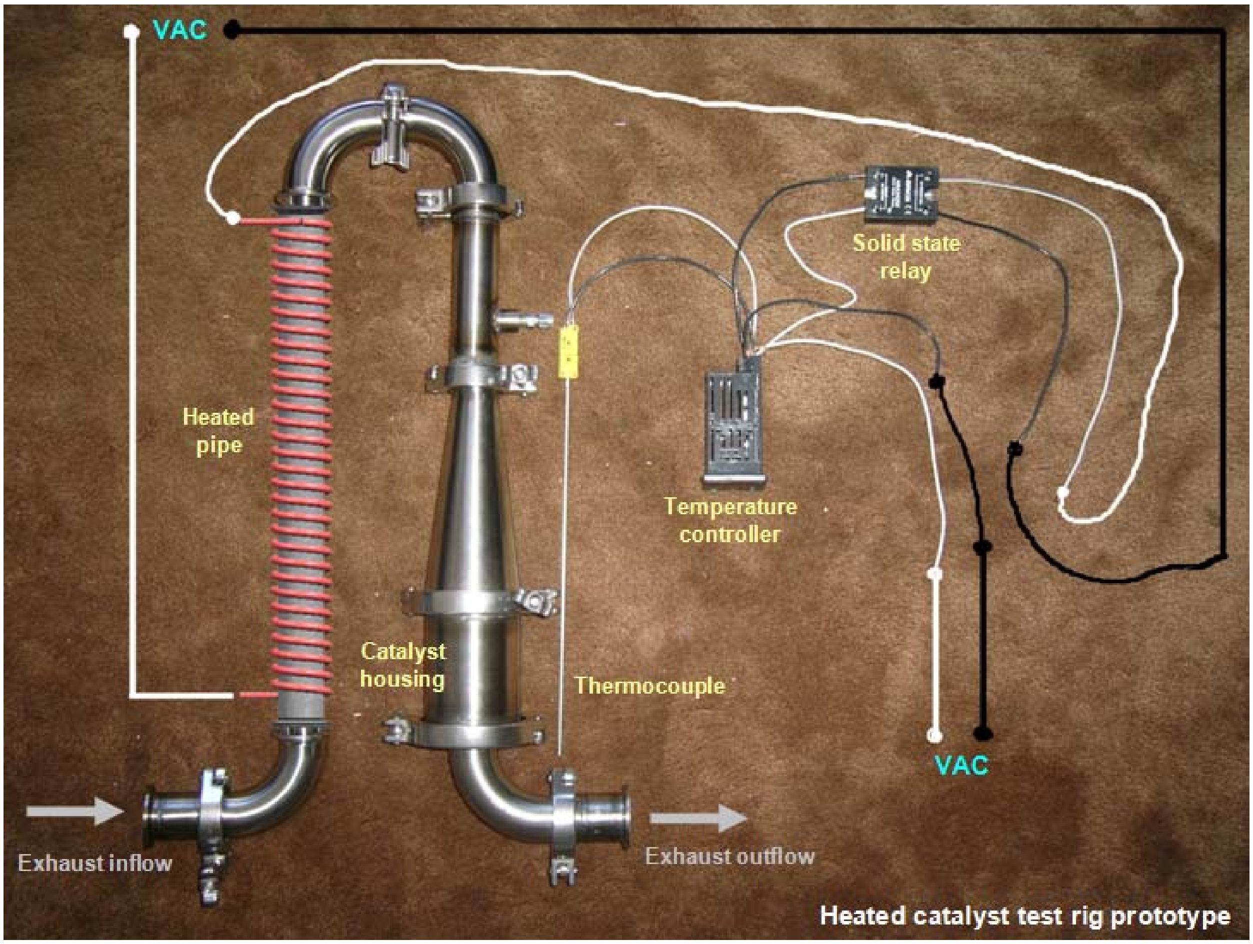

ABSTRACT

The University of Michigan is spearheading research in the area of low temperature combustion (LTC) with premixed compression ignition (PCI). This is a form of diesel combustion that is able to achieve high fuel efficiency with decreased nitrous oxides and soot emission but increased hydrocarbon and carbon monoxide emissions. A diesel oxidation catalyst (DOC) is therefore required. The project scope involves adding a catalyst test rig to the current single cylinder engine to allow researchers to quickly test catalyst bricks suitable for LTC/PCI. The rig should also be capable of controlling the exhaust gas temperature entering the catalyst so as to appropriately simulate the exhaust temperature profile from a multi-cylinder production engine for useful results. This new test-rig will be vital when the research team embarks on future testing involving biofuels since it allows for the easy and rapid switching of the catalyst brick to quickly test new catalyst formulations.

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INTRODUCTION

As an attempt to meet more stringent emissions regulations with ultra clean and efficient engines, the research team led by Professor Dennis Assanis at the University of Michigan has been experimenting with the development of a novel internal combustion method comprising of low combustion temperatures (LTC) and premixed combustion ignition (PCI) strategies. Although this approach leads to the near-elimination of NO_x and soot formation with little penalty in fuel efficiency and consumption, the low temperatures of combustion often lends itself to higher hydrocarbon (HC) and carbon monoxide (CO) emissions. These high emissions levels coupled with the low exhaust gas temperatures impose a great challenge to the catalytic after-treatment of the exhaust. Testing new catalyst formulations, in particular, the diesel oxidation catalysts (DOC), are thus of great utility, to find formulations that are compatible with these new diesel combustion method. Due to practical concerns, the team is currently performing LTC tests on a single-cylinder engine. However, the temperature profile (versus time) of the exhaust as it passes though the catalyst is not comparable to that of a multi-cylinder engine. Since the exhaust gas temperature (EGT) is critical in catalyst testing, matching that on the single-cylinder to that on the multi-cylinder production engine is necessary for acquiring useful test results and making catalyst testing on a single-cylinder engine viable.

The objective of our project is to address this problem through the design and fabrication of a heated catalyst sample test-rig system to allow the researchers to quickly and easily swap and test catalyst bricks suitable for LTC on a single-cylinder test engine. This test-rig should be able to house a 3″ long catalyst sample brick with a 2.83″ outer diameter (7.19 cm OD × 7.62 cm long) that is easily accessible to the user. In addition, the system should feature an adjustable temperature control, be easily integrated into the existing engine, and is leak-proof. It should also include the capability to measure the inlet velocity, and temperature of the exhaust entering the catalyst.

This new test-rig will be vital when the research team embarks on future testing involving biofuels because matching temperatures will be even more important then. Unburned fuel in biodiesel exhaust is prone to condensing out at lower temperatures, changing the chemical composition of the exhaust gas, and affecting catalyst performance.

LITERATURE SEARCH

ENGINEERING INFORMATION

EXHAUST EMISSIONS REGULATIONS Safe, clean and efficient engines are rapidly becoming more important today with an ever-increasing pressure placed on limited resources due to higher levels of mobility. The automotive diesel engine offers an attractive solution due to its superior fuel efficiency and low CO_2 emissions (less than 20%) [1] as compared to traditional gasoline engines. However, such engines are known to be notorious emitters of NO_x, particulate matter (PM), HC and CO. For these engines to remain competitive and be aligned with the increasingly stringent emissions regulations being implemented as shown in Table 1 below [2], vigorous efforts are being poured into developing new strategies to reduce the emissions of these pollutants.

	Exhaust emissions species			
Regulation	HC	CO	NO_x	PM
United States 2007	0.14 g/hp h NMHC	15.5 g/hp h	0.20 g/hp h	0.01 g/hp h

Table 1. Regulated exhaust emissions for 15 ppm sulfur petrodiesel

COMBUSTION STRATEGIES Prior research has yielded a couple of strategies to resolve this problem. One way, as studied in detail by Chae et. al [3] and Peng et. al.[4], is through the use of catalytic converters to remove NO_x and soot. This method has been a major technique employed since early 1980. Another highly effective alternative currently under development involves low temperature PCI combustion coupled with appropriate air-equivalence ratios to reduce the emission of NO_x and soot [5]. PCI combustion is defined as a diesel combustion process that is carried out at higher premixed-to-diffusion burn ratios and lower temperatures as compared to conventional diesel combustion processes. To enter the PCI regime, it is necessary to employ heavy exhaust gas recirculation (EGR) of at least 50% with re-optimized fuel and injection timing.

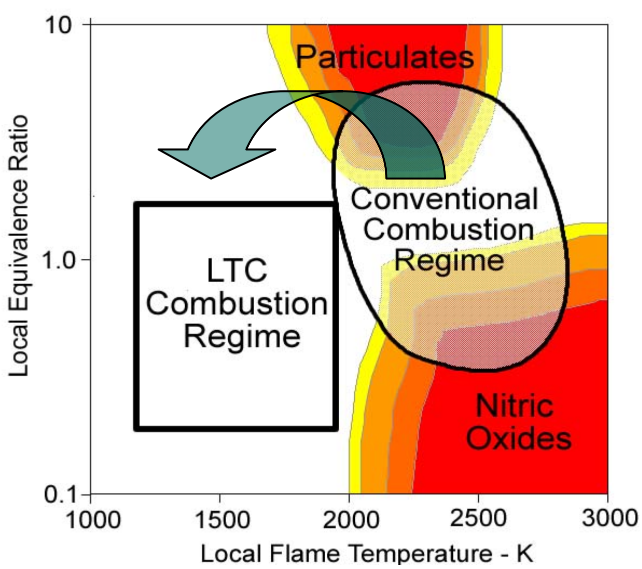


Figure 1. LTC regime avoids conceptualized NO_x and soot formation regimes

Kamimoto and Bae [6] have found that below 1500K and above 2300K, soot formation is suppressed. In addition, above 2000K, NO_x is formed in the presence of oxygen. Thus, as shown in the figure above, the LTC combustion regime that operates at lower temperatures has high potential in avoiding the emission of both pollutants. These lower combustion temperatures are achieved by re-circulating large amounts of cooled exhaust through EGR. The process prolongs the ignition delay time and results in an overly lean air-fuel mixture. Consequently, higher HC and CO emissions result since there is insufficient oxygen and temperatures are too low for complete oxidation of these molecules. The following figure compares the emissions of the four main pollutants from LTC to that from conventional diesel combustion.

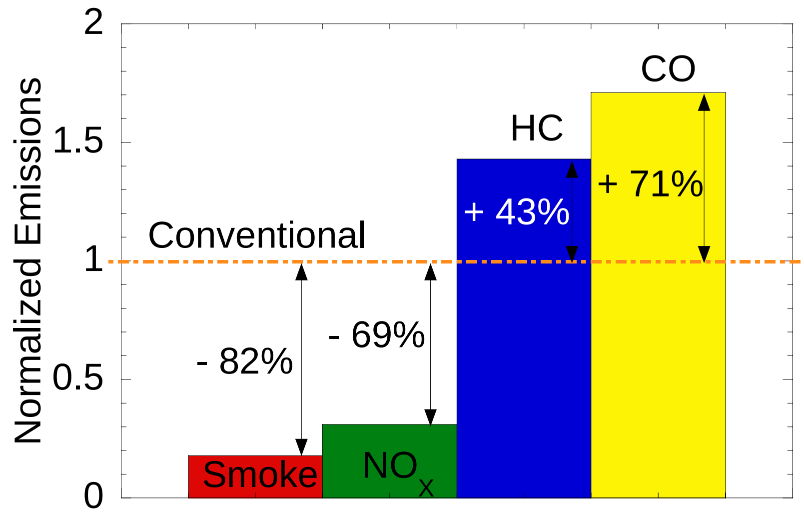


Figure 2. Emissions of LTC compared to conventional diesel combustion

To assist with the high emission of HC and CO which exceeds the federal regulations, a promising area of technology is the diesel oxidation catalyst (DOC). However, like any catalyst, the DOC requires a minimum gas temperature before it is activated to oxidize the respective species. The low exhaust temperatures generally associated with PCI thus poses a great challenge for the catalytic after-treatment of the exhaust. There continues to be an important need to find a suitable catalyst formulation that is compatible with this new combustion strategy, giving rise to the invaluable role of catalyst testing in this developmental process.

CATALYST TESTING AND EXHAUST GAS TEMPERATURE In catalyst testing, the temperature of the exhaust gas is critically important because it affects catalyst reactivity as aforementioned. The same catalyst being tested in a single-cylinder and multi-cylinder production engine will produce different results because the temperature profile (varying with time) of the exhaust passing through the catalyst for a single-cylinder engine is not comparable with that of a multi-cylinder production engine as shown in the following schematic. Currently, our team has been unable to acquire any actual statistical data for these temperature profiles. This data is important to our project as it provides a range of temperatures we can target in the implementation of our adjustable temperature control system for the single-cylinder engine. Our team will be working to close this information gap by performing actual measurements on the single-cylinder engine that the research team is testing or if necessary, looking to obtain research material that provides the necessary data. More in-depth research will be necessary to obtain similar data for that of the multi-cylinder engine.

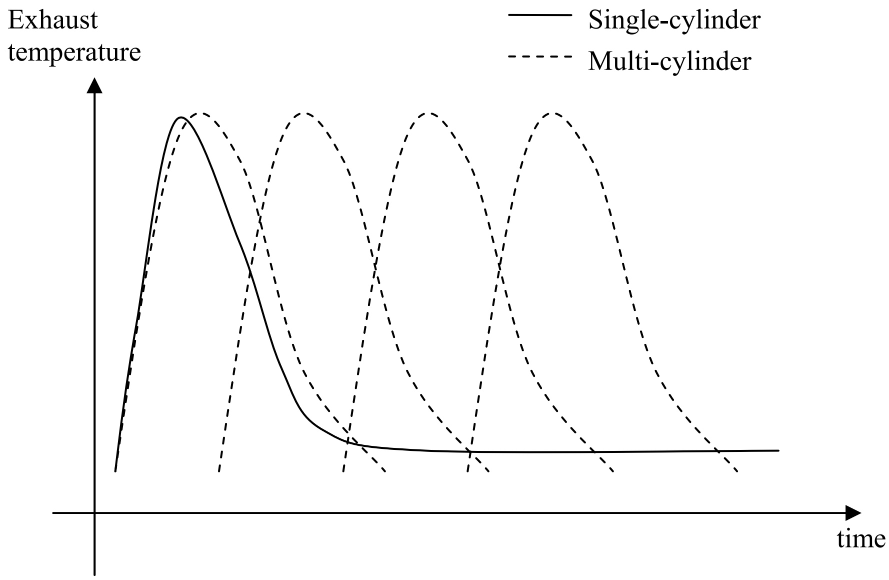


Figure 3. Schematic comparing the temperature profile of a single-cylinder engine with that of a multi-cylinder production engine

As a further note, single cylinders are often used in the experiments to develop these new combustion strategies because of the ease with which many parameters can be varied and useful results obtained. The exhaust gas temperature as a function of torque and speed is shown in the following figure [7]. The UM research team is currently running the engine at a reference speed of 1500 rpm. As shown, the exhaust temperature will increase with increasing load. Combined with knowledge of the various operating cycles for the current single-cylinder engine, this graph can be used to provide target values for our thermal control system as well.

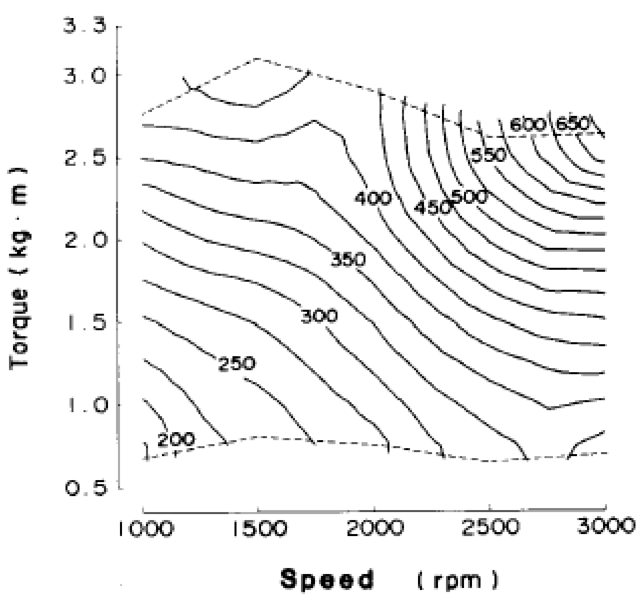
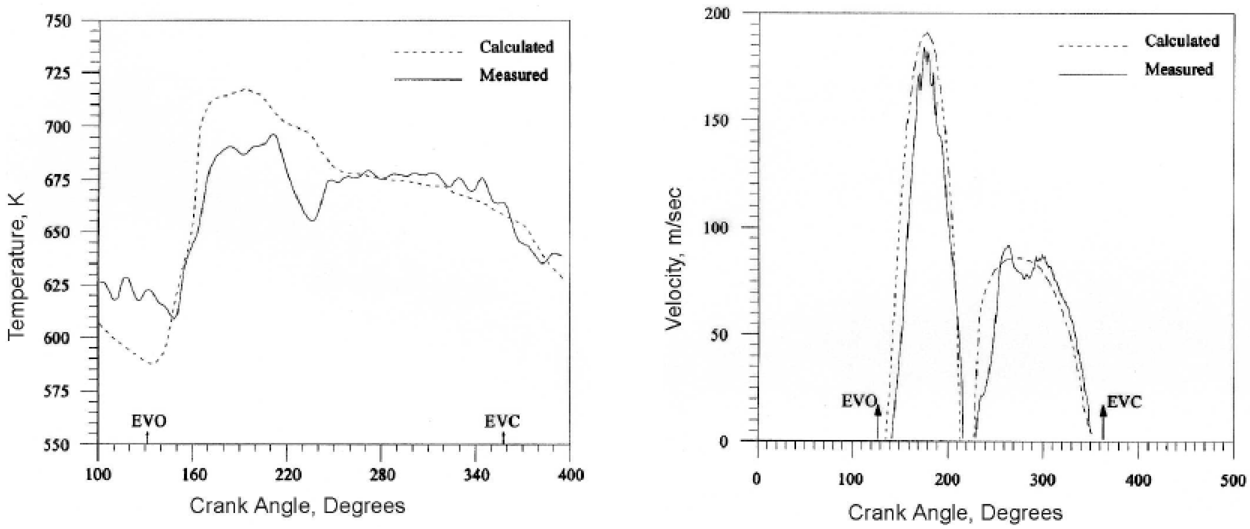


Figure 4. Exhaust gas temperature (ºC) as a function of engine torque and speed

A theoretical model developed by Abu-Qudais [8] allows the determination of instantaneous exhaust-port exit temperatures and velocities against crank angle for a single-cylinder diesel engine as shown in the figures below. It is noted that this model makes the assumption of a well-stirred reactor model (WSRM) and the inlet conditions to the exhaust port were computed from a computer model called AIRCYCLE, which simulates the engine cycle, developed by Kittelson and Amlee [9].



(a) **(b)**

Figure 5. Theoretical model largely agrees with experimental results for instantaneous exhaust-port exit temperature and velocity profiles of a single-cylinder diesel engine

The figures show that the temperature in the exhaust-port exit will vary from around 300°C to a high of 450°C before trailing to a moderate value of 360°C. The velocity undergoes two spikes and goes through a range of values up to 190 m s^{-1} from rest. Although this data is representative only of the exhaust port-exit as shown in the following schematic (Fig. 6) [8], it will be useful to us as rough approximations of the required exhaust temperature and velocity profile for our system. Ostensibly, we will have to account for the damping effects of an exhuast surge tank located before the designated location for the catalyst test-rig, which eliminates much of the pulsating flow from a single-cylinder engine. The distance the exhaust passes through in our system before reaching the catalyst rig is also much longer than that here so cooling effects in the pipe must be accounted for. Furthermore, our current engine operates on LTC with a compression ratio of 16:1, differing from the conventional combustion diesel engine used to obtain the above data.

From actual statistical data provided by our client who ran the engine at one typical steady-state operating condition, the exhaust temperature at the exhaust-port exit peaks at about 310°C, while the exhaust temperature at the exit of the exhaust surge tank and about six inches upstream of the designated rig location are about 250°C and 160°C respectively. When the operating condition is changed to lower the exhaust port temperature by 10°C, the other two temperatures experience a corresponding drop of 10°C as well (the temperatures were 300°C, 240°C and 150°C respectively). Hence for the range of engine operating conditions, the exhaust loses 60°C through the surge tank and then about an additional 90°C through the length of the exhaust pipe before reaching the designated catalyst test rig location.

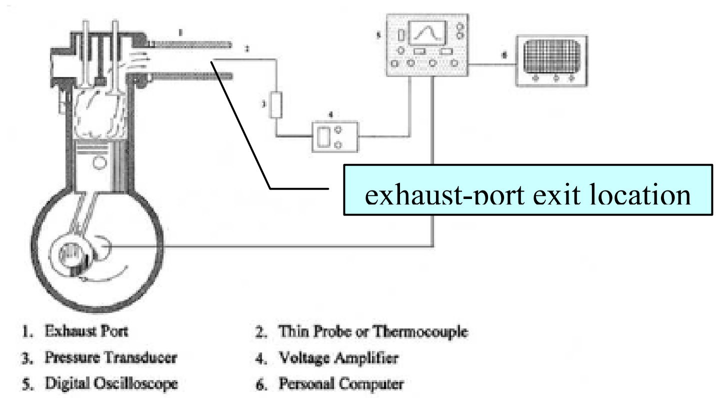


Figure 6. Exhaust-port exit location for the single cylinder diesel engine used by Abu-Qudais

The exhaust profiles of a multi-cylinder production engine operating under the same combustion conditions are different simply because of the consecutive-phase ejection of exhaust from its numerous cylinders. As shown in the schematic (Fig. 3), taking into account the averaging effects of the multiple peaks, the temperature profile of the exhaust through the catalyst more or less remains at a consistently high value as time passes. Hence, at the very least, our team must ensure that our thermal control system can achieve a high constant temperature of 300°C (with time) for the exhaust passing through the catalyst. For useful testing purposes such as determining the effect of temperature on catalyst performance, the thermal control system should allows users the ability to vary the constant temperature setting through a range from 150°C to 400°C.

BIOFUEL As Demirbas [10] argues, a sustainable biofuel has essentially two promising properties which are (1) its availability from renewable raw material and (2) its lower negative environmental impact than that of fossil fuels. Vegetable oil and animal fat (m)ethyl esters, more commonly referred to as "biodiesel", are prominent candidates as alternative diesel fuels [11]. These fuels can be used in any diesel engine without modification, and further experimentation will need to be carried out for re-optimized combustion strategies. Currently, the main obstacle to is commercialization of the product is its cost. Rough projected estimates range from USD0.34 to USD0.62 per liter. With pre-tax diesel priced at USD0.18 per liter in the United States, biodiesel is still not economically feasible and more research and technological development will be needed [12]. Presently, neat biodiesel and biodiesel blends used in an unmodified diesel engine are found to reduce PM, HC and CO emissions as compared with petroleum based diesel fuel [13]. The emission impacts of a 20 vol% biodiesel for soybean-based biodiesel added to an average base diesel fuel are given in the table below.

	Percent change in emissions (%)
Particulate matter (PM)	-10.1
Hydrocarbons (HC)	-21.1
Carbon monoxide (CO)	-11.0

Table 2. Emission impacts of 20 vol% biodiesel for soybean-based biodiesel added to an average base diesel fuel

With the potential environmental benefits of biodiesel, the UM research team is highly interested in examining them as possible renewable replacements for the conventional diesel fuel in LTC. However, since the conventional DOCs that diesel engines use may not behave the same when exposed to exhausts from biodiesel fueled engines, testing new catalyst formulations that are compatible with the new combustion strategy and biodiesel is a vital developmental process. Moreover, when testing with biodiesel fuels, matching the exhaust temperature profile of the single-cylinder engine to that of a multi-cylinder production engine becomes even more important, because unburned fuel in biodiesel exhaust is prone to condensing out at the lower temperatures, changing the chemical composition of the exhaust gas, and affecting catalyst performance and results.

TECHNICAL BENCHMARKS

Currently in the industry, there exist "catalyst cans" (shown in the figure below) which are used in the after-treatment of exhaust from multi-cylinder production engines only. Ostensibly, it is not necessary for these cans to simulate any temperature profiles of multi-cylinder engines carrying out LTC, and useful data on catalyst formulation can be directly obtained. Hence, they do not serve as appropriate technical benchmarks for our project, which involves designing such a test-rig "can" that can simulate required temperature profiles by heating the exhaust gas to desired states for the single-cylinder engine. However, it is conceded that these cans may serve as references for structural design purposes, although they are still much larger and less readily accessible than that required by our client.

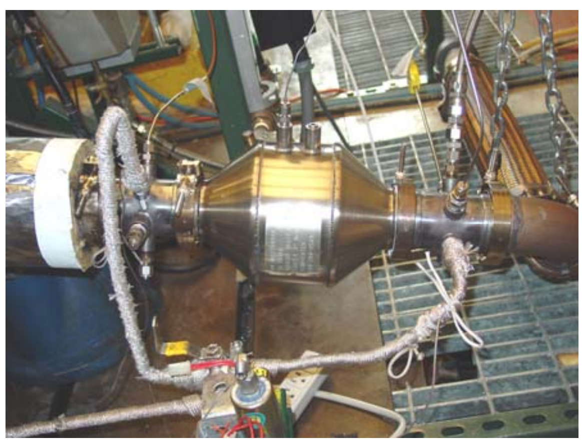


Figure 7. Catalyst can used in the multi-cylinder production engine

POTENTIAL CHALLENGES

Pertaining to our project, there are several areas in which we currently have insufficient information due to time constraints. Firstly, more research needs to be conducted in order to determine the most optimal sensors, actuators, control systems, electrical circuits, and heating elements to use. Information on the cost, availability and mechanics of these components are also needed. In addition, it is not known what type of housing geometry will be most suitable to ensure efficient catalytic reaction. The tradeoffs between leakage issues and the ease of accessibility of the catalyst also need to be studied further. In short, our team believes that a deeper understanding of heat transfer, control theory, thermodynamics, electrical circuits, and chemistry is needed to enable the successful completion of this project.

CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

In order to translate customer requirements into engineering specifications, we made use of a Quality Function Deployment (QFD). QFD is a systematic and structured approach to defining customer needs, thereby translating them into specific plans to produce products to meet those needs. In the QFD process, the understanding of the customer needs is summarized in a product planning matrix or "house of quality". This matrix is used to translate higher level "whats" or needs into lower level "hows" which are the engineering specifications required to satisfy these needs.

CUSTOMER REQUIREMENTS

A meeting was held with Andrew Ickes, a PhD student, and Professor Dennis Assanis who leads the research in this field in order for us to understand the project background and the customer needs. The central idea of our project is to match the exhaust gas temperature on a single-cylinder engine to that on a multi-cylinder engine so that useful experimental data on tests such as catalyst tests and engine tests can be obtained. To fulfill this objective, we need to develop and build a catalyst test-rig system which can be integrated onto the customers' single-cylinder engine.

As the combustion of different fuels can produce different exhaust gas temperatures due to varying chemical composition, the system should allow for adjustable temperature control so as to bring the temperature of exhaust gas entering a catalyst to desired levels. Since the exhaust gas temperature of a single-cylinder engine is significantly lower than that of a multi-cylinder engine, heating is required to raise the gas temperature. The system should be able to measure the temperature of the exhaust gas at both the inlet and outlet of the catalyst so that these temperatures can be monitored at all times. In addition, the system should have the capability to measure the exhaust gas velocity entering the catalyst so as to facilitate the formulation of ideal catalysts for certain fuels. A catalyst holder needs to be incorporated into the test-rig interior for a small catalyst sample brick to be used. The interior design of the system should also allow for efficient catalytic reaction. The entire test rig has to be well-sealed to prevent leakage of exhaust so that the exhaust gas can undergo catalytic conversion processes before being released into the surroundings.

The remaining customer requirements are focused on practical concerns which also have important implications on the outcomes of the project. The test-rig should be easy to integrate onto an existing engine test bed so that minimal adjustments are required to be performed to the latter. The test-rig should be of an appropriate size such that the system components could be contained in a compact volume which is available on an existing engine test bed. The design of the test-rig should also be ergonomic so that there can be easy access and replaceability with respect to catalyst handling. Finally, the cost of implementation must be low enough so that it is economically-feasible for manufacturing, handling and maintenance.

In order to determine the relative importance of the customer requirements, we interviewed Andrew Ickes. From the nine listed requirements, we examined all thirty-six possible combinations of two requirements and selected the more important one out of each pair. The selected requirement was given a value of '1' and the other one was given a value of '0'. After this, we summed all the values given to each requirement and divided by thirty-six (total number of comparisons) to normalize the values. The top three most important customer requirements are adjustable temperature control, measure gas temperature at inlet and outlet of catalyst and no leakage of exhaust.

ENGINEERING SPECIFICATIONS

Based on the list of customer requirements that we have come up with, we created a list of related engineering specifications that cover all of them as shown in Table 3 below. These engineering specifications are quantifiable parameters that were specified or could be controlled to meet the customer requirements. For each customer requirement, our group brainstormed the measurable parameters that are needed for the requirement to be fulfilled. Each of this measurable parameter has a target value pertaining to our design solution. These target values were determined by doing literature research from various sources, for example, technical journals, established websites and publications from the Society of Automotive Engineers (SAE). We also consulted Andrew Ickes because of his research experience and expertise in single-cylinder combustion engines.

Insulation Material	R-value of about 5
Insulation Thickness	Less than 0.02m
Heat Source Material	Thermal Conductivity to be at least 385 W/mK
Heat Source Geometry	Maximize contact surface
Housing Material	R-value of about 5
Geometry of Heating Chamber	<15.25" length and < 4" outer diameter
Geometry of Catalyst Surface	Maximize contact surface
System Volume	15.25" length and < 4" outer diameter
Response Time for Temperature Rise	Less than 1 minute
Design of Catalyst Access Mechanism	Replacement of catalyst requires 5 minutes
Catalyst Fixture Type	Replacement of catalyst requires 5 minutes
Heater Control Mechanism	Lag time less than 30 seconds and zero steady-state error
Power Input Required	1000 to 1500 Watts
Velocity Sensor Type	Detect velocities to an accuracy of 1 m/s and robust in the operational temperature range. Respond time less than 15 ms.
Temperature Sensor Type	Detect temperatures to an accuracy of 5ºC and robust in operational temperature range. Respond time less than 15 ms.
Sensor Location	Minimized distance from exhaust gas
Connection Assembly	Inlet and outlet diameters to match the pipe section to which test rig is affixed with clamps and suitable fittings

Table 3. Engineering Specifications and Target Values for Design

To illustrate specifically how customer requirements are translated into engineering specifications, we will use the most important customer requirement – adjustable temperature control to match exhaust gas temperature by heating. In order to raise the temperature of exhaust gas, a heat source will be needed. Therefore, we need to list down heat source material and geometry as engineering specifications. Before any temperature adjustment could be made, we need to be aware of the temperature of exhaust gas at the inlet and outlet of the catalyst brick. Hence, the type of temperature sensor was included in our engineering specifications. Subsequently, for an adjustable temperature control to be implemented, our system needs to have a heater control mechanism.

After going through the entire list of customer requirements, a list of seventeen engineering specifications were translated. These engineering specifications are tabulated in the QFD to show their correlations to customer requirements as well as cross-correlations among the specifications.

QUALITY FUNCTION DEPLOYMENT (QFD)

The QFD Diagram consists of a list of the customer requirements (leftmost column) and engineering specifications (uppermost columns) of our project as shown in the following figure. A relation matrix shows how the two are linked, and how the customer requirements were translated into the engineering specifications of our design. A weight rating was assigned to each customer requirement, and is entered beside it. This weight rating was then used to find out which engineering specifications are the most important.

The strength of the relationships between each customer requirement and engineering specifications was evaluated by the team through logical analysis and sound reasoning. The relation matrix was input with values of 1, 3 or 9, with 9 representing the strongest relationship, 1 a small relationship and an empty cell denoting no relation. We considered each team member's rationale for assigning a particular value and reached a consensus for every relationship pair.

After calculating the importance rating, we found that the most important engineering specification to achieve is temperature sensor type. We need to select a temperature sensor suitable for the range of temperatures and the medium in which it is to be used. The next most importance specification is the design of catalyst access mechanism. This implies that the test-rig should come with a well-designed catalyst access mechanism which facilitates the fixing and removing of a catalyst brick. Hence, different catalysts could be used with a single test rig and this can lead to substantial cost saving. The third-ranked specification is housing material. An appropriate housing material has to be chosen so that there will be no leakage of exhaust and the cost of implementation can be kept as low as possible.

The roof of the QFD shows the correlation between individual engineering specifications. Similar to the relation matrix, the cells were input with values of ++, +, -, -- or left blank. Double positive (++) signified a strong positive correlation, double negative (--) signified a strong negative correlation, and a blank cell meant there were no discernable correlation. Several significant correlations were shown after the completion of this roof. For instance, by increasing the heat source geometry such as surface area or length, the response time for temperature rise can be decreased. The response time can also be reduced by increasing the power supplied.

BioSoft

Quality Function Development (QFD)

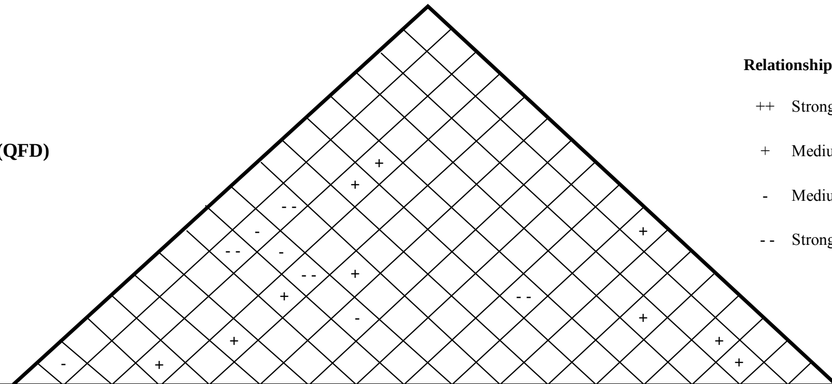
Relationships

++ Strong Positive

\+ Medium Positive

\- Medium Negative

\- - Strong Negative



	Weight*	Insulation material	Insulation thickness	Heat Source Material	Heat Source Geometry	Housing Material	Geometry of heating chamber	Geometry of Catalyst surface	System volume	Response time for Temperature Rise	Design of Catalyst Access Mechanism	Catalyst fixture type	Heater control mechanism	Power input required	Velocity sensor type	Temperature sensor type	Sensor location	Connection Assembly	Benchmarks		
Adjustable temperature control to match exhaust gas temperature by heating	9	3	3	9	9	3	1			3			9	3		9	3				
Measure gas temperature at inlet and outlet of catalyst	8															9	9				
Measure gas velocity	1														9		9				
Easy access and replaceability	6	1	1			1	3		3		9	9						9			
Suitable size	3	3	3		3	1	9		9		1	1									
Ease of integration into existing engine	5					1	9		3		3	9						9			
No leakage of exhaust	7	3	3			9	1				9	1						3			
Cost of implementation	4	9		9		9	1				3	3			9	9		3			
Efficient catalytic reaction	2						9	9	9			3									
Measurement Unit		R	m	W/mK	m	Km²/W	m	m	m³	s				W							
Importance Rating		**9**	**13**	**7**	**10**	**3**	**5**	**17**	**12**	**15**	**2**	**6**	**11**	**15**	**14**	**1**	**8**	**4**			
Total		99	63	117	90	140	128	18	78	27	147	127	81	27	45	189	108	132			
Normalized		0.06	0.04	0.07	0.06	0.09	0.08	0.01	0.05	0.02	0.09	0.08	0.05	0.02	0.03	0.12	0.07	0.08			

Key:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

***Weights are figured on a scale of 1 to 10**
(10 being most important)

Figure 8. Quality Function Deployment Chart

CONCEPT GENERATION

Based on our customer requirements, the main functions of the catalyst test rig have been identified as follows: (1) heating system, (2) pipe insulation, (3) fixture of catalyst, (4) accessibility, (5) thermal control system, (6) exhaust gas velocity measurement and lastly, (7) integration into single cylinder engine test bed. The morphological method is employed to develop various concepts for each function as shown in the table below.

Energy / Sub-functions	Electrical	Chemical	Mechanical	Miscellaneous
Obtain heat energy	Heating coil	Combustion	Friction	Draw from existing cooling system in engine
	Heating mesh			Solar panels
Transfer heat energy	External coil	Hot gas/ exhaust mixture	Heat pump	
	Internal coil	Counter-flow	Multiple pipes	
	Internal fins			
Prevent heat loss	Heating film		Adjust pipe diameter	Insulation around pipes
Fix catalyst in place			Stoppers	Magnetic force
			Tap-screws	
			Wire mesh	
			Clamp system	
Accessing catalyst		Chemical means to change composition directly	Door and hinge	Magnetic flap
			Removable pipe	
			Drain beads	
			Side fins	
			Lift-up hatch	
Control exhaust temperature	Control current/voltage	Vary valve opening to change hot-gas/exhaust ratio		
		Vary outer pipe temperature or volume flow rate		

Sub-functions	Differential pressure	Thermal	Fluidic	Mass	Acoustic	Mechanical
Measure exhaust flow velocity	Venturi meter, Flow nozzle, Orifice plate, Rotameter	Calori-metric, Hot-wire	Pressure transducer, Vortex flow meter, Pitot tube	Coriolis meter, thermal probe	Ultrasonic meter (clamp-on transducers)	Turbine meter, Positive disp.

Table 4. Morphological table

The chart that follows is a visual distillation of the more feasible ideas presented in the above table. Further elaboration of the concepts for each function is carried out following the chart.

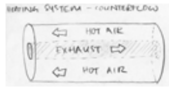
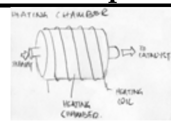
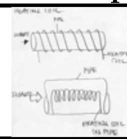
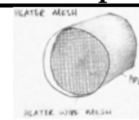
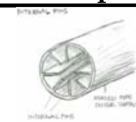
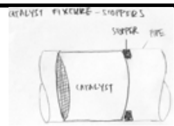
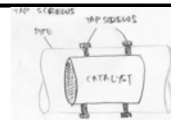
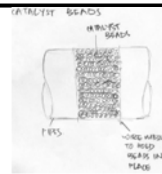
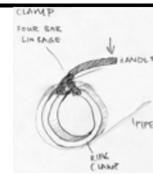
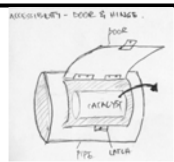
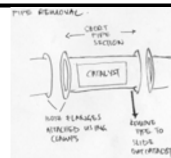
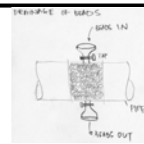
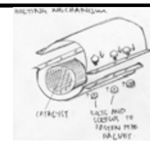
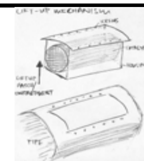
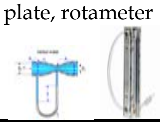
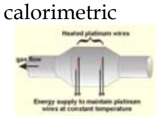
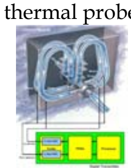
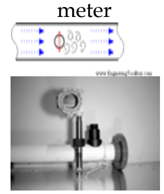
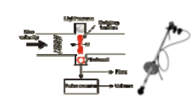
Function	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8
Heating system								
Prevent heat loss	Heating film 	Pipe insulation 						
Fix catalyst								
Accessibility								
Thermal control system	Vary outer pipe temp. or volume flow rate	Vary current/ voltage across coil	Vary current/ voltage across coil	Vary current/ voltage across mesh	Vary valve opening to control ratio of hot-gas mixture			
Measure exhaust velocity	Differential pressure meters: Venturi, flow nozzle, orifice plate, rotameter 	Pitot tube (annubar) 	Thermal meters: Hot-wire anemometer, calorimetric 	Mass meters: Coriolis, thermal probe 	Vortex flow meter 	Pressure transducer 	Ultrasonic (time of flight) meter 	Rotating blades: Turbine meter, positive disp. 
Integration into test bed								

Figure 9. Morphological chart showing generated design concepts for each function

FUNCTION 1: HEATING SYSTEM

The heating system should be able to heat the exhaust to a desired temperature while being energy efficient. This will ensure a low cost of implementation and allow easier integration into the existing engine system. The following section will present the design concepts for the heating systems our team came up with.

CROSS-FLOW HEAT EXCHANGER A separate heating system is first used to heat and store hot air at a certain desired temperature, T_s. The hot air is then fed into a cross-flow heat exchanger where thermal energy is transferred from the hot air to the exhaust gases. The main advantage of this system is that exhaust temperature will accurately match that of T_s given sufficient pipe length. This will allow easy control of the exhaust temperature. However, to have a separate air heating system will prove to be bulky and may cause problems during integration.

HEATING CHAMBER A heating element will be connected to the heating chamber in order to raise its surface temperature to a certain desired value, T_s. Exhaust gases will then be passed through the heating chamber to allow heat transfer. With a large cross-sectional area, exhaust gas velocity decreases and more time is allowed for the high temperature surface of the heating chamber to heat up the exhaust gas. As there already is a holding chamber for exhaust gases in the current engine system, this heating system can be easily integrated without many complications. However, there will be larger temperature fluctuations as the gases at the center will be cooler than the gases at the perimeter. Also, temperature control of the exhaust may be difficult as it will not be equal to T_s.

HEATED PIPE Similar to the heating chamber, a heating element will be used to obtain a constant surface temperature. However, instead of having a heating chamber, the heating element will be connected to the piping systems whereby the exhaust flows through. This will allow the exhaust to be more even heated, and reduce temperature fluctuations. This system can also be easily integrated into the existing engine system. However, due to the high exhaust velocity, a high surface temperature, or an increased length of piping may be needed to achieve the desired exhaust output temperature. An alternative to heating the pipe will be to place the heating element within the pipe, and allow thermal transfer to occur directly between the element and the exhaust gases. This will cut down on the energy used to heat up the pipe. However, inserting a heating element within the pipes might prove difficult, and there might be undesired chemical reactions between the exhaust gases and the heating element.

WIRE MESH HEATER A heating element can be used to raise the temperature of a wire mesh inserted perpendicular to the flow of the exhaust. This will allow even heating of the exhaust gases that are passing through the pipes. However, as the exposure of the exhaust gas to the wire mesh is very limited, multiple meshes and high mesh temperatures may be required in order to achieve the desired exhaust output temperature.

HOT AIR MIXER A separate heating system is once again used to heat and store hot air at a desired temperature. The hot air is then fed and mixed into the exhaust pipe in order to increase the exhaust temperature. This system will be able to raise the temperature of the exhaust in the shortest amount of time and also be able to control the temperature accurately by adjusting the mixing ratio. However, there will also be a dilution effect whereby the original composition of the exhaust emission is altered by the mixing.

INTERNAL FINS As an improvement to the heated pipe system, internal fins are added to the interior of the pipe to allow more efficient heat transfer. This will allow a shorter pipe length, and a lower pipe surface temperature to achieve the same exhaust output temperature. It will also allow easier integration due to the reduced system size. However, the internal fins will be hard to manufacture and might be difficult to replace when damaged.

HEAT PUMP A heat pump can be used to extract thermal energy from a low temperature source and deposit it at a high temperature source. With a high efficiency rating, a heat pump will ensure that minimal power is consumed. However, it may not be able to operate at the desired temperature of our engine exhaust system.

FUNCTION 2: PIPE INSULATION

In our current single cylinder engine setup, the exhaust leaves the engine exhaust port at 310°C. Upon exiting the surge tank, its temperature decreases to 250°C and finally reaches approximately 160°C when it enters the catalyst test rig. However, heating the exhaust by 150°C within a short distance is extremely difficult, costly, and taxing on the heating system. This large heat loss is mainly due to the use of bare steel pipes that have a very high thermal conductivity. Hence, by insulating the piping that leads up to the test rig with materials that have a low thermal conductivity, the amount of heat lost to the surroundings is decreased. This smaller temperature difference will be much easier to eliminate than a large one.

Taking into account the existing single cylinder test engine setup, the pipe insulation needs to be sufficient to significantly reduce the loss in temperature. In addition, this insulation should be flexible enough to wrap around the pipe, and should be able to withstand the high surface temperatures. Our system requires approximately 6.5 ft of insulation to cover pipes with an outer diameter of 2 inches.

Preliminary research into possible insulating materials resulted in the following choices and their respective temperature ranges, as seen in the table below:

Insulation Material	Low Temperature Range (°C)	High Temperature Range (°C)
Calcium Silicate	-18	650
Fiberglass	-30	540
Mineral Wool	0	1040
Polyurethane	-210	120
Polystyrene	-210	120
Cellular Glass	-260	450

Table 5. Temperature ranges of various insulation materials.

Polyurethane and polystyrene were deemed unsuitable due to their low operating temperature range. More research was then conducted on the remaining materials to determine cost and suitability.

Product Name	Insulation Material	Cost (USD)	Max. Operating Temp (°C)	Thermal Conductivity (W/m-K)	Flexibility	Other Properties
Insulite	Calcium Silicate	9/ft	1050	0.11 [600°C]	No	-NA-
Roxul RW 40 Blanket	Mineral wool	150/roll	650	0.14 [400°C]	Yes	Fire resistant
FoamGlass	Cellular Glass	10/ft	480	0.10 [300°C]	No	-NA-
Knauf KwikFlex	Fiberglass	100/roll	454	0.101 [300°C]	Yes	-NA-
Knauf Pipe and Tank	Fiberglass	100/roll	454	0.110 [300°C]	Semi-rigid	-NA-
Knauf ET Blanket	Fiberglass	110/roll	538	0.120 [300°C]	Yes	Can be custom made
Knauf 1000 Pipe Insulation	Fiberglass	3.93/ft	538	0.089 [316°C]	Semi-rigid	
Knauf PVC Fitting Covers	Fiberglass + PVC jacket	5/joint	260	0.130 [260°C]	No	Requires double insert; for joints

Table 6. Summary of properties of insulation materials

Insulite and the Knauf PVC fitting covers are rigid materials, and come in fixed sizes corresponding to industry standards. The PVC fitting covers, in particular, are specially used for curved joints and come in a variety of different angles for standard pipe diameters. Knauf Pipe and Tank insulation and 1000 Pipe Insulation are semi-rigid, and are fitted around pipes and sealed together. The remaining materials are all flexible and can be wrapped around pipes and tightened. They are particularly good for irregular pipe shapes.

FUNCTION 3: FIXTURE OF CATALYST

For the purpose of our test rig design, our team determined that the fixture should be able to securely fasten the catalyst to the pipe. It should also be easily adjustable to accommodate different catalyst sizes and shapes. Lastly, it is desirable to have an accessible fixture to facilitate ease of adjustment or removal. Four different ideas were conceived, and they are detailed below. The respective illustrations can be seen in the morphological chart in Figure 9.

STOPPERS Two rings of approximately 0.5” thickness will be attached to the inner diameter of the pipe. These rings will serve as supports or stoppers for the round catalyst brick, which will be placed in between them. In this way, a snug fit between the catalyst brick and the pipe walls will be ensured. Due to the high operating temperature of the catalyst test rig, the ring material will likely be of a high temperature rubber or similar synthetic. In implementation, one ring will be glued to the inner pipe wall, while the other will be removable to facilitate insertion of the catalyst. It should have adhesive sides such that it can be readily reattached to the pipe wall.

TAP SCREWS In this concept, the catalyst will be held in place via pairs of screws on each side. Such screws will be inserted into the pipe via holes on the outside and will serve to secure the catalyst. Holes will be drilled into the pipe wall and nuts with threads will be welded onto them to allow us to insert the screws. A simple screwdriver would then be used to tighten the catalyst down.

WIRE FRAME FOR CATALYST BEADS A more revolutionary option would be to utilize ceramic beads coated with the catalyst instead of a single cylindrical catalyst brick. If such beads were to be used, a possible fixture mechanism would be two round wire mesh frames attached to the inner diameter of the pipe. The beads would thus be held in place within both meshes. The meshes can also be adjusted to accommodate different amounts of beads.

CLAMP Our final and most complicated concept involves the use of a simple clamping mechanism to hold the catalyst in place. As shown in the morphological chart, one would need to place the catalyst between two metal rings within the pipe. Pushing down on the handle attached from the outside would then tighten both rings around the catalyst and secure it.

FUNCTION 4: ACCESSIBILITY

The design of the test-rig should allow easy access to the research team for swift replacement of the catalyst brick to test new catalyst formulations. Our team brainstormed for five such possible design concepts as shown in the morphological chart. Each of these choices will be systematically compared in the concept evaluation section that follows.

FUNCTION 5: THERMAL CONTROL SYSTEM

The main function of a thermal control system is to control the temperature of the heating element which in turn determines the temperature of the exhaust gas by heat transfer mechanisms such as convection, conduction and radiation (to only a small extent). The thermal control system can be broken up into two smaller components which are the temperature sensors and the temperature controller.

TEMPERATURE SENSOR TYPES After researching for suitable temperature sensors, we have narrowed down to three possible choices: (1) thermocouple, (2) resistance temperature detector (RTD) and (3) thermistor.

A thermocouple usually consists of a pair of different metals and makes use of thermal gradient between the metals to generate electric voltage for temperature measurements. A resistance temperature detector exploits the predictable change in electrical resistance of some materials with changing temperature. As they are almost invariably made of platinum, they are often called platinum resistance thermometers (PRTs). A thermistor is a type of resistor used to measure temperature changes, relying on the change in its resistance with changing temperature [14].

TEMPERATURE CONTROLLERS We have identified two main types of controllers that could be implemented for our system. The first type would be to obtain an auto-tuning PID temperature controller from a commercial supplier, for example, WATLOW's Series 96 [15].

The second type would be to design our own temperature controller algorithm and use LABVIEW as our controller interface.

FUNCTION 6: GAS VELOCITY MEASUREMENT

The basis of a good flow meter selection is a clear understanding of the requirements of the particular application. Hence, it is recommended that time be invested in fully evaluating the nature of the process fluid and of the overall installation [16]. The requirements and specifications relevant to a flow meter for our system are summarized in the following table. It is noted that the thermodynamic properties of the exhaust is assumed to approximate that of air [17] and hence, the density and dynamic viscosity values can be trivially found from standard thermodynamic tables for the specified operating pressures and temperatures. Also, if possible, we would like the flow meter to output the flow rate as an electronic signal since its value may be incorporated into the thermal control system model to improve accuracy of the model.

Requirement/Specification	**Operating conditions**
Operate at high temperatures	150 to 400°C.
Measure range of exhaust velocities	15 to 25 m/s
Sensitivity of instrument	Resolution of 0.2 m/s
Accuracy of measurement	Less than 5% (%AR) [1]
Desired reading output units	Average flow velocity[2] (m/s)
Fluid thermodynamic properties	Exhaust gas (ρ = 0.519 to 0.834 kg m^{-3}, $\mu = 2.42 \times 10^{-5}$ to 3.32×10^{-5} kg/m-s , Re ≈ 12000, i.e. turbulent flow conditions)
Cleanliness of fluid	May contain some soot particles (Quite clean)
Range of exhaust pressures	99 to 102 kPa [18]
Chemical properties of parts in contact	Chemically inert to exhaust
Pipe size	About 3" OD
Type of output	Local display on meter or electronic signal output (if possible)
Response time	Less than 1 second
Desired location of meter	Just upstream of the catalyst
Little wear and tear (robust)	Preferably no moving parts
Ease of usage	Simple or no calibration
Data sampling rate	~10 to 100 kHz

Table 7. Requirements and specifications for desired gas flow meter

Our team decided that designing and fabricating the desired gas flow meter ourselves is not a viable option due to limited resources, especially time. Hence, we look towards searching for various gas flow meters commonly used in industry applications similar to our system and corresponding suppliers. OMEGA Engineering, Inc. [16] provides a very useful flowmeter evaluation form that allows us to systematically identify appropriate meters based on some of our more important process parameters. This form is included in Appendix B for reference.

[1] Error stated as percentage of actual reading (AR). This value is generally accepted as an industry standard.
[2] Full flow meters are preferred over point sensors. Direct velocity meters are preferred over mass or volume flow rate meters.

Because our process requirements are quite stringent, many of the brainstormed concepts have to be rejected. Although it is the most versatile and least invasive meter, the ultrasonic (time of flight) meter is unsuitable because it cannot be used at high temperatures above 260°C. Positive displacement meters have a maximum temperature limit of 120°C. Our requirement is for the meter to be located just before the catalyst, and at that point, the exhaust will be heated up to at least 300°C. Mass flow rate meters like the Coriolis and thermal probe meters are inappropriate because they do not measure the velocity directly. Instead, the mass flow rate is measured and then divided by the product of the gas density and flow area to obtain the velocity. One of the major disadvantages of this method is that the gas density must be more or less constant and known. In our system, the density of exhaust gas is not constant and is largely dependent on many variables like gas composition, temperature and pressure. Furthermore, for some meters, the fluid must have very low viscosity or high speeds so that the Reynolds number (*Re*) is sufficiently high for them to operate. The averaging Pitot tube (or annubar) requires a minimum process *Re* of 40000 because it operates on the principle of converting kinetic energy of the flow into potential energy. For an accurate reading, kinetic energy must be sufficiently high. The flow nozzle is also unsuitable because the minimum process *Re* required is 50000.

Our research ultimately narrowed our choices to the following suitable meters: (1) differential pressure meters like the Venturi tube, orifice plate and rotameter, (2) thermal meters, (3) vortex flow meter, (4) turbine meter and lastly, (5) pressure transducer method. The working principle behind each of our choices is briefly explained as follows. For brevity, equations and schematics that highlight their exact operating principles have been omitted. Considerable information concerning their design, use and installation can be found in many literature sources (easily sourced online or in the library) and recommendations are made to refer to them when necessary. Two particularly comprehensive sources are The Engineering Tool Box [20] and the OMEGA Complete Flow and Level Handbook and Encyclopedia® [21].

DIFFERENTIAL PRESSURE METERS The Venturi meter, orifice plate are two common devices that operate on Bernoulli's principle that a decrease in flow area in a pipe causes an increase in velocity that is accompanied by a decrease in pressure. This is a direct consequence of conservation of energy for a fluid. The pipe where flow is to be measured must be designed to allow the insertion of a constricted tube (Venturi meter) or flat plate with a hole (orifice plate) with known diameter. A manometer measures the pressure drop and by utilizing the Bernoulli's and continuity equation, the instantaneous velocity can be determined. To account for the real-world effects brought about by non-zero viscosity and substantial compressibility of gases, empirical coefficients such as the Venturi and orifice discharge coefficients (functions of the orifice opening and/or Reynolds number) must be used in the flowrate equations. Depending on the required accuracy and pipe size, the orifice plate may have different orifice shapes. It is noted that the Venturi tube is the more precise but more expensive of the two [22].

Another relatively inexpensive meter that operates on differential pressure is the rotameter or variable area meter. This meter consists of a vertically oriented glass (or plastic) tapered tube containing a float within. The pipe must be designed to allow the meter to be attached vertically to the pipeline. Fluid flow causes the float to rise as the upward pressure difference and buoyancy of the fluid overcome the effect of gravity. It eventually stops at an equilibrium height that is a function of the flow rate. The tube may be calibrated and graduated in the appropriate flow units. Magnetic floats may also be used for the signal transmission functions.

THERMAL METERS The hot-wire anemometer and calorimetric meter are two thermal meters identified for our system. The anemometer measures a fluid velocity by determining the heat convected away by the flow across a very fine wire (on the order of 4 to 10 µm OD and 1 mm in length) being heated electrically. The change in wire temperature under constant current or current required to maintain a constant temperature can be expressed as a function of the heat loss, and thus related to the fluid velocity in accordance with the convective theory. Typically, the wire is made of tungsten or platinum. Due to its fragility (tiny size), it is mainly suitable for very clean flows. For dirtier flows, a platinum hot-film coated on a quartz fiber or glass tube (1″ long) or on a pyrex glass wedge at the edge tip may be used as shown in the schematics below.

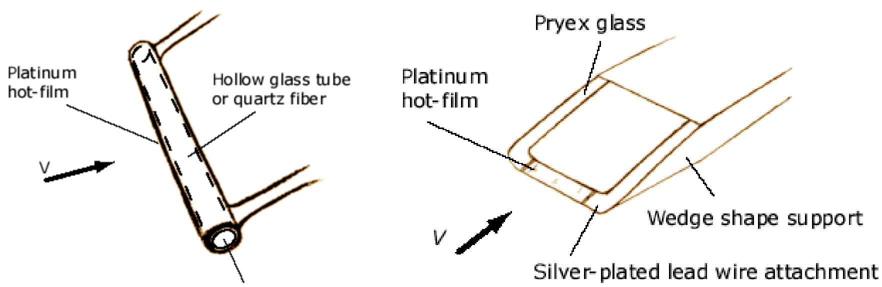


Figure 10. Schematics of hot-film anemometers

The calorimetric principle for measuring flow is based on two temperature sensors in close contact with the fluid but thermally insulated from each other. One of the two sensors is constantly heated and the cooling effect of the flowing fluid is used to monitor the flow rate. Under stationary conditions, there is a constant temperature difference between the two temperature sensors. When the flow increases, heat energy is drawn from the heated sensor and the temperature difference between the sensors are reduced. The reduction is proportional to the flow rate of the fluid. Response times depend on the thermal conductivity of the fluid. In general, lower thermal conductivity will require higher velocity for proper measurement. Such flow meters can achieve relatively high accuracy at low flow rates [20].

VORTEX FLOW METER Vortex shedding flow meters work by measuring the vibrations of the downstream vortexes caused by a barrier (bluff object) in the moving stream. The vortex shedding frequency is directly proportional to the velocity of the fluid in the pipe and is independent of fluid properties such as density, viscosity and conductivity. The only requirement is that the flow must be turbulent for vortex shedding to occur. In the piping system, the vortex effect is dissipated within a few pipe diameters downstream of the bluff body and causes no harm. The meter is usually made of stainless steel and includes the bluff body, a vortex sensor assembly and the transmitter electronics although that may be mounted remotely. Piezoelectric or capacitance-type sensors are used to detect the pressure oscillation around the body. External sensors, typically piezoelectric strain gages can sense the vortex shedding indirectly through forces exerted on the shedder bar. This is the preferred method in our application due to the high temperatures and possibly corrosive process involved. The meters are typically available in flange sizes from ½″ to 12″. Although flangeless meters (wafer body meters) have the lowest cost, the flanged ones are recommended for high temperature processes like ours.

TURBINE METER There are many different designs for turbine meters but they are all based on the same general principle. If a fluid moves through a pipe and acts on the vanes of a turbine, the turbine will begin to spin. The rate of spin is then measured to calculate the flow rate. It is essentially a mechanical relation between the average fluid velocity and angular speed. This angular velocity may be detected magnetically and calibrated to provide a very accurate measure of the flowrate through the meter [20]. These meters may be installed by integration directly into the pipeline or inserted as a probe.

PRESSURE TRANSDUCER METHOD To validate his theoretical model, Abu-Qudais [8] performed experimental measurements of instantaneous exhaust velocity using a fast-response dynamic pressure transducer that measures the instantaneous dynamic pressure at the exit of the exhaust port. His experimental set-up is shown in the schematic (Fig. 6). A thin, small volume probe is placed in at the desired location and connected to the piezoelectric pressure transducer. The exhaust velocity (V_e) is related to dynamic pressure (P_d) and exhaust gas density (ρ) by the relation $V_e = (2P_d/\rho)^{0.5}$ [8]. The response time of such a system is extremely fast (rise time ~2 ms) and the probe diameter and volume may be chosen to be very small so the flow pattern of the exhaust gas is not disturbed. It was difficult to obtain any other literature regarding the use of this method to measure flow velocity and verify the equation provided by Abu-Qudais. However, since he is able to use this method for his experiment on a single-cylinder engine exhaust, a system extremely similar to our application, we believe it is worth considering and effort is made to evaluate this method in comparison with the others.

FUNCTION 7: INTEGRATION INTO EXISTING ENGINE TEST BED

The catalyst test-rig system will be integrated into the location (where there is a removable pipe length of 15.125”) as shown in the following figure. The design of the pipe inlet and outlet of our system will be flanged and the diameters made exactly compatible with the rest of the pipe line. Clamps will be used to fasten our system to the test bed.

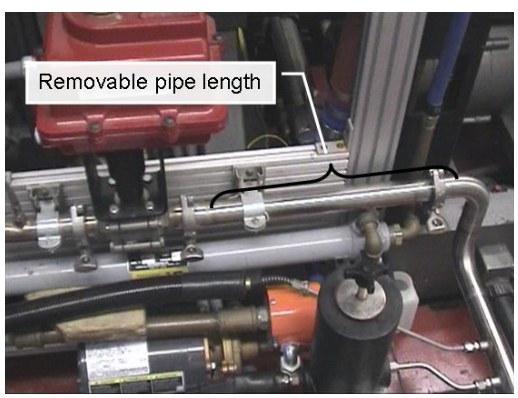


Figure 11. Designated location of catalyst test-rig

CONCEPT EVALUATION AND SELECTION

EVALUATION

To systematically facilitate the evaluation of all the concepts, we take advantage of the fact that each of our system sub-functions is largely independent of each other. Hence, we will evaluate the concepts separately under each function, and selecting the concept that gives the best performance for that function. Finally, the top choice for each function is combined together to arrive at our single solution for the system. It is noted that some refining of the concepts will be necessary to fully integrate the sub-functions.

FUNCTION 1A: HEATING SYSTEM From our design concepts, we took into consideration the feasibility of implementation and the ease of integration of the design systems in order to narrow down our options. Based on our team's initial assessment, we determined that the hot air mixer is unsuitable as it will affect the experimental results due to continuously varying air mix ratios. The wire mesh heater will not be as effective as the heated coil within the pipe due to the short exposure time. The internal fins system will be difficult to manufacture and hard to replace when damaged, while the heat pump system is not feasible at the desired operating temperature. These systems will thus be dropped from consideration. Our team did a preliminary engineering analysis on the remaining systems, and the results are presented as follows.

As we are currently unable to measure the gas velocity in the exhaust system, our team did a literature search in order to obtain an estimate for usage in our calculations. From the experimental results conducted on a four cylinder internal combustion engine [18], we determined with the engine running at 1000 rpm, a typical exhaust velocity that we can expect averages out to be 20 m/s, with a volume flow rate of 0.02 m^3/s.

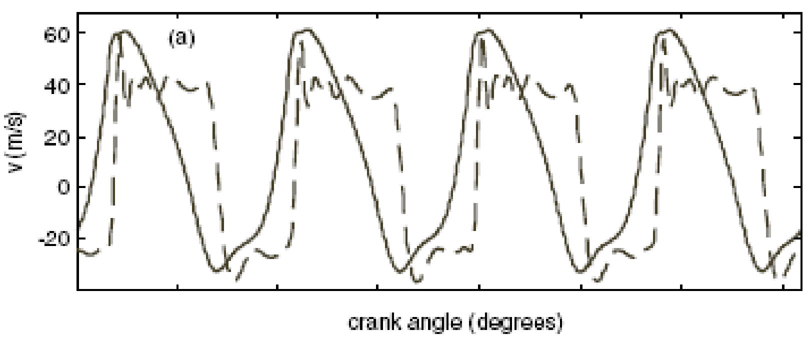


Figure 12. Exhaust velocity profile of an engine running at 1000 rpm

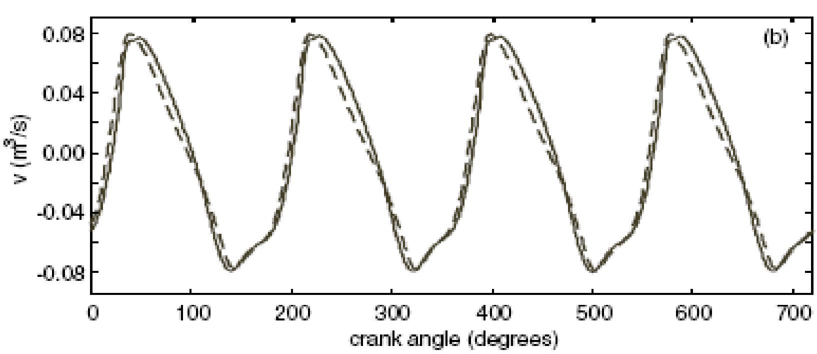


Figure 13. Exhaust volume flow rate profile of an engine running at 1000 rpm

Cross-flow Heat Exchanger By choosing arbitrary values for the outer pipe diameter, inner pipe diameter, cross-flow velocity and cross-flow air temperature, and assuming negligible conduction resistance between the two cross-flows, we determined that length of cross-flow piping required. The equations used for the calculations are included in Appendix C.

Variable	**Value**
Exhaust Velocity	20 m/s
Cross-flow Velocity	20 m/s
Cross-flow Initial Temperature	1000 K
Exhaust Initial Temperature	500 K
Exhaust Target Final Temperature	600 K
Diameter of Outer pipe	0.1 m
Diameter of Inner flow pipe	0.05 m
Reynold's Number of Cold Stream	26810 (Turbulent Flow)
Reynold's Number of Hot Stream	8525 (Transition Flow)
Nusselt's Number of Cold Stream	69.17
Nusselt's Number of Hot Stream	6.248
Total Conduction Resistance	0.00003 K/W
Total Convection Resistance	0.0372 K/W
$\left(\dot{M}c_p\right)_h$	188.7 W/K
$\left(\dot{M}c_p\right)_c$	112.8 W/K
Ratio of thermal capacitance	0.598
Number of Transfer Units	0.238
Heat exchanger effectiveness	0.2
Pipe length required	23.5 m

Table 8. Calculated values for cross-flow heat exchanger

The main advantage of this heat exchanger system is that exhaust outlet temperature can be easily controlled by varying the cross-flow volume flow rate. At higher volume flow rates, a higher exhaust outlet temperature can be achieved. However, this heat exchanger system requires a significantly long pipe length in order to achieve the desired exhaust temperature. The need for a separate air heating and storage system further increases the amount of space required. As such, integration of this system will be highly complicated.

Heating Chamber With a holding chamber already installed in the current engine system, our team carried out the engineering analysis based on the measurements we took from the laboratory. Assuming a similar volume flow rate, we calculated the new exhaust velocity in the larger heating chamber. An arbitrary value was selected for the chamber surface temperature, and the conduction resistance was calculated together with Biot number to ensure that a lumped capacitance model is applicable. The equations used for the calculations are included in Appendix C.

Variable	Value
Exhaust Velocity	20 m/s
Chamber Surface Temperature	1000 K
Exhaust Initial Temperature	500 K
Exhaust Target Final Temperature	600 K

Diameter of Chamber	0.15 m
Reynold's Number of Exhaust	4552 (Transition Flow)
Nusselt's Number of Exhaust	16.47
Total Conduction Resistance	0.0002 K/W
Total Convection Resistance	0.312 K/W
Biot Number	0.0006
Number of Transfer Units	0.223
Chamber length required	1.567 m

Table 9. Calculated values for heating chamber

The heating chamber system requires significantly less chamber length as compared to the counter-flow heat exchanger. However, since the chamber surface needs to be heated up to a high temperature, heat loss through surface conduction and radiation may be significant and proper insulation of the heating chamber needs to be considered.

Heating Pipe Similar to the heating chamber system, the heated pipe is set up on existing pipe lengths of the engine system. Measurements were taken from the laboratory for application in our calculations. An arbitrary value was selected for the pipe surface temperature, and the conduction resistance was calculated together with Biot number to ensure that a lumped capacitance model is once again applicable. The equations used for the calculations are included in Appendix C.

Variable	Value
Exhaust Velocity	20 m/s
Pipe Surface Temperature	1000 K
Exhaust Initial Temperature	500 K
Exhaust Target Final Temperature	600 K
Diameter of Pipe	0.05 m
Reynold's Number of Exhaust	26810 (Turbulent Flow)
Nusselt's Number of Exhaust	69.1
Total Conduction Resistance	0.002 K/W
Total Convection Resistance	0.312 K/W
Biot Number	0.008
Number of Transfer Units	0.223
Pipe length required	0.375 m

Table 10. Calculated values for heating pipe (external)

The heated pipe has the most feasible pipe length among the three systems. A length of 0.375 m can be easily selected from the existing engine exhaust pipe system for the fixture of heating elements. However, similar to the heated chamber system, the high pipe surface temperature might result in high heat losses and will require significant attention in the area of installing insulation.

If the heating element is placed inside the pipe instead of outside the pipe, the following values were obtained. The equations used in the calculations are included in Appendix C.

Variable	Value

Exhaust Velocity	20 m/s
Heating Element Temperature	1000 K
Heating Element Diameter	0.0125 m
Exhaust Initial Temperature	500 K
Exhaust Target Final Temperature	600 K
Diameter of Pipe	0.05 m
Reynold's Number of Exhaust	20107 (Turbulent Flow)
Nusselt's Number of Exhaust	54.9
Total Convection Resistance	0.312 K/W
Number of Transfer Units	0.223
Pipe length required	1.41 m

Table 11. Calculated values for heating pipe (internal)

The pipe length required for this system design is longer than the heated pipe design. Although energy is saved from not heating up the pipe, the transfer of thermal energy from the heating element to the exhaust gas is not as efficient as before. As having a heating element within the pipe is also not easily achieved, this system might face some complications in the integration phase.

FUNCTION 1B: HEATING ELEMENT The heating elements that are compatible with our design heating systems include a tubular heater, a band heater and a strip heater. Tubular heaters are versatile heaters which can be formed and shaped into various geometries for contact surface heating application. Band heaters can provide high temperature heating and can be clamped onto the required pipe sections easily. Strip heaters are also versatile heaters which can be bolted or clamped onto solid surfaces for heating applications. A schematic of the heating elements is shown in Figure 14 [19]. With the assumption of a mass flow rate of 0.02 m3/s, the amount of power required to raise the exhaust temperature by 100 K is estimated to be 1400 W. The characteristics of the heating elements are broken down below, together with the cost and the number of units required.

Heating Element	Size	Maximum Temperature	Maximum Watt Densities	Cost per unit	Number of Units required
WATROD Tubular Heater	Diameter: 0.0124 m	815 °C	18.6 W/cm^2	$150	1
Stainless Steel Band Heater	Diameter: 0.05 m Width: 0.125 m	760 °C	15.5 W/cm^2	$100	3
MI Strip Heater	Diameter: 0.05 m Width: 0.125 m	760 °C	15.5 W/cm^2	$100	3

Table 12. Summary of heating elements characteristics

(a) (b) (c)

Figure 14. Schematic of the heating elements under consideration: a) Tubular Heaters b) Band Heaters c) Strip Heaters

FUNCTION 2: PIPE INSULATION The following table summarizes the benefits and disadvantages of the various insulation options:

Product Name	Benefits	Disadvantages
Insulite	• Low thermal conductivity • Long lifespan • High maximum working temperature	• Expensive • Not flexible for pipe bends • Requires customization for our system • Not available in small quantities
Roxul RW 40 Blanket	• Flexible • Fire resistant • High maximum working temperature • Low thermal conductivity	• Expensive • Not available in small quantities
FoamGlass	• High maximum working temperature • Low thermal conductivity	• Rigid • Expensive • Not available in small quantities
Knauf KwikFlex	• Flexible • Low thermal conductivity	• Lower maximum working temperature • Expensive • Not available in small quantities
Knauf Pipe and Tank	• Somewhat flexible • Supports pipe structurally • Tough and durable	• Lower maximum working temperature • Expensive • Not available in small quantities • Hard to wrap around small diameters due to stiffness.
Knauf ET Blanket	• Flexible • Lightweight • Low thermal conductivity • High maximum working temperature	• Expensive • Not available in small quantities

Knauf 1000 Pipe Insulation	• Available in required pipe diameter • Inexpensive • Sold in small quantities • Easy to install	• Lower maximum working temperature • Not flexible
Knauf PVC Fitting Covers	• Available in required pipe angle and diameter • Inexpensive • Sold in small quantities • Easy to install	• Lower maximum working temperature • Not flexible

Table 13. Comparison of pipe insulation materials

FUNCTION 3: FIXTURE OF CATALYST The respective benefits and disadvantages are summarized below.

Concept	Benefits	Disadvantages
Stoppers	• Easy to obtain or manufacture • Easy to attach to pipe • Space between is adjustable → catalyst length can vary	• Might obstruct air flow • Might be hard to position the ring properly due to small pipe diameter • Catalyst has to have the same diameter as the pipe.
Tap screws	• Easy to acquire required parts • Low cost • Easy to incorporate on existing piping • Will be able to fix the catalyst securely • Allows for different lengths and diameters of catalyst brick.	• Possible leakage through the screw holes • Some air might pass around the catalyst but not through it.
Wire mesh for catalyst beads	• Easy to obtain or manufacture • Space between is adjustable to accommodate different sizes and volumes of catalyst beads.	• Difficult to attach to inner wall • Hard to position mesh properly • Attachment needs to be strong to pack beads tightly together
Clamp	• Able to secure catalyst well • Requires only one motion to tighten • Allows for different diameters or catalyst brick	• Possible leakage through holes in wall • Difficult to incorporate into existing pipe • Low manufacturability • Air might pass around the catalyst but not through it

Table 14. Comparison of design concepts for catalyst fixture

FUNCTION 4: ACCESSIBILITY The benefits and disadvantages associated with each of the concepts are summarized in the table below.

Concept	Benefits	Disadvantages
Door and hinge	• User access is effortless	• Leakage through the door

	• Relatively easy to manufacture	clearance for hinge operation
Removable pipe	• User access is almost effortless since clamps are easy to operate • High manufacturability • Highly leakage-proof	• Low cost with no excessive material
Drainage of beads	• Relatively easy access with funnel design allowing good bead drainage • Extremely air-tight due to taps • Effortless replacement of catalyst since only simple tap operation required	• Allows only catalyst composition to be tested • Structure of catalyst carrier cannot be tested since only beads are used • May obstruct exhaust flow • Relatively low manufacturability
Bolting side fins	• Good access to catalyst since it can be exposed entirely • Relatively easy to manufacture	• Time-consuming to replace catalyst because of bolts • Pipe halves may be difficult to manufacture • Some leakage through fins
Lift-out hatch	• Good access to catalyst since it is exposed entirely • Housing may interfere with exhaust flow	• Some leakage through screws • Time-consuming to replace catalyst because of screws • Higher cost due to more material • Relatively complicated to manufacture

Table 15. A comparison of the five design concepts for accessing the catalyst

FUNCTION 5: THERMAL CONTROL SYSTEM The design of the thermal control system should provide accurate, quick and sensitive temperature measurements in hot exhaust gas environment and allow for fast and easy adjustments to control parameters in order to reach desired temperature levels with minimal deviation from the actual state. After much discussion within the team, we have come up with three main concepts as shown in the morphological chart. These possible concepts are closely related to the possible concepts for the heating system as the chosen heating system will set certain requirements which the thermal control system has to follow. Each of the three design concepts has its advantages and disadvantages as shown in the table below.

Concept	Advantages	Disadvantages
Vary hot fluid temperature or volume flow rate in a counter-flow heater setup	• There is no contact between the exhaust gas (heated object) and the hot fluid (heating object), thus the composition of the exhaust gas will not be affected.	• Need to heat up hot gases to temperatures greater than the catalyst effective temperature of at least 300°C. This would require a huge amount of energy which translates to high cost. • A long length (in the order of 10m) is required for the heat transfer process to be effective.

		This would make our entire system too huge and impractical.
Vary temperature of heating material by adjusting current/voltage	• There are various types of heating materials available commercially. • Calibration can be performed easily to relate the surface temperature of heating material to the current or voltage running through or applied across it. • It is compact as the heating material surface could be maximized by making use of certain geometry.	• High power requirement to bring the heating material up to temperatures much greater than 300°C (approximately 700°C) in order to keep within a compact volume for practical purposes.
Vary valve opening to control ratio of hot gas to exhaust gas to adjust mixture temperature	• This is the most effective heat transfer process because the heating component (hot gas) is directly in contact with the heated component (exhaust gas).	• Need to heat up hot gas to temperatures greater than the catalyst effective temperature of at least 300°C. This would require a huge amount of power which translates to high cost. • By adding hot air, the exhaust gas gets diluted, this might adversely affect the catalytic conversion process. • We cannot account for any chemical reaction between the emission compounds and the hot gas which might release more harmful or undesirable compounds.

Table 16. Comparison of temperature controller concepts

After examining the overview of possible concepts, we have proceeded to a deeper level of concept generation by breaking down the system into two smaller components: (1) the temperature sensors and (2) the temperature controller.

As shown in our QFD, the most important customer requirement is for the catalyst test rig to be integrated with an adjustable temperature control in order to match the exhaust gas temperature of a single cylinder engine to that of a multi-cylinder engine by heating. Therefore, it is critical to come up with a thermal control system which could meet the target values that we have set as shown in tables below.

Requirements/Specifications for temperature sensors	**Target Values**	**Justifications**
Accurate temperature measurements	• At least within 5°C of actual temperature	• Accurate measurements are needed as inputs so that the controller will be able to adjust the control parameters to achieve the desired output. • The efficiency of catalysts varies with temperature, thus accurate measurements are required for research on catalyst performance.
Quick response to temperature changes	• Ready for accurate measurements within 10 seconds after temperature change	• A sensor with fast response time minimizes inaccuracy due to noise. • A fast response is required so that the controller will be able to make adjustments quickly. • Minimize amount of time spent on experimental data acquisition.
Adequate degree of sensitivity	• Able to detect at least 5°C in temperature change	• A sensitive sensor will not require a signal amplifier, thus reducing the amount of equipment needed. • Higher degree of sensitivity is not required as it is not a major concern to monitor minute temperature changes, for eg. ±1°C in our project.
Wide temperature range	• Standard room temperature of 25°C to at least operating temperature of 400°C	• Exhaust temperatures can vary when different fuels are burned. • Exhaust temperature entering and leaving our heater is about 160°C and 300°C respectively, thus it needs to measure a wide range of temperature. • Desired range is set to account for any system fluctuations.
Capable of withstanding operating conditions for continuous operation	• Able to remain perfectly functional at 400°C for at least 5 hours	• Only contact sensors could be employed due to the transparent nature of gases. Sensors must be suitable for gas applications. • Experiments can last for hours, thus sensors must be able to work in harsh conditions due to the composition and high temperature of exhaust gas.

Ease of integration	• Must be small enough to be inserted into pipe • Must be able to be removed and replaced within 5 minutes	• There is limited space for inserting sensors because leakage of exhaust gas has to be prevented at all times. • The sensor should be able to be customized easily into required specifications to fit into the existing engine test bed.
Affordability	• Should not take up a huge portion of project budget ~ $50	• Cost of equipment can affect the feasibility of our project. • Having the best sensors is not the most critical thing in our system, we need to find the right balance between cost and quality.

Table 17. Temperature sensor requirements and specifications

Requirements/Specifications for temperature controller	Target Values	Justifications
Minimize steady state error	• To be within 5% of steady state value	• The controller should be able to adjust the exhaust temperature to as close to the desired level as possible in order to minimize experimental errors.
Fast response	• To adjust its output parameters so that desired temperature of heating material could be reach in 5 minutes.	• This is also dependent on the specifications of the heating system. The controller should be able to adjust its output parameters fast enough to reach this aim. • The shorter the time required, the more the number of tests could be conducted.
Supports operation, data logging and control configuration via a Window® PC		• This makes it much easier for data collection, processing and analysis. • LABVIEW or other controller interface/software could be used.
Affordability	• Must be kept within allocated budget of $400 dollars for entire system	• Cost of equipment can affect the feasibility of our project. • Having the best sensors is not the most critical thing in our design; we need to find the right balance between cost and quality.
Overall Performance		• The controller must be able to

		work in theory and more importantly, in our application.

Table 18. Temperature controller requirements and specifications

FUNCTION 6: GAS VELOCITY MEASUREMENT The pros and cons of each suitable gas flow meters as described previously are summarized in the table below.

Flow meter	Merits	Disadvantages
Venturi	• Easy installation as a flange insert • Relatively low pressure loss • High degree of accuracy (± 0.5%) • Robust and low in maintenance leads to cost savings • High reliability	• High set-up cost (~ 1000 USD) • Not flexible (permanent installation) • Requires careful calibration • Soot particles may choked pressure taps • Interference with actual flow conditions due to constriction
Orifice plate	• Highly flexible installation (easy replacement of different orifice shapes to accommodate different flow conditions) • Relatively low cost (~ 200 USD) • Low in maintenance • Possibility of manufacturing it ourselves	• Relatively large head loss • Lower degree of accuracy (± 4%) • Relatively high wear and tear • Interference with actual flow condition due to constriction • Requires careful calibration
Rotameter	• Easy to install • Relatively less invasive	• Requires special design for high temperatures (higher cost ~ 500 to 900 USD) • Requires careful calibration • Moving parts subject to wear and tear • Low degree of accuracy (up to ± 10%)
Hot-wire anemometer	• Great degree of accuracy (± 0.1%) • Extremely high frequency response (> 10 kHz) • Very non-invasive • Easy to install	• Needs to be recalibrated frequently due to soot accumulation • Relatively high cost (~ 400 USD) • Fragile and easily subject to damage especially with relatively dirty exhaust although this may be overcome by special design
Calorimetric	• Relatively high degree of accuracy (± 2%) • Very non-invasive • Easy to install	• Slower response time due to low conductivity of gas • Relatively high cost (~400 USD) • Requires calibration
Vortex shedding	• High degree of accuracy (± 0.75 to 1.5%) • Robust, relatively low wear • Low in maintenance • Easy installation with mating flanges	• Soot particles may affect accuracy • Requires special design for high temperatures (higher cost ~600 to 900 USD) • Requires long straight upstream piping to first condition flow

		• High degree of interference with actual flow • Requires calibration
Turbine	• Great degree of accuracy (± 0.5%) • Easy to install	• Requires special design for high temperatures (higher cost ~ 500 to 1000 USD) • Moving parts subject to wear and tear • Requires calibration
Pressure transducer	• High response time (~ 2 ms) • Very easy to install • Currently in use in the system already	• Requires knowledge of exhaust gas density which is not constant (affects accuracy) • Relatively expensive (~ 500 USD) • Requires calibration

Table 19. A comparison of the various gas flow meters for our system

It is noted here that the specified costs for each meter are estimated values provided by various flow meter suppliers such as OMEGA Engineering, Topac, and North Central Engineering from our system specifications. Although the figures for one particular meter may vary from supplier to supplier, the cost of the different meter types can be differentiated into distinct classes from low to high. Many of these suppliers can be sourced through the Flowmeter Directory [23], an extremely comprehensive online resource that features well-known manufacturers of all types of flow meters. More detailed specifications and price information from various suppliers will be sourced after the most appropriate meter type is selected.

SELECTION

Pugh charts are drawn up for each function to systematically select the option that gives the best overall performance based on a set of specific criteria. The criteria are derived from our QFD diagram and will differ slightly for each function depending on the nature of the function. It is noted here that the term "functionality" refers to how "user-friendly" the design is. For example, a meter may be easy to read but if it requires excessive calibration, it will rate low on this criterion. A list of criteria was stated in each chart in order to compare whether the possible design concepts can satisfy it. A "(+)" sign is given when the criterion could be satisfied easily, a "(0)" is given when the criterion may or may not be satisfied easily and a "(-)" is given when the criterion could not be satisfied at all.

FUNCTION 1: HEATING SYSTEM The selection of the heating element and heating system is presented in the Pugh chart below. The criteria for the selection of the heating system are as shown in the leftmost column.

	Cross-flow Heat Exchanger	Heating Chamber	Heated Pipe (External)	Heated Pipe (Internal)
Length	–	0	+	0
Ease of Installation	–	+	+	–
Heat Loss	0	–	–	+
Even Heating	0	–	0	+
Fast System Response	–	–	+	+

Cost of Installation	–	+	+	+
Total (+)	0	2	4	4
Total (-)	4	3	1	1
Total	– 4	– 1	+ 3	+ 3

Table 20. Pugh chart for heating system

	WATROD Tubular Heater	Stainless Steel Band Heater	MI Strip Heater
Maximum Temperature	+	0	0
Maximum Power	+	+	+
Overall Cost	+	–	–
Ease of Installation	–	+	+
Fast System Response	+	+	+
Total (+)	4	3	3
Total (–)	1	1	1
Total	+ 3	+ 2	+ 2

Table 21. Pugh chart for heating element

From the Pugh charts above, we can conclude that the optimal heating system is the heated pipe design, with an external heating element. The most suitable heating element is this case is the WATROD Tubular Heater.

FUNCTION 2: PIPE INSULATION In the Pugh Chart below, effectiveness is judged by comparing the maximum working temperature of each material. Materials with values lower than 500°C were assigned neutral values. PVC fitting covers were assigned a positive value for aesthetics since it features a smooth white PVC outer covering as compared to the other matted and uncoated materials. For availability, the 1000 pipe insulation and PVC covers were assigned a positive value since they were available in small quantities, unlike the others. Lastly, for ease of installation, the materials were assigned a positive value if they can be easily placed around the pipe and secured.

	Insulite	Roxul Blanket	Foam Glass	Kwik Flex	Knauf Pipe and Tank	ET Blanket	1000 Pipe Insulation	PVC Fitting Covers
Effectiveness	+	+	+	0	0	+	+	0
Aesthetics	0	0	0	0	0	0	0	+
Cost	-	-	-	-	-	-	+	+
Availability	-	-	-	-	-	-	+	+
Ease of Installation	-	+	-	+	0	+	+	0
Total (+)	1	2	1	1	0	2	4	3
Total (-)	3	2	3	2	2	2	0	0
Total	-2	0	-2	-1	-2	0	+4	+3

Table 22. Pugh chart for various types of insulation

FUNCTION 3: FIXTURE OF CATALYST The Pugh chart is shown below. Functionality was determined by the ease of securing the catalyst. Stoppers and the wire mesh were given negative values since it is difficult to install the second stopper/wire mesh to fix catalyst. The clamp and tap screws were easy to use, hence the positive value.

A concept's effectiveness was judged by how well it performed its function. Stoppers and the wire mesh were assigned neutral values since they were able to secure the catalyst quite well. The clamp and tap screws would be much more effective, hence the positive value.

In terms of aesthetics and cost, positive values were assigned if the idea had a simple outline and the materials were inexpensive to acquire. The clamp would be costly due to the amount of machining that would be required to install it onto a pipe. Tap screws and clamps had negative aesthetics ratings since they featured bulky outlines. Manufacturability also took these factors into account.

	Stoppers	Tap Screws	Wire Mesh for Catalyst Beads	Clamp
Functionality	-	+	-	+
Effectiveness	0	+	0	+
Aesthetics	0	-	0	-
Cost	+	+	+	-
Manufacturability	+	+	+	-
Total (+)	2	4	2	2
Total (-)	1	1	1	3
Total	+1	+3	+1	-1

Table 23. Pugh chart for fixture elements

FUNCTION 4: ACCESSIBILITY The concepts are ranked according to the following criteria: (1) cost, (2) functionality, (3) leak-proof, (4) aesthetics, (5) manufacturability, and lastly (6) effectiveness.

	Door-hinge	Removable pipe	Bead drainage	Bolt side-fins	Lift hatch
Cost	0	+	+	0	–
Functionality	+	0	+	–	–
Leak-proof	–	+	+	–	0
Aesthetics	+	+	+	–	0
Manufacturability	0	+	+	0	–
Effectiveness	0	+	0	+	+
Total (+)	2	5	5	1	1
Total (-)	1	0	0	3	3
Total	+1	+5	+5	–2	–2

Table 24. Pugh chart for accessibility concepts

From the Pugh chart, the concepts of bead drainage and removable pipe offer the optimal performance for the accessibility function. However, the bead drainage limits catalyst testing to only composition. Catalyst carrier structure cannot be tested. Hence, our team decided on the removable pipe as our selected concept for accessing the catalyst because it is the most leak-proof and fulfills the function to our satisfaction.

FUNCTION 5: THERMAL CONTROL SYSTEM Using the requirements/specifications summarized in Table 17 and Table 18, we set up two Pugh charts separately below for the possible temperature sensors and temperature controllers that were identified during the process of concept generation.

	Thermocouple	RTD	Thermistor
Accuracy	+	+	+
Response	+	–	+
Sensitivity	+	+	+
Temperature Range	+	+	–
Capable of continuous operation	+	+	–
Ease of integration	+	+	–
Affordability	+	–	+
Total (+)	7	5	4
Total (–)	0	2	3
Total	+7	+3	+1

Table 25. Pugh chart for temperature sensors

	Commercial Controller	Self-design Controller
Minimize Error	+	0
Response	+	0
Can be linked to Window® PC	+	+
Affordability	–	+
Overall Performance	+	0
Total (+)	5	2
Total (–)	1	0
Total	+4	+2

Table 26. Pugh chart for temperature controllers

After using the Pugh charts, we have selected the thermocouple and the commercial controller as the most suitable options for our temperature sensor and temperature controller.

FUNCTION 6: GAS VELOCITY MEASUREMENT The various flow meters are ranked according to the following criteria: (1) ease of integration, (2) cost, (3) accuracy, (4) reliability, (5) functionality and (6) durability. It is noted here that the functionality rating for all the meters except the calorimetric meter is zero. This is because all the meters will require some calibration process before use. In the case of the anemometer, frequent calibration is required but the calibration process is relatively simple to perform, hence, it still attains a rating of zero.

	Venturi meter	Orifice plate	Rotameter	Hot-wire anemometer	Calorimetric	Vortex shedding	Turbine	Pressure transducer method
Ease of integration	0	+	+	+	+	0	+	+
Cost	–	+	–	0	0	–	–	–

Accuracy	0	–	–	+	–	+	+	–
Reliability	+	+	–	+	+	–	0	-
Functionality	0	0	0	0	0	0	0	0
Durability	+	+	–	0	–	0	–	0
Effectiveness	0	0	0	+	+	–	0	–
Total (+)	2	4	1	4	3	1	2	1
Total (-)	1	1	4	0	2	3	2	4
Total	+1	+3	–3	+4	+1	–2	0	–3

Table 27. Pugh chart for gas flow meters

The above Pugh chart shows that the two most optimal gas flow meters are the orifice plate meter and hot-wire anemometer. These two meters offer the best performance for measuring the exhaust velocity just before the catalyst. Essentially, there is a trade-off between cost and accuracy for these two meters. The orifice meter is cheap in comparison to the anemometer but has a much lower degree of accuracy. Accuracy is an important requirement and our team believes that the anemometer will be a better investment in this respect. Although the instrument may be more fragile, special designs like coating a thin platinum film on a glass tube instead of using an actual thin wire can be implemented to increase durability. On the other hand, the orifice plate suffers from wear and requires constant replacement. Since a plate costs about 50 USD, the maintenance costs will eventually offset the initial savings.

SELECTED CONCEPT

HEATING SYSTEM

The most suitable heating system as determined from the Pugh chart is the heated pipe. A tubular heating element will be coiled around a selected section of the existing exhaust pipe (0.05 m outer diameter) system for up to a length of 0.375m. The tubular element will heat the surface of the exhaust pipe till it reaches a desired temperature (1000 K used in calculations). With a energy density of 18.6 W/cm^2, having the tubular element coiled around 50% of the 0.375 m external surface area would provide a power input of 5500 W, which is sufficient to cover the 1400 W requirement of heating up the exhaust gas. The heated pipe is part of the existing engine system, and will be free of cost, while the heating element is estimated to cost around 150 USD.

PIPE INSULATION

We see that the 1000 pipe insulation by Knauf is the most suitable for our purposes. However, since it is semi-rigid, it would not be suitable for the joints in the piping. Hence, the PVC fitting covers with the second highest rating would be used for such joints. Based on calculations from the industry standard 3EPlus v4 software provided by the National Association of Insulation Manufacturers, we obtained a suitable 1000 pipe insulation of 2” (0.0508 m) in order to prevent a maximum temperature drop of 60°C. The entire system would have an estimated cost 40 USD.

CATALYST FIXTURE AND ACCESSIBILITY

From the Pugh Chart, we see that the tap screws have the highest rating and are the most suitable for our needs. We will thus utilize this in our system. However, the possible leakage through the sides of the catalyst needs to be considered. In this sense, perhaps rubber padding and tight tolerances can be included to the system to restrict possible air flow pass the outer surface of the catalyst brick. It was also felt that the tolerance in the diameter of the housing may be tight enough for the catalyst to fit snugly through it without any need of a securing mechanism like the tap screws. In this respect, our team has decided to wait for the catalyst to be first provided and then test the fit before ascertaining if the tap screw mechanism should be included. For accessibility, the quick-clamp removable pipe concept is selected due to its leak resistance and functionality.

THERMOCOUPLE SELECTION

The selected thermocouple is a Type K (Chromel (Ni-Cr alloy) / Alumel (Ni-Al alloy)), known as the "general purpose" thermocouple. It is low cost and, owing to its popularity, it is available in a wide variety of probes. They are available in the −200 °C to +1200 °C range. Sensitivity is approximately 41µV/°C. It has a standard limit of error of the greater of 2.2°C or 0.75% of temperature range. Based on a selection tool on omega.com [16], we managed to obtain a list of suitable products whose prices ranged from 27 USD to 45 USD a piece.

CONTROLLER SELECTION

The controller for our system will be purchased commercially rather than self-designed using LabView. One such suitable controller for our system would be a simple on-off controller which supports operation, data logging and control configuration using a Windows® PC. It should be able to run on a regular power supply in lab. A variety of suitable models are available on watlow.com.

GAS FLOW METER

Our team has decided on the hot-wire anemometer as the most optimal meter to measure the exhaust velocity. This instrument satisfies all of our requirements and can easily produce an analog signal as an output so data is easily collected. Although it is a bit costly, the initial investment will be offset by cost savings later on due to the relatively low maintenance. Furthermore, this is also the least invasive of meters, requiring only the insertion of a small thin wire or probe. Currently, our team is waiting for the response of various suppliers we contacted for quotations and detailed specifications in order to ascertain the specific accommodations we have to make to our actual test-rig design to integrate the meter. A schematic of a typical constant-temperature hot-wire anemometer [24] is shown below as a reference. It is anticipated that only a small tap hole needs to be drilled in the pipe for the insertion of the probe. Should the budget present an obstacle to acquiring such a meter, the worst-case scenario is that we can make do with an orifice plate meter, our second-best option

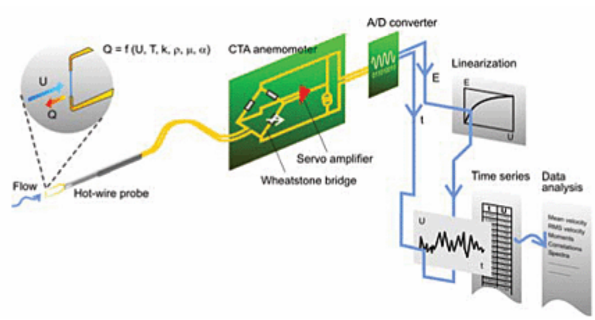


Figure 15. Typical modern constant-temperature hot-wire anemometer

Finally, our entire test-rig will be integrated as a system into the engine test bed at the designated location as shown by Figure 11. For compatibility, the material used in building our test-rig will be stainless steel T304L (same material as the existing pipes in the engine) or other metals like aluminum with similar properties. The entire rig will fit into a length of 0.384 m (15.125"). A rough picture of how our system will look like is shown in the following figure.

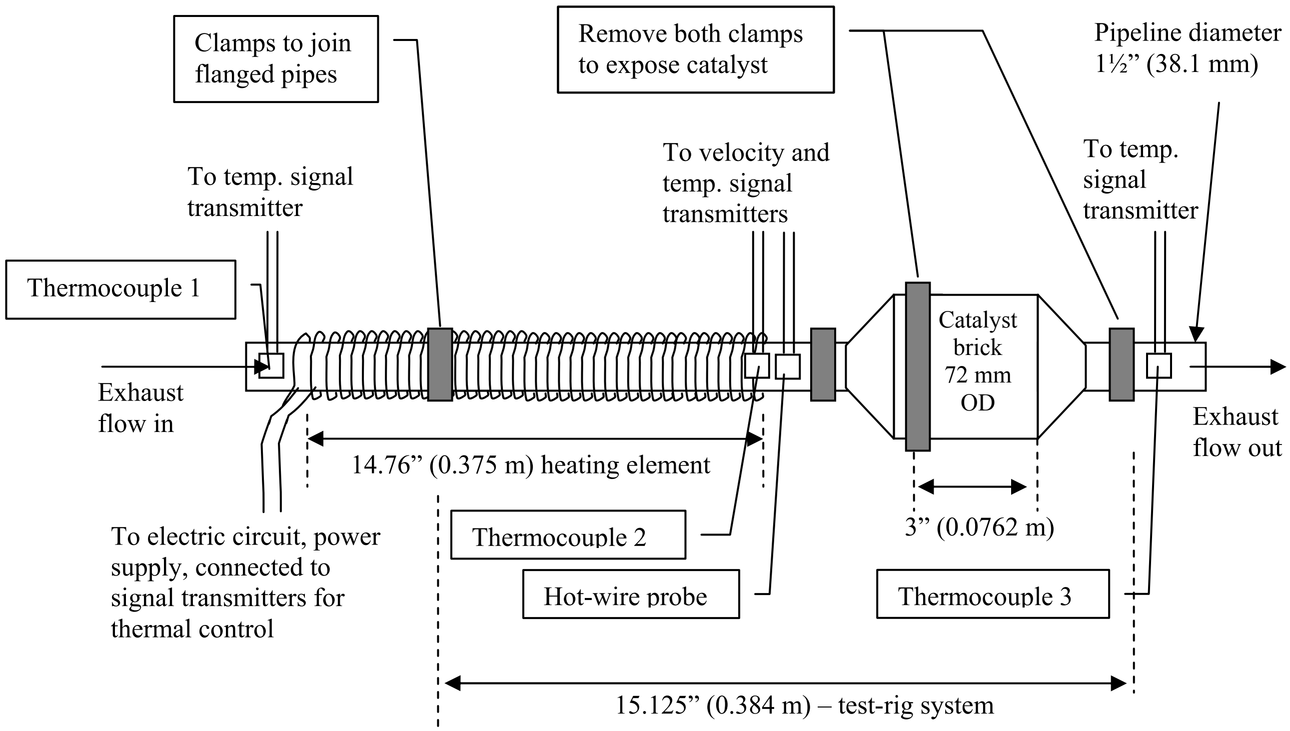


Figure 16. Sketch of full catalyst test-rig system integrated into engine test bed

The estimated cost breakdown of our test-rig system is summarized in the table below. Clearly, we will exceed the budget of 400 USD. It may be necessary to modify the selection of some of our components in order to reduce costs. However, at the same time, we must not overlook the importance of certain client requirements such as the degree of accuracy in the measurements. Thus, it may be necessary to increase our budget to accommodate the more expensive instrumentation that will meet the stringent process requirements.

Sub-system	**Estimated cost (in USD)**
Heating system	150
Pipe insulation	40
Housing material	100[3]
Thermal sensors	105[4]
Thermal controller	500
Gas flow meter	400

[3] This is an estimated budget we decided on to account for any special customization we may require from suppliers.
[4] Price of three thermocouples at 35 USD per piece.

Total estimated cost of prototype	1295

Table 28. Estimated cost breakdown for catalyst test-rig prototype

ENGINEERING ANALYSIS

QUANTITATIVE ANALYSIS

HEATING SYSTEM The heated pipe segment is our selected heating concept. The following figure provides a schematic of the pipe segment which will be heated to a surface temperature, T_s. The engine exhaust enters with a velocity of u_f and temperature $\langle T_f \rangle_0$. Constant velocity throughout the pipe is assumed and the exhaust exits at a temperature of $\langle T_f \rangle_L$.

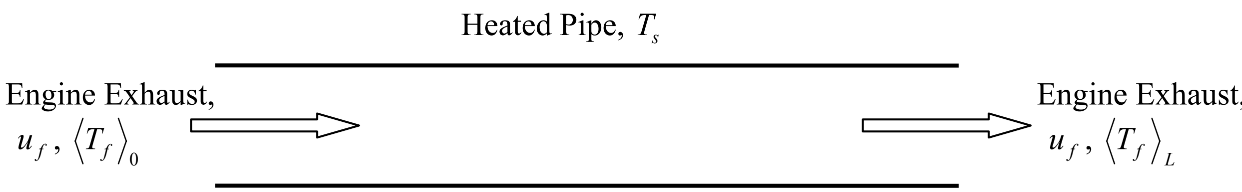


Figure 17. Schematic of heated pipe system

The most important design variable in this system is the length, L, of the heated pipe segment required for the exhaust to achieve the specified temperature before it enters the catalyst. Since the heated pipe system is placed only a short distance upstream of the catalyst, it is relatively reasonable to assume that $\langle T_f \rangle_L$ is a close representation of the exhaust temperature just before entering the catalyst. The following details the heat transfer calculations used to obtain L.

The nomenclature table below summarizes the variables used in the calculations that follow.

u_f	Mean fluid velocity
D	Pipe diameter
T	Wall thickness
ν_f	Kinematic fluid viscosity
Pr	Prandtl number
k_s	Thermal conductivity of pipe
k_f	Thermal conductivity of fluid
L	Length of heated pipe
c_p	Specific heat capacity of fluid
Q	Volume flow rate
ρ	Density of fluid

Table 29. Nomenclature table for heat transfer calculations

Several assumptions are made for our model and important parameter values are assigned as follows.

- Volume flow rate[5], Q = 0.02 m³/s
- Pipe diameter, D = 0.0381 m (1.5")
- Wall thickness, t = 0.001651 m (0.065")
- Properties of exhaust are comparable to air so that ν_f = 37.3 x 10-6 m²/s, ρ = 0.706 kg/m³ and c_p = 1017 J/kg·K,

The velocity through the pipe is thus calculated as $u_f = \dfrac{Q}{\pi D^2/4}$ = 17.5 m/s.

The two important parameters, Reynolds number (Re_D) and Nusselt's number for turbulent flow ($\langle Nu\rangle_{D,t}$) are calculated according to the following equations. The Prandtl number (Pr) is 0.69.

$$\mathrm{Re}_D = \frac{u_f D}{\nu_f} = 17875, \qquad \langle Nu\rangle_{D,t} = 0.023\,\mathrm{Re}_D^{0.8}\,\mathrm{Pr}^{0.4} = 50.0 \tag{1,2}$$

The convection resistance $R_{ku,C}$ is calculated as follows, where k_f = 0.0395 W/ m·K and A_{ku} is the area of convection so that $A_{ku} = \pi DL$.

$$R_{ku,C} = \frac{D}{A_{ku}\langle Nu\rangle_{D,t} k_f} = \frac{0.161}{L} \tag{3}$$

The number of transfer units (NTU) then calculated, where R_Σ is the summation of convection and conduction resistance. Conduction resistance is assumed to be negligible at the present moment. $\dot{M}$ refers to the mass flow rate of the fluid and is easily calculated from Q and ρ.

$$NTU = \frac{1}{R_\Sigma\left(\dot{M}c_p\right)} = 0.595L \tag{4}$$

Heat exchanger effectiveness for bounded flow (ε_{he}) is related to NTU via the following equation.

$$\varepsilon_{he} = \frac{\langle T_f\rangle_0 - \langle T_f\rangle_L}{\langle T_f\rangle_0 - T_s} = 1 - e^{-NTU} \tag{5}$$

Assuming the maximum heating scenario and assigning values to the following parameters such that $\langle T_f\rangle_L$ = 600 K (326.85°C), $\langle T_f\rangle_0$ = 500 K (226.85°C) and T_s = 1000 K (726.85°C), equation 5 and 4 can be used to solve for L. The required length of heated pipe is thus, determined to be 0.375 m (14.76").

To ensure that our assumption of negligible conduction resistance is valid, the conduction resistance R_k is calculated, where R_1 and R_2 refer to the inner and outer diameter of the pipe respectively, with R_2 = 0.01905 m (0.75") and k_s = 15 W/m·K.

$$R_k = \frac{\ln\left(\frac{R_2}{R_1}\right)}{2\pi L k_s} = 0.0026\ \text{K/W} \tag{4}$$

The Biot number (Bi) is then found to be less than 0.1 as shown in the following equation.

$$Bi = R_k / R_{ku} = 0.006 < 0.1 \tag{5}$$

[5] Q is estimated previously from the literature review [25]

Hence, our assumption of negligible conduction resistance is valid.

Besides the required length, the second important variable is the necessary heating power. From prior work, the WATROD Tubular Heater was selected to be the optimal heating coil to provide this power. Based on estimations of the exhaust volume flow rate [25], the heating power required is determined to be 1436 W as follows.

Heating power = $Q\rho c_p \Delta T$
$= 0.02\ m^3/s \times 0.706\ kg/m^3 \times 1017\ J/kgK \times 100\ K = 1436\ W$

To compensate for heat losses, a tubular heater of 2000 W was selected for our final design.

We like to make a special note here concerning the Nusselt's number used in our calculations. This number was estimated using the classical Dittus-Boelter equation given by equation 2. However, according to Depcik and Assanis [26], a better correlation can be given by the following equation. This correlation was developed from the microscales of turbulence and is proposed by the authors to be universal for both the intake and exhaust flow of an internal combustion engine. The coefficient in the equation was determined using a least squares curve-fit to all available experimental data (from spark-ignition engines of varying size and speed ranges) at the intake and exhaust ports provided by past literature. Thus, this correlation is assumed to be valid for the entire range of spark-ignition engines, including that of ours.

$$\langle Nu \rangle_{D,t} = 0.07\,\mathrm{Re}_D^{0.75} = 108 \qquad (6)$$

As shown, the new correlation yields a Nusselt's number that differs from our original one by a rough factor of two. Following through the same steps to obtain the required length of heated pipe, we find that L will now be almost halved from the original value. Our team took a more conservative stance and chose the original design length (which is longer) because significant heat losses have to be accounted for. A longer heated pipe length will also allow more room for error, which may be quite significant due to the necessity of making so many simplifying assumptions in our heat flow calculations. Furthermore, the experimental data used to develop the new correlation are measured at the exhaust port, whereas our system is located much further downstream. Lastly, manufacturing considerations meant that it was more convenient to have a longer pipe so that conical section that expands the cross-section for the catalyst to pass through can be made longer. Longer conical sections can be purchased from McMaster-Carr as 7-inch reducing couplers. If the shorter pipe length were chosen, our design may be fitted as a straight length (without any bends) into the system, but this meant that we had to fabricate the very short conical sections out of stainless steel stock ourselves. After speaking with the shop technicians, we found that such a process will require a lot of time (stainless steel requires a slow feed rate) and is not even feasible within the facilities of the shop. We also could not find a supplier who would customize the required part for us at a reasonable price.

THERMAL CONTROL SYSTEM The system to be implemented is a commercial simple and direct on-off thermal controller, which aims to regulate a single set-point temperature by adjusting the power input to the heating system. This set-point is designated as the exhaust temperature just before it enters the catalyst or $<T_f>_L$. As the power input is varied, the surface temperature of the heated pipe length, T_s, is adjusted accordingly. From equation 5, the changing value of T_s

necessarily implies a corresponding change in $<T_f>_L$ in the same direction since the right-hand side must be constant (*NTU* is dependent only on parameters with fixed values). Hence, when the regulated $<T_f>_L$ is above the set threshold, the power input is turned off. T_s decreases and $<T_f>_L$ also falls. Once $<T_f>_L$ drops below the set threshold, the power input is turned on again. Consequently, T_s increases and $<T_f>_L$ is brought back up to the regulated temperature point.

To obtain a more complete picture of this simple thermal control system, we attempted to derive a mathematical model of the system. Assuming small deviations from steady-state operation, the equation describing the system behavior is found to be

$$RC\frac{d\theta_o}{dt} + \theta_o = Rh + \theta_i \quad (7)$$

where θ_o and θ_i are small increases from the steady-state outlet and inlet temperature. Note that the outlet temperature here refers to $<T_f>_L$ if we assume that the distance between the heated pipe oulet and the designated set-point just upstream of the catalyst is sufficiently small to neglect any temperature effects in between. *C* and *R* refer to the thermal capacitance of the exhaust and heat transfer resistance in the heated pipe respectively. Since conduction resistance is neglected, *R* is found from equation 3 and assumed to be constant (i.e. convection coefficient is almost constant). The heat input to the exhaust from the heat source is referred to as *h*. Taking Laplace transforms with zero initial conditions then yields the following model for our system.

$$\Theta_o(s) = \frac{R}{RCs+1}H(s) + \frac{1}{RCs+1}\Theta_i(s) \quad (8)$$

The model shows that the outlet temperature depends on two factors, the heat input and the inlet temperature of the exhaust. For now, we will assume that the steady-state point has no heating and an inlet temperature of 423 K (150°C). This also means that the outlet temperature at steady-state is approximately 423 K.

First, we consider the case where there is heating without any control. Our heat input *H* is modeled as exponentially increasing from steady-state zero until 1100 W. Although our heater operates at 2000 W, we chose a lower value to account for heat losses, significant due to the difference in ambient temperature and the external heating coil. Furthermore, a rough estimate of the convective heat transfer coefficient h_c, is found to be 51.8 from the Nusselt's number since $h_c = <Nu>_{D,t}\, k_f / d$, where *d* refers to the inner diameter. This allows us to calculate with some uncertainty, the heat transfer rate $q = h_c \pi d L(T_s - <T_f>_o)$ = 1164 W. This value is in agreement with our heat input model. The time constant, τ, associated with the rise is taken as RC_T where *R* is as previously defined and C_T is the capacitance of the steel pipe, calculated to be 267 J/K. Again, conduction resistance is negligible. τ is found to be 114.6 s. θ_i is modeled as a repetitive sequence of signals comprising of a sinusoidal part and an exponential part as shown in the following figure. It varies from 0 to about 80 K from the steady state value of 423 K. We note that this figure is only an approximate to the actual input signal since the extremely short time span makes it difficult for us to obtain actual readings to plot the signal. Only average figures could be obtained (as reported in the literature search) and we have thus, resorted to approximating the signal using those figures.

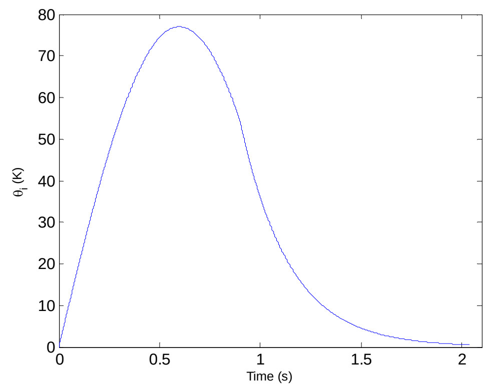


Figure 18. Input signal (inlet temperature) of system model

The model with its two inputs as described above is then simulated on the Simulink program in MATLAB as shown below.

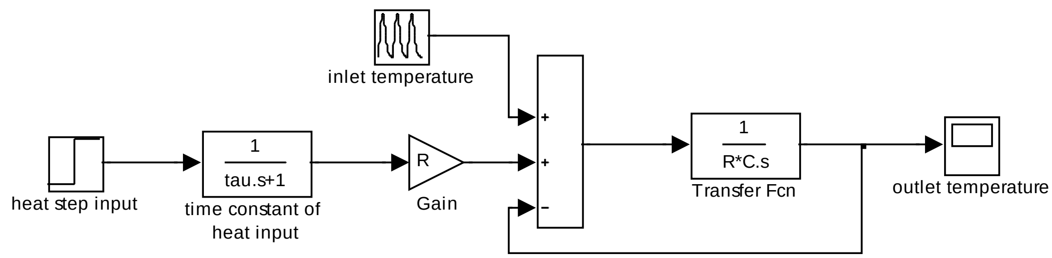


Figure 19. Simulink model of system without any thermal control

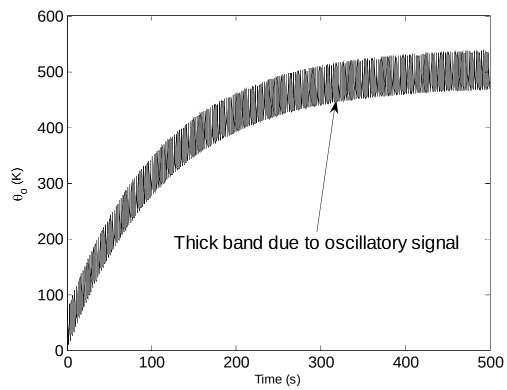


Figure 20. Output of system without control

As shown above, the output of the system is an oscillatory signal (frequency of 0.5 Hz) that reaches a steady-state varying between 470 K and 540 K. This implies that if our system were to carry on heating without any control, the exhaust outlet temperature will eventually reach temperatures oscillating between 890 K and 960 K. Hence, we know that we should be able to specify control temperatures in the range from 423 to 960 K (150 to 690°C). Our system will also take approximately 300 s (5 minutes) to reach this dynamic equilibrium.

After studying the system without control, we now implement the simple commercial "bang-bang" controller as shown in the figure below. We will assume that there is no time delay in the temperature sensor probes.

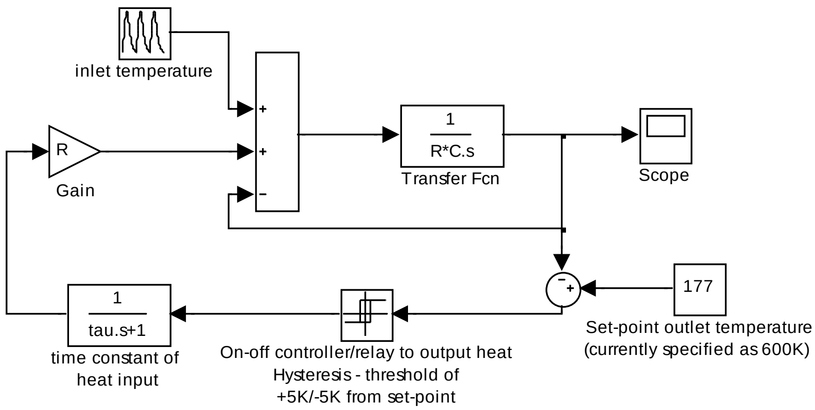
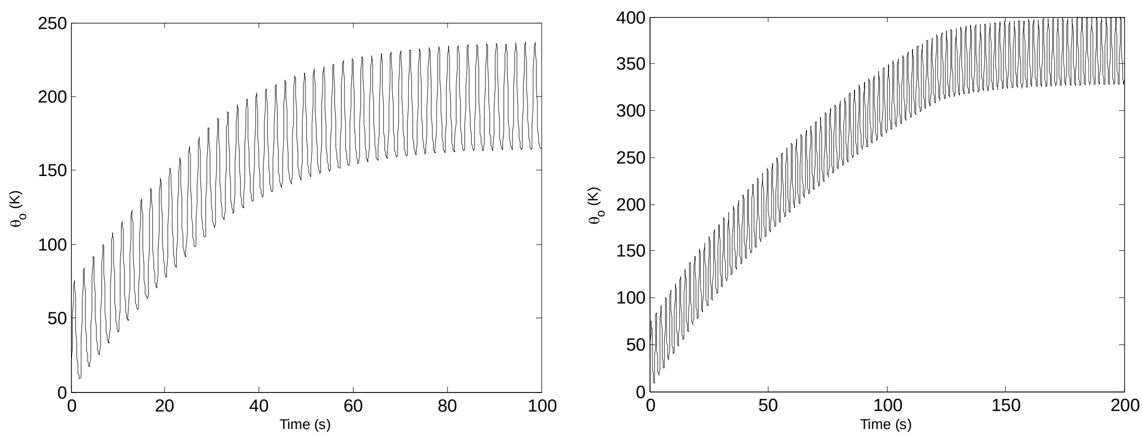


Figure 21. Simulink model of system with simple on-off thermal controller



(a) **(b)**

Figure 22. Output of controlled system where set-point temperature is (a) 600 K and (b) 800 K

Simulating the controlled model for two different set-point outlet temperatures, we obtained the two responses as shown above. For a set-point temperature of 600 K, the output temperature reaches steady-state and varies from 588 to 660 K and for a set-point temperature of 800 K, the output signal reaches steady-state temperatures ranging from 753 to 823 K. The former takes about 1 minute to reach the desired temperature and the latter takes a longer time of about 2 minutes to reach the desired temperature. In both cases, the on-off cycling of the heater and the output signal occurs at a frequency of 0.5 Hz, not unlike the system without control.

The simulated performance of the controlled system at various set-point temperatures is summarized in the following table.

Set-point temperature (K)	Deviation of steady-state temperature limits from set-point (K)		Range of deviation (K)	Mean temperature achieved (K)	Time taken to settle around desired point (mins)
	Upper bound (+)	Lower bound (–)			
500	66	6	72	530	0.75

600	60	12	72	624	1
700	45	27	72	709	1.67
800	23	47	70	788	2
900	5	66	71	870	4
Average	39.8	31.6	71.4	-	1.9

Table 30. Simulated performance of the on-off controlled system

A few trends are observed from the table for our controlled system. First, as the set-point temperature is increased, the steady-state temperatures will oscillate between a decreasing upper bound and an increasingly lower bound. In other words, the steady-state temperatures will deviate less on the upper-side of the desired temperature but deviate more on the lower-side of the desired temperature. However, the width of the oscillating band remains the same at about 71 K around the desired temperature. The maximum deviation of the achieved mean temperature from the desired is 30 K (relative error of 6%) and performance is best when the set-point temperature is around 700 to 800 K. At this range, the mean temperature achieved deviates from the desired by about 12 K only (relative error of 2%) . In the worst-case scenario, the achieved temperature at steady-state can deviate from the set-point temperature by up to 66 K. The last trend is that the time taken to settle around the desired point increases as the set-point temperature increases. This is expected since more heat will be required to reach higher temperatures. The controlled system will also respond slightly faster than that without control, taking only 4 minutes to reach temperatures up to 900 K.

The oscillatory behavior of our output signal can be attributed to two factors. First, the input signal (exhaust inlet temperature) itself is assumed to have an oscillatory behavior varying from 423 to 500 K as the engine undergoes each cycle of combustion. Second, based on the principle behind the on-off controller, an oscillatory output will be expected. The wide band of oscillations is most likely caused by the widely-varying inlet temperature as well as the lag time associated with heat transfer from the heater to the exhaust. Heat transfer to the exhaust will continue even after the heater is turned off so that the exhaust outlet temperature will exceed even the upper threshold we set for the desired temperature. Similarly, some time will be required for the exhaust outlet temperature to reverse its downward direction when the heater is turned on, and the lower bound of the threshold will also be exceeded.

Currently, the simulation shows that our controller is not able to completely eliminate the broad departure from the set thresholds and the flaws of the uncontrolled system. A PID controller may be able to achieve better performance by limiting the overshoots and hence, narrowing the band of oscillations. Furthermore, it may reduce steady-state errors and the mean temperatures achieved will lie closer to the desired set-points. Hence, our team decided that the commercial controller we are sourcing for should also preferably allow control via a single-loop PID process. Also, in the practical implementation, the input signal (inlet temperature) may not vary as much as shown in Figure 18 because the damping effects of the exhaust surge tank located before the catalyst test rig eliminates much of the pulsating flow from the single-cylinder engine. Thus the oscillatory behavior of the output signal may be much improved in actuality. Lastly, the derived mathematical model given by equation 7 makes the simplifying assumption that the gas is perfectly mixed in the pipe so that it is at a uniform temperature. Thus, a single temperature can be used to describe the temperature of the gas in the pipe and of the out-flowing gas. However, realistically speaking, this is not true for our system. Hence, our simulated response may not accurately reflect an experimentally obtained response.

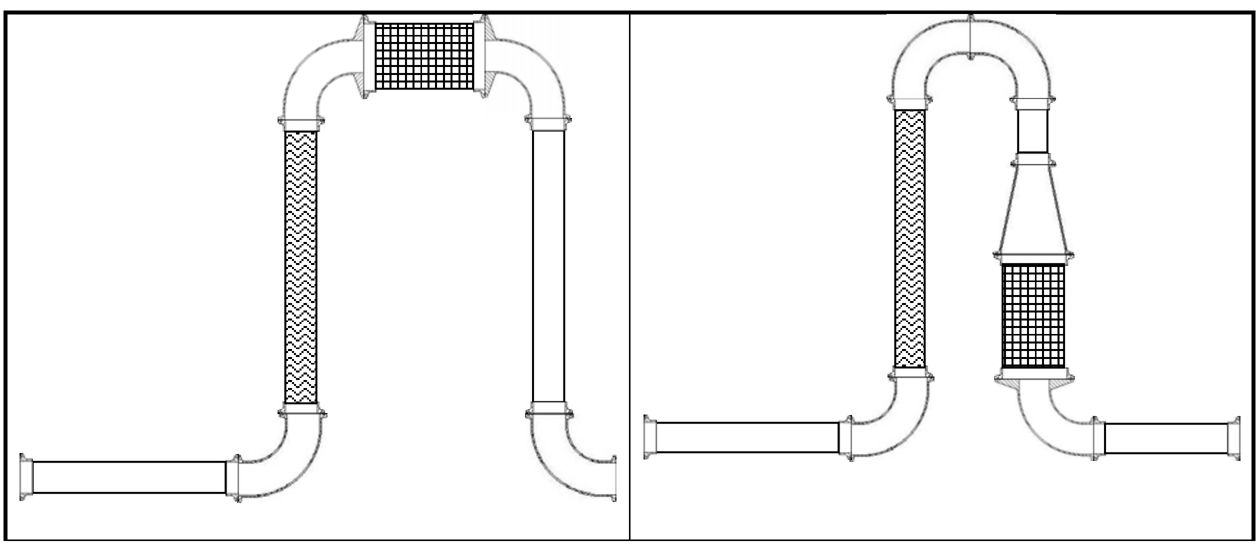
QUANLITATIVE ANALYSIS

HOUSING AND TEST-RIG INTEGRATION After determining the length of heated pipe required, we designed the pipe system so that the entire test rig could satisfy the geometric constraints and be successfully integrated into the test bed.

Measurements at the actual engine test bed indicated that the entire test rig must fit into a rectangular area of approximately 15″ by 22″. In fact, the horizontal length of the whole rig must span exactly 15.125″ and the end flanges at both inlet and outlet ends must be sized for 1.5″ tube OD so that the rig can be fastened to the rest of the pipe line with wing-nut clamps. Since the catalyst differs in diameter from the rest of the pipe line, the system will consist of pipe segments with varying cross-section (i.e. conical-shaped). This necessarily implies welding of the different pipe segments to complete our test-rig. To that purpose, the material stainless steel T304L is chosen because of its excellent welding properties.

Our material choice presents a great challenge to fabrication. Stainless steel is very hard and in order to achieve good surface finishing, it is necessary to slow down the machining, making it extremely time-consuming. Technicians we have spoken to at the machine shop recommend that whenever possible, we should approach suppliers such as McMaster-Carr for the parts we may require. Hence we carried out an online search at their online website[6], and found the necessary stainless steel tubing, reducing couplings (available in 7″ length only), elbows, wing-nut clamps and quick-clamp to butt-weld tube adapters that we require. The geometric constraint placed on the horizontal length of the system and the required long length of heated pipe made it necessary to include elbows to increase the total pipe length that can be fitted into the narrow space.

We developed the four schemes as shown in the following figure. A key is included for reference.



[6] http://www.mcmaster.com

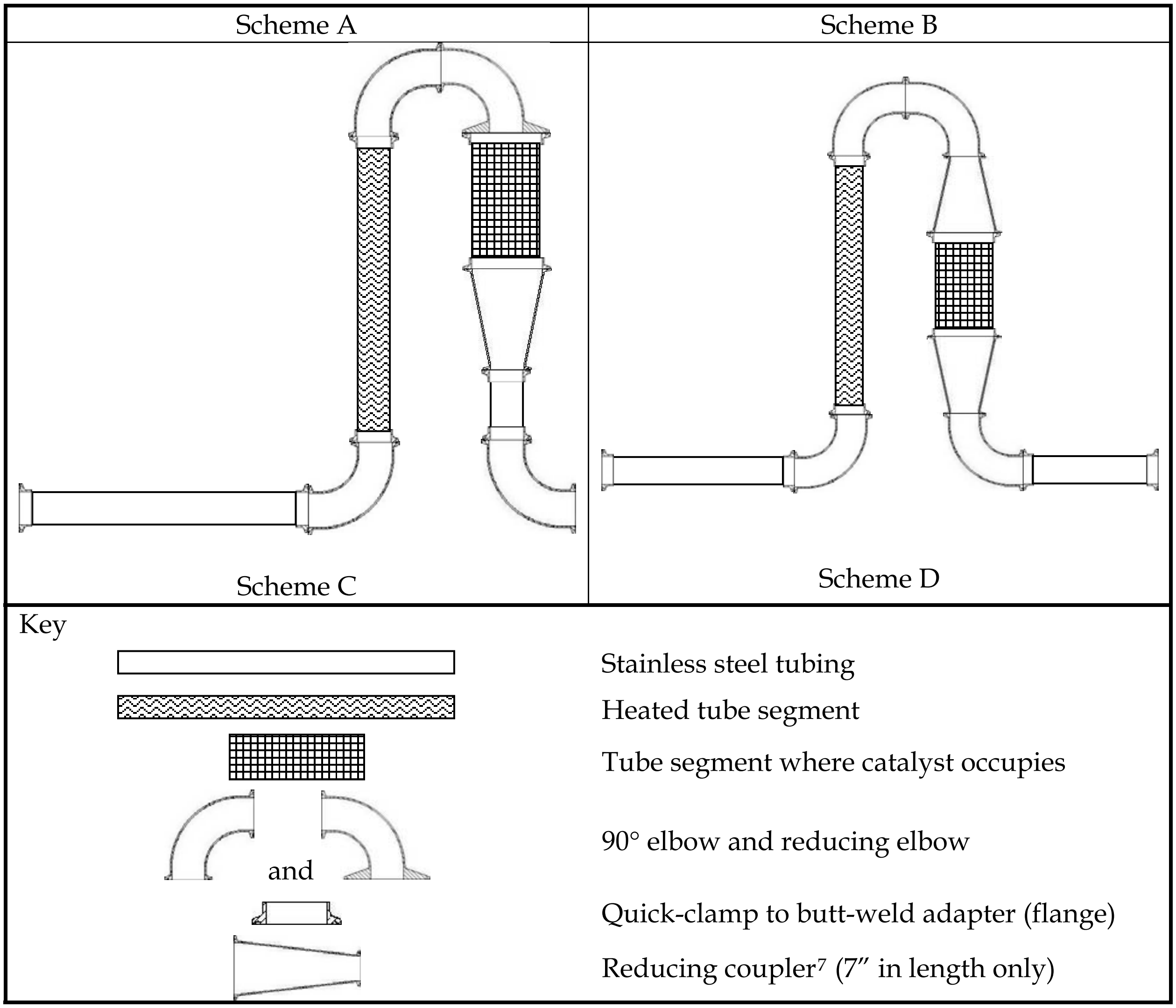


Figure 23. Four housing schemes for catalyst test-rig system

It is duly noted that the cost of the reducing elbow is the highest (at over 100 USD each) relative to all other components. Hence, scheme A was rejected because it requires two of those parts. In terms of economical cost, scheme D is the cheapest since no reducing elbows are required. However, since the reducing couplers have to be fabricated out of stainless steel instead, the labor costs are immense. Besides, a quote from ASAP Source[8] indicates that the round raw stock required for fabrication costs USD109.28 alone. This offsets the savings achieve in not acquiring the reducing elbow. Scheme B is largely similar to scheme C except that the positions of the catalyst and reducing coupler are reversed. Scheme B is finally selected because we believed that a gradual change in cross-section upstream of the catalyst is better than having a sudden change in cross-section upstream. The exhaust is allowed to expand slowly to flow through the catalyst.

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[7] The ones shown in Scheme D are not 7" in length so they are not available in McMaster-Carr and must be fabricated.

[8] http://www.asapsource.com

FINAL DESIGN

HOUSING

A CAD model of the proposed catalyst test rig was created using Unigraphics NX 4.0 to provide a visualization of the completed system. Screenshots of the CAD model are included below.

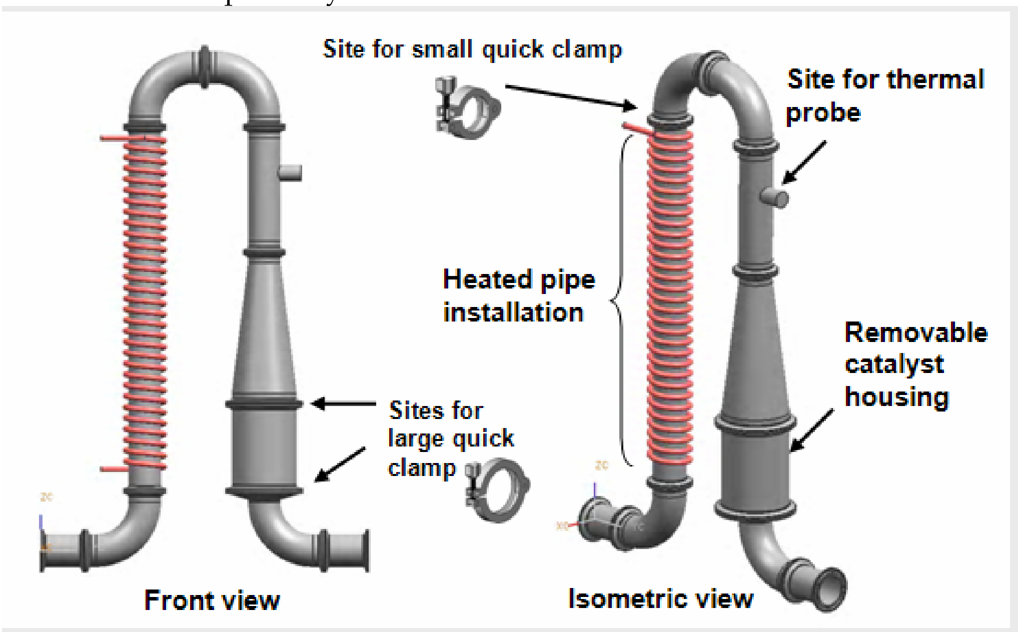

Figure 24. CAD model drawing of the completed catalyst test rig

A list of the pipe sections of the test rig is included in the table below. The part number denotes the McMaster-Carr serial number of the purchased part that we will be modifying from. The pipe dimensions below were selected based on spatial and cost considerations.

Part No.	Part	Quantity	Dimension
4466K152	Horizontal pipe	2	L – 1.0625″, OD – 1.5″
4466K152	Vertical pipe 1	1	L – 15.76″, OD – 1.5″
4466K152	Vertical pipe 2	1	L – 4.76″, OD – 1.5″
4466K211	Vertical pipe 3	1	L – 3″, OD – 3.0″
4322K112	90^{o} Elbow 1	3	OD – 1.5″ – 1.5″
4322K125	90^{o} Elbow 2	1	OD – 3.0″ – 1.5″
4322K236	Reducing Coupling	1	L – 7″, OD – 1.5″ – 3.0″
4322K52	Quick-Clamp 1	7	ID – 1.5″
4322K155	Quick-Clamp 2	2	ID – 3.0″
	Swagelok fitting	1	OD – 0.375″, 1/8-27 NPT

Table 31. List of parts for the housing of test-rig

A detailed dimensioned drawing of the proposed catalyst test rig is included in Appendix D. The design will require a total of seven gaskets to be placed between the flanges of the pipes with the smaller OD (i.e. in the small quick clamp). These gaskets must have high temperature resistance.

The manufacturing and assembly plan will be presented in a later section.

HEATING SYSTEM

The WATROD Tubular Heater will be supplied by WATLOW according to the following specifications, as determined by our housing system.

Voltage input	220 V
Power output	2000 W
Performance	22 W/in^2
Tubular diameter	0.26″
Sheath length	112.819″
Design	Coiled with 1.5″ ID, 15″ coiled height

Table 32. Specifications of heating system

The Tubular heating element will be installed by WATLOW onto a section of stainless steel T304L pipe provided by us and delivery time is expected to be around three weeks. The cost breakdown of the parts and labor is included in the Bill of Materials. A brochure of the WATROD Tubular Heater is included in Appendix E1. A CAD drawing of how it may look like when it is installed on the pipe is provided below. The exact dimensioned drawing of the heater as designed by our supplier is provided in Appendix E2.

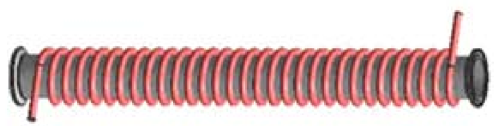

Figure 25. CAD model drawing of the installed heating system

THERMAL CONTROL SYSTEM

Our team looked into commercially available temperature controllers which would be suitable for our design project. Currently, we have approached Hiwatt Inc. which is a distributor of process heaters, temperature sensors and temperature controls. Hiwatt Inc. provides top manufacturer's brands including WATLOW, RKC, OMRON & OMEGA products as well as other lines. After discussing the technical specifications of our design with Hiwatt Inc., they have recommended a WATLOW Series SD temperature controller (refer to Appendix F) which could fulfill the objectives of our thermal control system. This temperature controller would allow us to achieve a single set point control and maintain the exhaust gas temperature at that set point by adjusting the power input to the heating system. The technical specifications of the temperature controller are summarized in the table below.

Part Number	SD6C-HCJA-AARG
Control Type	On-off or Auto-Tuning PID
Dimensions	1/16 DIN (Behind Panel: 97.8mm; Width: 52.1mm; Height: 52.1mm)
Line Voltage/Power	100-240V(AC/DC)
Accuracy	+/- 0.1% of span, +/- 1°C @ calibrated ambient temperature.
Input	Single Universal Input: Type K thermocouple (Allowable Operating Range: -200 to 1370°C)

Output	2 outputs Output 1 : Switched DC Output (Solid State Relay Compatible) Output 2 : Mechanical Relay, Form A, 2A

Table 33. Technical specifications of temperature controller

A schematic of the thermal controller system and how it is to be implemented in our system is shown below.

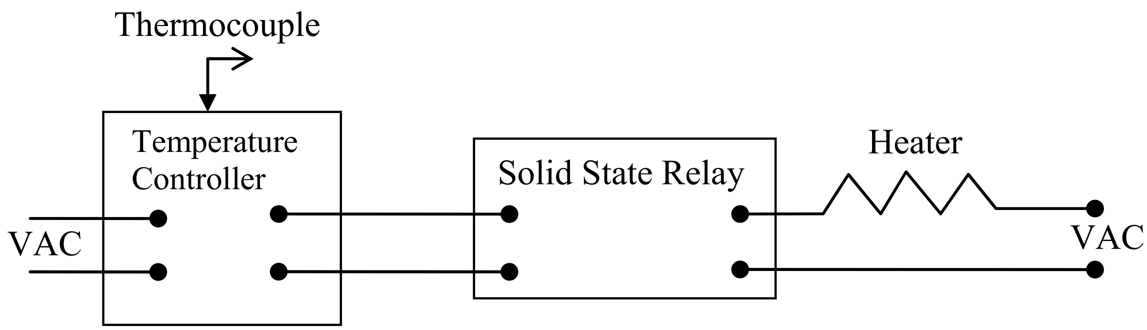

Figure 26. Schematic of thermal controller implemented in our system

GAS FLOW METER

The selected concept for the gas flow meter is an anemometer with probe insertion. Several gas flow meter and more specifically, anemometer manufacturers were approached. It must be noted that due to the high temperatures (up to 400°C) involved in our application, only two distributors were found to carry a suitable anemometer that can operate in that range. The following summarizes their various quotations, which exclude taxes and shipping charges. Further technical information and their different specifications may be perused in the supplier catalogs provided in Appendix G.

Supplier/Distributor	Model	Price
Calright Instruments[9]	Kanomax Anemomaster Model 6162 High Temperature Anemometer (with Probe Model 0204)	USD3002
Omni Instruments[10]	MiniAir 20 Mini Inox vane anemometer (up to 250°C steel air probe) from Schiltknecht Messtechnik AG	USD1666

Table 34. Two suppliers of high-temperature anemometers

Although more expensive, the Kanomax Anemomaster model is exactly aligned with the requirements of our high-temperature application. Furthermore, it allows for a digital output to a PC, whereas the Schiltknecht model only allows a meter reading. The latter also operates up to 250°C only, and this is lower than what we expect the exhaust temperature to reach (up to 400°C). Hence, the only suitable product for our application is the Kanomax model provided by Calright Instruments. However, this presents a real budget challenge. Since velocity measurement is not critical to our main objective of achieving a thermally-controlled catalyst test-rig, our team believes that acquiring this meter is not a pressing issue and may be deferred. In future, if and when high-temperature anemometers become commercially available at low

[9] http://www.calright.com/pd_810.aspx
[10] http://www.omniinstruments.co.uk/airweath/ma20_e.htm

cost, it may be possible then to integrate the meter into our test-rig system. We are ensuring that our prototype will allow room for such a possibility.

After acquiring the meter, it is a simple matter to insert and fix the probe to the pipe line at the required location using a swagelok-compatible instrumentation fitting of appropriate size.

PIPE INSULATION

Based on system specifications, we were able to decide on a final insulation configuration that will best suit our interests. This configuration consists of two types of insulation being used, namely Knauf 1000° Pipe Insulation for straight pipe sections, and Knauf Proto PVC Fitting Covers for 90° pipe sections.

KNAUF 1000° PIPE INSULATION This is a "molded, heavy-density, one-piece insulation made from inorganic glass fibers bonded with a thermosetting resin[11]". It will be used to insulate all straight pipe sections leading up to the catalyst test rig in the existing system. This type of insulation satisfies our 300°C temperature requirement since it has a working temperature of -18°C to 538°C. For the purposes of our system, we will be using pieces of the following dimensions:

Length (inch)	Diameter (inch)	Thickness (inch)
10.5	8	2
17	1.5	2
7	2	2

Table 35. Summary of pipe insulation dimensions.

Each piece will be cut down to size, mounted onto the pipe, and the lip sealed with the self-adhesive strip provided. It should be noted that these insulation pieces are not easily removed after installation. This will prevent the user from reaching or replacing the pipe sections being insulated easily. If needed, an insulation piece may be further cut manually into two semi-circular halves that can be attached using industrial tape. Further technical information regarding the insulation can be perused in Appendix H1.

KNAUF PROTO PVC FITTING COVERS These are "one-piece, pre-molded, high-impact PVC fitting covers with fiberglass inserts[12]" that will be used on the 90° pipe sections. The maximum operating temperature of these is 260°C, which is slightly lower than the pipe's operating temperature. However, by using a double insert, this will not be a problem. The insert will first be installed onto the pipe in the same way as the pipe insulation mentioned above. We will then install the PVC cover over the insert and secure it using adhesive. Again, this type of cover is not easily removed after installation. If the pipes need to be accessed frequently, it is suggested to cut the pieces into semi-circular halves that can be affixed using industrial tape. For more technical information regarding the covers please refer to Appendix H2.

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[11] Knauf Data Sheet PE-DS-1 04-06.

[12] Knauf Information Sheet <http://knaufusa.com/products/commercial__industrial/pipe_and_equipment_insulation/proto_pvc_fitting_covers.aspx>, accessed 03/14/07.

BILL OF MATERIALS

Quantity	Part Description	Purchased from	Part Number	Price each (USD)
Heating system				
1	WATROD Tubular Heater	WATLOW		212.30
1	Heater Installation	WATLOW		175.00
1	Engineering Charge	WATLOW		150.00
Thermal control system				
1	Mini-Plug Thermocouple with Bendable Probe Flat-Pin Connector, Type K, 12" L, 1/8" Diameter, W/O Cable	McMaster-Carr	39095K64	17.10
1	Thermocouple and RTD Connector Female Jack, Flat-Pin (Mini), Type K, Yellow	McMaster-Carr	3869K34	3.67
1	Steel Yor-Lok Tube Fitting Adapter for 1/8" Tube OD X 1/8" NPT Female Pipe (swagelok)	McMaster-Carr	5929K41	22.05
1	WATLOW SERIES SD6C PID Temperature Controller	Hi-Watt Inc.	SD6C-HCJA-AARG	213.00
Housing (material: T304 stainless steel)				
3	90° elbow, radius 2¼″ for tube OD 1½″	McMaster-Carr	4322K112	21.67
1	90° reducing elbow, 3″ × 1½“ tube OD,	McMaster-Carr	4322K125	131.39
1	36″ T304L stainless steel tubing, 1½″ OD, 1.37″ ID	McMaster-Carr	4466K152	35.88
1	12″ T304L stainless steel tubing, 3″ OD, 2.87″ ID	McMaster-Carr	4466K211	26.12
1	Reducing coupling, 3″ × 1½“ tube OD, 7″ length	McMaster-Carr	4322K236	79.26
7	Wing-nut clamp, 1½“ tube OD	McMaster-Carr	4322K152	8.80
2	Wing-nut clamp, 3″ tube OD	McMaster-Carr	4322K155	12.90
8	Quick-clamp × short weld tube adapter, 1½″ tube OD	McMaster-Carr	4322K212	3.46
2	Quick-clamp × short weld tube adapter, 3″ tube OD	McMaster-Carr	4322K215	9.36
1	1″ OD T304L stainless steel round stock (one pound)	ASAP Source		8.00
1	G-9900 compressed graphite fiber gasket material	Garlock		Provided by client
Insulation				
1	Knauf 1000° Pipe Insulation (3′ length, 8″ OD, 1.5″ thickness)	Midwest Insulation		18.87

1	Knauf 1000° Pipe Insulation (3′ length, 1.5″ OD, 1.5″ thickness)	Midwest Insulation		8.13
1	Knauf 1000° Pipe Insulation (3′ length, 1.5″ OD, 1″ thickness)	Midwest Insulation		4.80
1	Knauf 1000° Pipe Insulation (3′ length, 2″ OD, 1.5″ thickness)	Midwest Insulation		8.97
3	Knauf Proto PVC Fitting Cover (90° joint, 1.5″ OD, double insert)	Midwest Insulation	#10 fittings	1.25
	Shipping costs	Midwest Insulation		16.50
1	Tape made with Teflon PTFE, 2" width, 5 yard length	McMaster-Carr		20.94
	Shipping costs	McMaster-Carr		4.00
			Total cost:	1358.54
Gas flow meter (Optional)				
1	Kanomax 6162 Anemomaster, main unit	Calright Instruments		1501.00
1	Kanomax 0204 High Temperature Probe (400°C)	Calright Instruments		1501.00
			Total (includes optional cost):	4360.54

Table 36. Bill of materials

MANUFACTURING AND ASSEMBLY OF PROTOTYPE

MANUFACTURE OF HOUSING

Since the prototype material required is stainless steel, shop technicians advised our team to obtain most, if not all, of our parts commercially. Hence, fabrication of our prototype was limited to modifying the purchased parts and welding them together. These purchased parts are listed in the bill of materials (BOM) as shown in Table 36. We did manufacture some of the smaller parts which we could not obtain commercially, such as the additional sensor fitting for attaching the thermocouple and a few gaskets to be placed between the quick-clamp flanges.

The modifications to the purchased parts are described in the following manufacturing plans.

Purchased part to be modified: 36″ T304L stainless steel tubing, 3″ OD, 2.87″ ID Flanges (×8) to be welded: Quick-clamp × short weld tube adapter, 1½″ tube OD					
No.	Process description	Machine	Speed (rpm)	Tools	Fixture
1.	Cut out stock to the required 4 parts, each slightly more than required lengths Required lengths are: Pipe 1 & 2 —1.0625″, Pipe 3 — 15.76″, Pipe 4 — 4.76″	Automated saw			
2.	Mill down Pipe 3 from both ends to exact dimensions	Mill	150	1″ end mill	Vise

3.	Secure Pipe 1 into lathe chuck. Face both rough ends until exact length dimension	Lathe	150	Side tool	Lathe chuck
4.	Repeat step 3 for Pipes 2 and 4				
5.	Secure Pipe 4 on mill. Locate center axis of pipe using a jump-edge finder.	Mill	600	Jump edge finder	Vise
6.	Locate center of hole to be drilled 1.635″ from one end of Pipe 4 using jump-edge finder.	Mill	600	Jump-edge finder	Vise
7.	Center drill hole	Mill	150	1/8″ center drill	Vise
8.	Drill a ¼″ hole through the pipe surface	Mill	150	¼″ drill bit	Vise
6.	Butt-weld flanges to both ends of each of the straight pipes.				

Table 37. Manufacturing plans for straight pipe sections (1½" OD)

Purchased part to be modified: 12″ T304L stainless steel tubing, 1½″ OD, 1.37″ ID Flanges (×2) to be welded: Quick-clamp × short weld tube adapter, 3″ tube OD					
No.	Process description	Machine	Speed (rpm)	Tools	Fixture
1.	Cut out stock to the required part, with slightly more than required length. Required: Pipe 5 — 3″	Automated saw			
2.	Secure Pipe 5 into lathe chuck. Face both rough ends until exact length dimension	Lathe	150	Cutting tool	Lathe chuck
3.	Butt-weld flanges to both ends of the pipe				

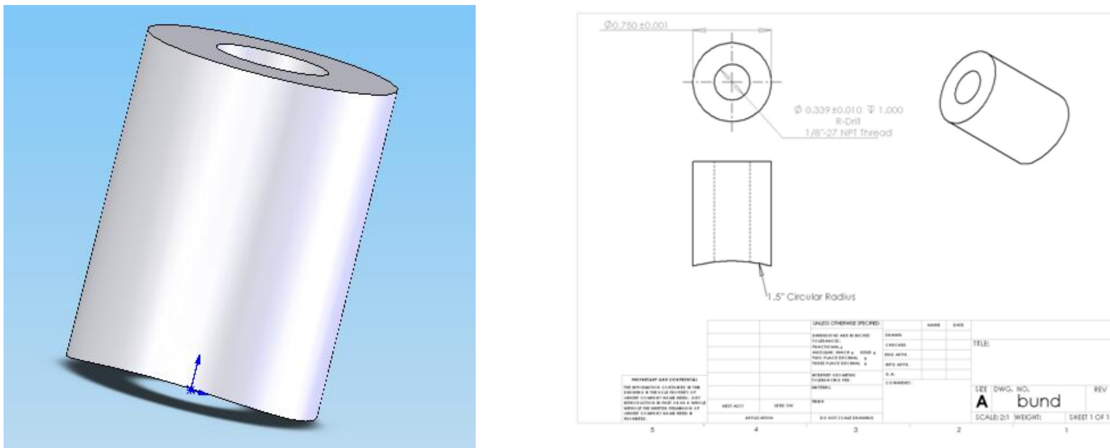
Table 38. Manufacturing plans for straight pipe section (3" OD)

Our team fabricated the sensor fitting out of raw stock as described below. The dimensioned drawing and CAD model of the part are shown in the figures that follow.

Purchased raw stock: 1″ OD T304L stainless steel round stock (1 lb)					
No.	Process description	Machine	Speed (rpm)	Tools	Fixture
1.	Secure stock into lathe chuck. Face both ends.	Lathe	150	Side tool	Lathe chuck
2.	Turn down diameter to ¾″, slightly more than 1″ into round stock	Lathe	150	Side tool	Lathe chuck
3.	Center drill center of stock	Lathe	150	1/8″ center drill	Lathe chuck
4.	Drill hole more than 1″ into stock	Lathe	150	R drill bit	Lathe chuck
5.	Cut part to 1″ length (from end with hole)	Bench saw	150		
6.	Secure 1″ part in mill. Locate center axis of round part using jump-edge finder	Mill	600	Jump-edge finder	Vise
7.	Mill out curvature (1″ OD) of one end	Mill	150	1″ end mill	Vise
8.	Widen curvature to 1.5″ OD using file.			File,	Vise

	Place sandpaper around 1.5″ OD tube and sandpaper curvature on it.			sandpaper	
9.	Tap hole for 1/8-27 NPT thread to screw in the swagelok			1/8-27 NPT tap, tap handle	Lathe chuck
10.	Weld part to Pipe 4, with the center of holes aligned.				

Table 39. Manufacturing plans for sensor fitting



(a) **(b)**

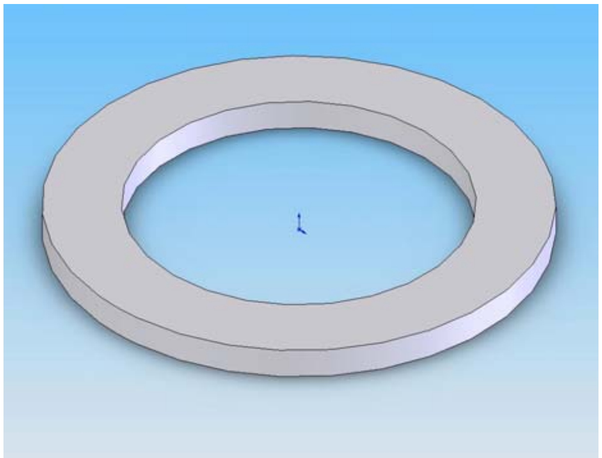
Figure 27. (a) CAD model and (b) dimensioned drawing of sensor fitting

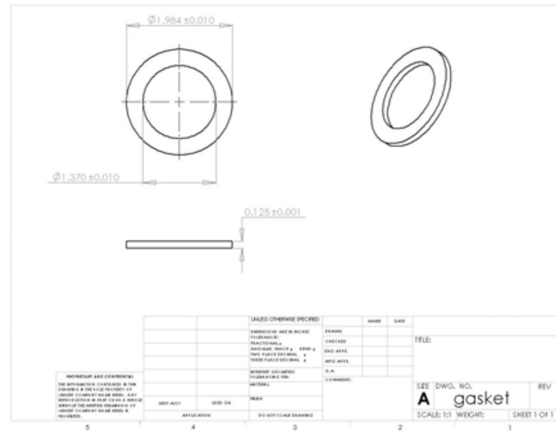
Five gaskets are cut out of the Garlock G-9900 compressed graphite fiber gasket material provided by the client using a pen knife. Each gasket is of the dimension 1.5″ OD × 1.37″ ID × 1/8″ thick. This material has high temperature resistance and is currently used in the rest of the engine pipe line. However, for the heated pipe (Pipe 3) in our prototype, the temperatures will reach 1000 K, which is out of the operating range for this material. The two gaskets that will be placed at both end flanges of the heated pipe must be made out of another material. To save costs, our team decided to fabricate these out of raw steel stock in the shop. The manufacturing process is as described below. The CAD model and dimensioned drawing are also provided.

Purchased raw stock: 1.5″ OD steel round stock					
No.	Process description	Machine	Speed (rpm)	Tools	Fixture
1.	Secure stock into lathe chuck. Face both ends.	Lathe	150	Side tool	Lathe chuck
2.	Turn down diameter to 1.5″, slightly more than 1″ into round stock	Lathe	150	Side tool	Lathe chuck
3.	Center drill center of stock	Lathe	150	1/8″ center drill	Lathe chuck
4.	Drill hole more than 1″ into stock	Lathe	150	¼ ″ drill bit	Lathe chuck
5.	Drill and expand diameter of hole	Lathe	150	1″ drill bit	Lathe chuck

6.	Bore the hole to required diameter of 1.37″	Lathe	150	Boring bar	Lathe chuck
7.	Cut off 2 parts from stock, each of 1/8″ thickness	Lathe	150	Cutting-off tool	Lathe chuck

Table 40. Manufacturing plans for steel gasket





(a) **(b)**

Figure 28. (a) CAD model and (b) dimensioned drawing of steel gasket

ASSEMBLY OF HOUSING

After acquiring all the necessary parts, we assembled them to complete the prototype as shown below. The dotted lines represent the location of the welds performed. The two steel gaskets are placed between the flanges on either ends of Pipe 3, while the other five gaskets (of G-9900 compressed graphite fiber) are placed between the other five pairs of flanges (1½″ tube OD). The gaskets are placed in between the flanges in the quick-clamp as shown in Figure 30. No gaskets are required for the larger pairs of flanges (3″ tube OD). Wing-nut quick clamps are placed around the flanges of the corresponding size and secured to affix the various pipe components together.

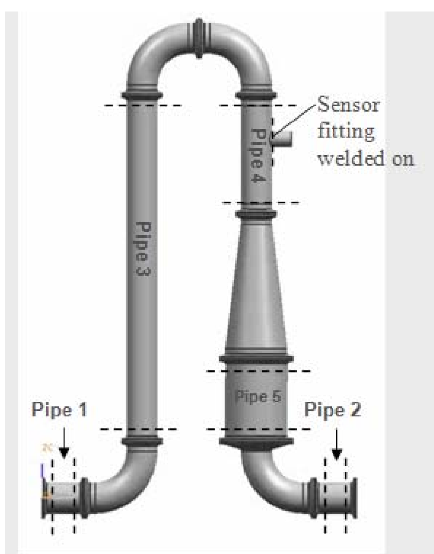


Figure 29. Schematic of pipe arrangement

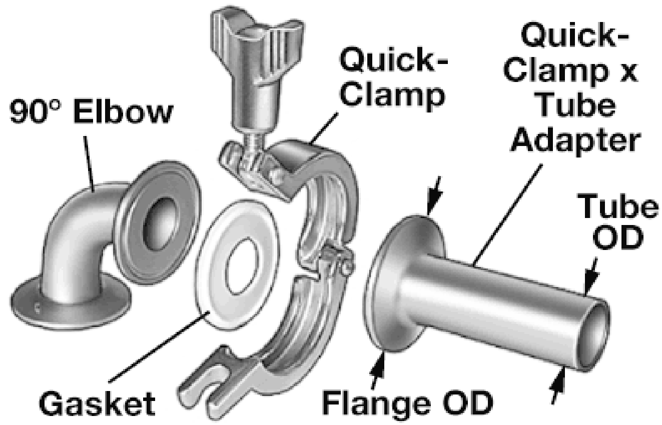


Figure 30. Schematic of how gasket is placed between flanges in the quick-clamp[13]

The long pipe section (Pipe 3) has been sent to our supplier, Hiwatt, for the installation of the tubular heater. Our team is currently awaiting the return of the part so that we can reinstall it onto our prototype. The temperature control unit can then be connected to the heating system and the entire prototype connected to the appropriate power supply as shown in the schematic (Figure 26). The actual set-up is shown in the figure below. The thermocouple is then inserted through the sensor fitting via the swagelok, which secures the thermocouple and is screwed into the sensor fitting. As a final step, the completed prototype is fitted onto the existing engine test bed at the designated location shown in Figure 11. Wing-nut quick clamps are used to secure the system to the pipe line.

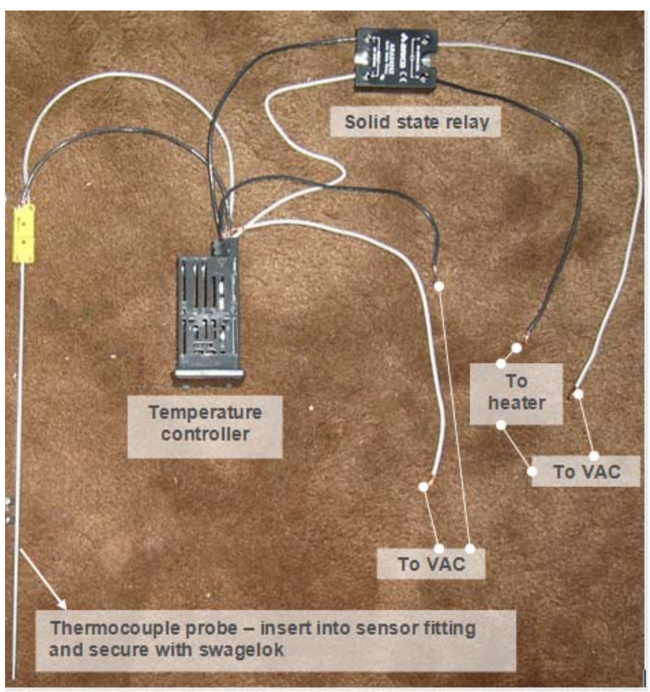


Figure 31. Actual set-up of thermal control system

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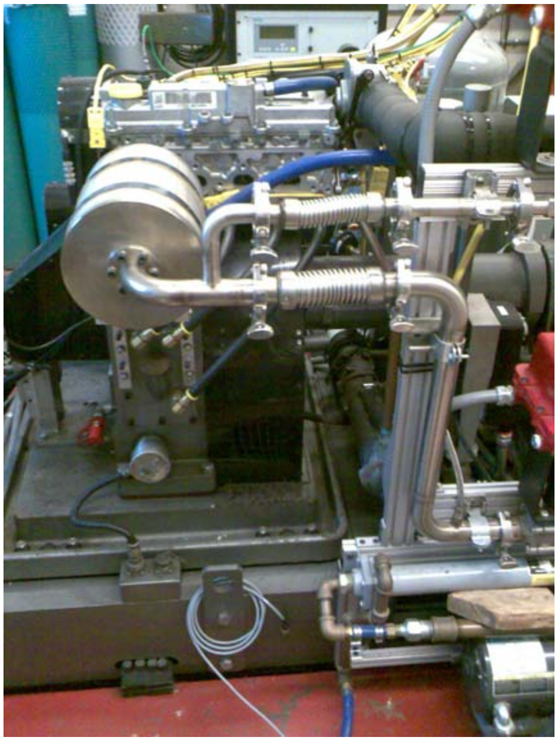
[13] Figure provided by McMaster-Carr, accessed from http://www.mcmaster.com

INSULATION INSTALLATION

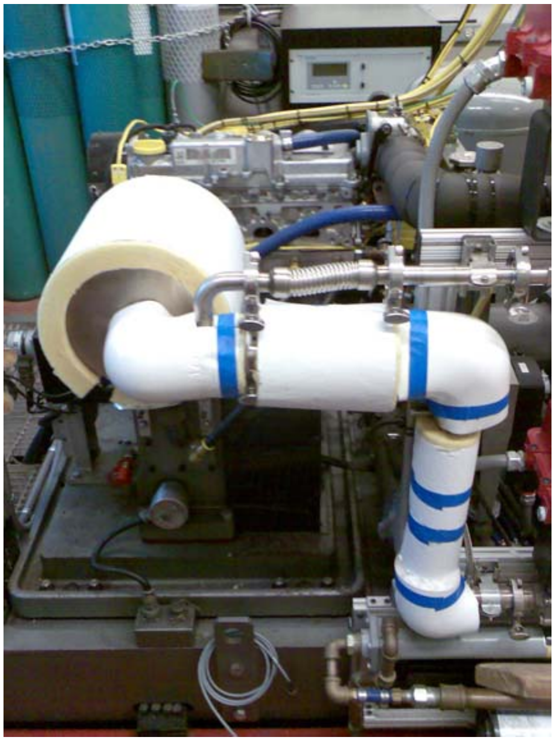
The pipe insulation is installed upstream of the pipe as described as follows.

1. Cut the 1000° Pipe Insulation into their required lengths.
2. Affix the insulation onto each pipe section.
3. Seal open lip with adhesive tape provided.
4. Install inserts for PVC fitting covers.
5. Enclose inserts with the PVC covers and seal them.

The following figures show the engine before and after installation of the insulation.



(a)



(b)

Figure 32. (a) Before and (b) after installation of the pipe insulation upstream of prototype

TESTING AND DESIGN VALIDATION

Currently, we are waiting for our supplier, WATLOW, to return the pipe with the installed heater back to us. The initial delivery time was expected to be around three weeks but due to unforeseen circumstances, the supplier has requested an extension and we are unable to deliver the prototype together with the heating element before the deadline of this report. Since the heater is the most critical element in our design, the prototype cannot be tested until it arrives. We are thus, unable to validate the simulated theoretical performance as summarized in Table 30.

THEORETICAL RESULTS

The simulation of the on-off controller on MATLAB, shows that it can somewhat achieve the desired set-point temperature, but the temperature will oscillate around it at a frequency of about ½ Hz when dynamic equilibrium is reached. The width of the oscillation band remains constant at about 70°C, whilst the mean temperature at this "steady-state" can deviate from only 9°C to as much as 30°C from the desired value, giving a relative error from 1.5% up to 6%. The system response time taken to settle around the desired state will also vary from ¾ to 4 minutes, which is still acceptable for a heating system like ours. Finally, the insulation installed upstream of the catalyst test rig can limit the exhaust temperature drop from the combustion chamber to our rig inlet to less than 80°C, which is about half that of the original drop of 150°C.

A comparison of the simulated controlled system performance to that without control is presented in the table below.

Parameter	System with control	System without control
Response time	Fast (¾ to 4 minutes)	Slow (~ 5 minutes)
Cycling frequency	0.5 Hz	0.5 Hz
Width of oscillation band	70°C	70°C
Achieved desired temperature	Somewhat (with relative error up to 6%)	No

Table 41. Comparison of system with control to that without control

A PID controller may be able to achieve better system performance than an on-off controller. The commercial controller that we have purchased for implementation in our prototype allows the user to switch from on-off control to an auto-tuning PID mode. This feature allows the controller to measure the system response to determine effective settings for PID control. When auto-tuning is initiated, the controller reverts first to on-off control. The temperature must then cross the Autotune Set Point (90% of the process set point) four times to complete the auto-tuning process. From there onwards, the controller is able to control at the normal set point, using the new parameters. We anticipate that this new controller mode will be able to reduce the overshoot, steady-state error and further stabilize our system output. Should the auto-tune process fail to come up with the PID parameters that will provide the desired process characteristics, a manual tune can still be performed using the controller to obtain the required parameters. The user functions and interface of our thermal controller are fully explained in the manual provided by our supplier, Hiwatt. We will be providing this manual with the delivery of our prototype to our client as well.

The on-off cycling frequency of 0.5 Hz shows that the system reverses direction once every two seconds and the range of oscillation is still very wide for both the controlled and uncontrolled systems. This characteristic is unavoidable because of the high speed of the exhaust through the pipe line and the widely oscillating inlet temperature. The actual inlet signal may be more damped due to the effects of the exhaust surge tank upstream of the test rig, so our team strongly believes that the actual output will be very damped out, so both the frequency and range of oscillation will be further reduced. We expect that in reality, our actual results may be much improved from the theoretical results.

TESTING PLAN

When the heater system arrives in the near future, our team plans to set up the entire prototype with the thermal control system and insulation in place and test the system according to the following plan. This plan will be carried out to prove that the prototype satisfies the engineering specifications it intends to meet and validate our design.

1. Place catalyst into holding compartment of prototype.
2. Power on engine test bed.
3. Allow system to run for 45 minutes until steady state is reached.
4. Turn on heating system and switch the temperature control unit to the on-off mode.
5. Set desired temperature for exhaust gas entering the catalyst.
6. Record the temperature of the exhaust entering the catalyst every one minute until equilibrium is reached. Reduce the time between readings if oscillatory behavior occurs quickly.
7. Observe whether the set temperature is achieved. Use mean temperature as a gauge if oscillatory behavior continues without stabilizing to a set value.
8. Repeat steps 5 to 7 for different temperature settings at 100 K intervals from 500 to 900 K to ensure our system is functional over the broad range of temperatures.
9. Compare the actual performance with the theoretical performance
10. Repeat the whole procedure with the temperature control switched to the auto-tuning mode.

DISCUSSION FOR FUTURE IMPROVEMENTS

Although we are unable to obtain the actual performance of the prototype and validate our design, we still have several suggestions that can be expected to improve our design further or provide a better picture of the actual system behavior.

1. Future changes to the existing test bed structure may accommodate a straight-length design and eliminate the bends in our current prototype. The modular nature of our prototype will allow easy reassembly to the new design. Eliminating the bends will result in less interference with the exhaust flow profile and pressure losses.
2. If the catalyst provided does not fit snugly into the catalyst housing as expected, tap screws can be added to secure the catalyst properly. All that is required is some simple drilling and tapping operations in the shop.
3. The steel gaskets fabricated for the flanges of the heated pipe should be replaced with ceramic fiber sheet gaskets that can withstand the higher temperatures without rusting. These gaskets can also act as insulating material and reduce much heat loss from the heated pipe via conduction to the adjoining pipes.
4. Model the system heat transfer and fluid flow using advanced computational fluid dynamics (CFD) software such as Fluent to obtain a more accurate reflection of system behavior so that we can better validate experimental results.
5. Measure the thermodynamic properties of the exhaust to obtain more accurate system parameters to improve design calculations
6. Simulate the PID controller in MATLAB to validate test results of auto-tuning PID

CONCLUSIONS

In order to satisfy more stringent emissions regulations with cleaner and more efficient engines, research is being conducted to further the development of LTC and PCI strategies using diesel and other alternative fuels for commercial vehicles. Such processes are able to significantly reduce NO_x and soot emissions. However, as a result, HC and CO emissions are much higher than regulated levels. There is thus a need to test new catalyst formulations to specifically decompose such particles. Currently, LTC testing is carried out on a single-cylinder engine for practical reasons. However, catalyst testing cannot be done on such test systems since the exhaust temperature profile for the single cylinder engine is not comparable to that of a commercial multi cylinder engine. Hence, our team hopes to address this problem through the design and fabrication of a heated sample system to allow testing of various DOCs on a single cylinder test engine. This test-rig should satisfy various requirements, including the ease of access to the catalyst, and an adjustable temperature control.

To ensure that our design is able to fulfill the customer requirements, a QFD was deployed to translate such requirements into tangible engineering specifications, as shown in Figure 8. Our team then identified the various sub-systems required of the project and organized them using a morphological chart. Design concepts were subsequently developed for each sub-function, and the best ideas were further explored to evaluate the validity of the design. Detailed engineering calculations, together with cost analysis and practical implementation considerations were taken into account to determine the most suitable approach. A Pugh chart was used to summarize the strengths and weaknesses of each design, and justify the final design selection. We finally determined that we should implement the heated pipe system, together with the WATROD Tubular Heater as the optimal choice. Knauf and PVC fitting covers will be used for insulation purposes, and a Type K (Chromel (Ni-Cr alloy) / Alumel (Ni-Al alloy)) thermocouple and commercial on-off temperature controller system will be adopted for thermal control. A hot-wire anemometer will be used to measure the exhaust gas velocity. Tap screws will be used to secure the catalyst block in place, and a removable pipe section as the catalyst housing will allow easy accessibility.

Following the selection of our design concept, our team performed the necessary engineering analysis for our heating, temperature control system and housing to determine the critical dimensions of our design. We also found that the on-off controller may not be quite satisfactory and it is most preferred for the commercial controller to allow for PID control as well. Subsequently, we completed CAD drawings showing the detailed dimensions of the system housing (Appendix D) as well as purchased the necessary system components found to be available commercially. Certain manufacturing processes such as cutting, welding and drilling, were still necessary to modify the parts to our system specifications, and these have been elaborated on in Table 37 to Table 40. Our prototype is then assembled as shown in Figure 29 and the design of the heater is provided in Appendix E2. The total cost breakdown of the prototype is summarized in the Bill of Materials (Table 36).

In conclusion, our team has designed, developed and fabricated a heated catalyst test rig that should meet the customer specifications. Due to unforeseen circumstances, the supplier, WATLOW, is unable to deliver the critical element of our project, the heated pipe, to us in time to meet our project deadline. We are thus unable to implement the testing phase of our project and provide a validation of our design. However, our team has been able to simulate its thermal control performance as summarized in Table 30 and obtain a theoretical picture of the system behavior. While doing so, we have taken a conservative approach and assumed worst-case scenarios, which may not occur in the actual system. Hence, our team strongly believes that our actual system behavior will be much improved over that shown by the theoretical results. When the heated pipe arrives, we will complete the installation of our prototype on the engine test bed, and implement the testing plan as outlined previously. In the event that the part arrives only after the end of the semester, our team hopes that either the catalyst research team can install and test out our prototype over summer or this testing phase can be left to another team for the next school semester.

ACKNOWLEDGMENTS

We would like to extend our gratitude towards Professor Katsuo Kurabayashi and our client, Professor Dennis Assanis and his graduate student, Andrew Ickes for their invaluable guidance in the course of this review. We would also like to acknowledge both Professor Assanis and Shell Oil Company for their financial support. Lastly, we thank the shop technicians, Bob Coury, Marv Cressey and Steven Emanuel for their help in our fabrication process.

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BIOS

QIONGHUI FUNG

Qionghui comes from Singapore, the "little red dot" located in South-east Asia. Since young, she has been interested in how things work, and it was this interest that led her to take up Mechanical Engineering in the University of Michigan. Last summer, she participated in the University's Study Abroad Program in Shanghai and took a course on Engineering Statistics for Manufacturing Systems. That, together with her internship in Delphi Shanghai, has led her to become interested in manufacturing processes and industrial operations engineering. Upon graduation from the University of Michigan, she hopes to further her studies with a Masters degree in Industrial Operations Engineering. In her free time, she is involved in floorball and organizing the Seniors' Day for the Singaporean students association. She is also deeply interested in archery, Japanese culture and graphic design.

CHUN YANG ONG

Chun Yang was awarded the Civil Aviation Authority of Singapore Overseas scholarship back in 2004, which allowed him to come to the United States to pursue his tertiary education. Before entering college, he was serving in the Singapore Armed Forces as an infantry wing instructor in Officer Cadet School. At the University of Michigan, he is majoring in Mechanical Engineering, with a minor in Economics. Outside the classroom, Chun Yang likes to participate in outdoor sports like kayaking and he plays floorball on a regular basis at the U of M Floorball Recreational Sports Club. During the holidays, he spends his time traveling within North and South America. The countries that he has visited include Mexico, Panama, Costa Rica, Peru and Canada. In the summer, he goes back to Singapore to visit his family and friends, and does his internship at CAAS, his scholarship company. He will eventually return to CAAS as an Assistant Manager where he hopes to contribute to the development of one of the best airports in the world.

CHEE CHIAN SEAH

Chee Chian was originally from Singapore, a small but strategically-located island in Southeast Asia. In April 2002, he earned himself an overseas scholarship from Singapore Airlines to study in the United States. Since young, Chee Chian has developed strong interests in problem solving and in the design of mechanical systems. Therefore, he decided to pursue a bachelor's degree in Mechanical Engineering (ME) at the University of Michigan. After taking ME classes from a wide range of topics, Chee Chian has identified solid mechanics and thermodynamics to focus on by choosing relevant higher-level classes. Currently, he is in his final semester before graduating in April 2007. Chee Chian's involvement in activities beyond academics has underscored his desire to gain an all-round college experience. In January 2006, Chee Chian was elected to become the Vice-President of the University of Michigan Singapore Students Association (UMSSA) in which he is responsible for the well-being of its 140 members. In addition to the busy academic schedule and heavy responsibilities in UMSSA, Chee Chian has been an active member of the Michigan Floorball Club since September 2004. His post-graduation plan is to earn a master's degree in management science related graduate programs. Subsequently, Chee Chian will return to Singapore to begin his career with Singapore Airlines as an engineer.

JOANN TUNG

Coming all the way from Singapore, Joann is just one of the many international students who are here in US to pursue their dreams of an overseas education. Presently a senior working towards a Bachelors of Science in Mechanical Engineering, her strong passion in the field is reflected in the enthusiasm and commitment that have been the chief reasons for her academic excellence to date. From the simple applications of Mathematics and Physics in her childhood years, her desire to innovate, engineer and design continues to grow even further.

For her, this project will add even greater enjoyment and enrichment to her learning experience at Michigan, allowing her to further her interest in the field and gain invaluable hands-on experience and exposure working with researchers at the cutting-edge of technology. Outside of her academic interests, she likes to travel widely, and have planned her own budget trips to Canada, and many parts of China, Europe and the United States. As she likes to put it, she is a “full-time student, part-time tourist”. Her dream destinations lie in even more exotic places like Africa and Turkey. After she finishes her final semester this winter, she hopes to continue her Masters in management science or industrial operations. Eventually, she hopes to reciprocate the generosity bestowed by her scholarship board, Temasek Holdings (Private) Limited, who is sponsoring her overseas education, by applying the skills and experience she has garnered throughout the years to improve their operations and engineering competence.

APPENDIX A DESCRIPTION OF SINGLE-CYLINDER EXPERIMENTAL SET-UP

The following is a description of the experimental set-up of the single-cylinder test engine in the W. E. Lay Automotive Laboratory. This description is provided by Andrew Ickes.

Overview

The test engine that will be used is a single-cylinder version of a production diesel engine. The cylinder head and intake manifold system were kept as unmodified as possible so that the in-cylinder flow characteristics of the single-cylinder engine are as similar to the production engine as possible. However, unlike the production engine, all other engine systems are controlled by individual control systems to give the greatest degree of freedom possible. For example, changes in boost on the parent production engine require changing the turbocharger VGT settings, which will cause changes in other parameters such as backpressure and EGR rate. On the single-cylinder engine, these effects are decoupled, and boost can be adjusted mainly independent of other parameters. Finally, the engine is well instrumented to provide detailed and accurate measurements of its behavior.

Engine System

The work of this research project will be carried out on a test engine in the Walter E. Lay Automotive Laboratory. The test engine is a single-cylinder version of an Isuzu 1.7 liter high-speed direct-injection four-cylinder diesel engine. The engine is based on a Ricardo Hydra crankcase, but utilizing a specially built cylinder jug and liner. A cylinder head from a production Isuzu 1.7L engine is employed with the valve gear removed from the three unused cylinders. Figure I shows the test engine system, and Table I gives detailed specifications of the test engine geometry.

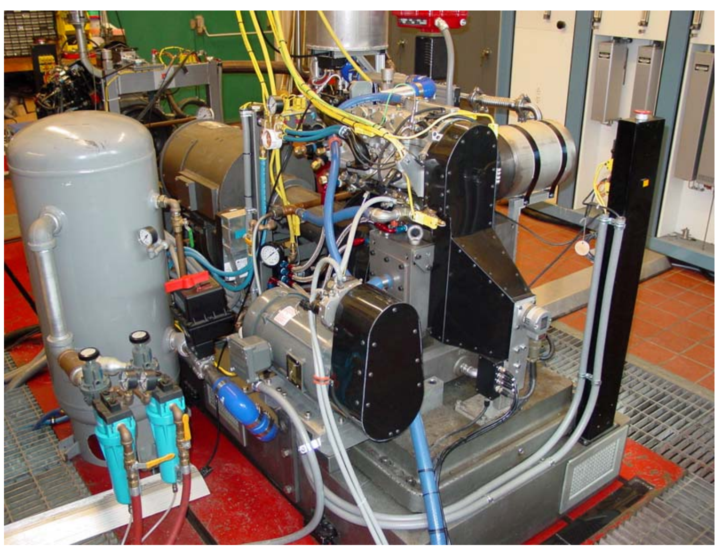


Figure I: Single-cylinder Isuzu derivative Diesel Research Engine.

Number of Cylinders	1
Displacement	425 cm3
Bore	79.0 mm
Stroke	86.0 mm

Connecting Rod Length	160.0 mm
Wrist Pin Offset	0.6 mm
Compression Ratio	16:1
Valves per cylinder	4
Camshafts	2
Injector Nozzle Hole Number	6
Injector Nozzle Cone Angle	150º
Injector Flowrate	320 cc/30s
Intake Valve Open (IVO)	366º BTDC-c
Intake Valve Close (IVC)	136º BTDC-c
Exhaust Valve Open (EVO)	122º ATDC-c
Exhaust Valve Close (EVC)	366º ATDC-c

Table I: Basic Specifications of the Ricardo Hydra CI test engine.

One important difference from the production engine is the decreased compression ratio. In a related prior study, Lechner decreased the compression ratio of the engine from 19:1 to 16:1 by employing a piston with a new, larger volume, piston bowl geometry (Lechner, 2003). The same piston geometry used in the prior work by Lechner (2003) and Jacobs (2005) was utilized in this engine.

Engine Swirl Control

Swirl is controlled with a manually selectable swirl control valve that restricts flow entering through one of the intake ports. The two different intake ports cause different levels of swirl in the cylinder with the overall swirl in the cylinder the balance of the high and low swirl from the two ports. By closing a throttle in the low-swirl port, higher levels of swirl are generated, but with a corresponding increase in the flow losses due to the reduction in port area. The production port throttle is used in the single-cylinder engine with 10 different positions, every 10 degrees from open to closed. The production port throttle does not fully block the low-swirl port, so the swirl ratio varies over a small range, from 2.77 to 3.17. Extending the port throttle plate to fully block the port increases the range of swirl numbers up to 5.61.

Fuel Injection System

The single-cylinder test engine uses the Bosch 1800 bar common rail injection system from the production engine. A Bosch 1210 common rail injector is used, and the factory selected copper depth spacer is retained to keep the injector at the depth optimized during assembly. The timing, duration, and number of injections are controlled with a Magnetek Engine Control Module. This unit allows for up to four independent injection events per engine cycle. Injection timing is controlled to within 0.1º crank angle, or the minimum resolution of the encoder. Injection duration (pulsewidth) is adjustable in increments of 1□s.

A Bosch CP3 high pressure pump, driven through a 4:3 reduction belt drive by a 3.7 kW (5hp) electric motor, supplies high pressure fuel to the production fuel rail. The production supply line and injector for the number one cylinder is retained, with the other three ports sealed off. Fuel rail pressure is controlled by a flow control valve on the CP3 pump, which restricts the inlet fuel flow. Adjusting and maintaining fuel pressure requires balancing the controlled flow into the pump and the quantity of fuel injected into the cylinder. A Pulse Width Modulation (PWM) controller manufactured in-house controls the fuel control valve.

Intake System

The engine is operated on oil-free, dry compressed air. Entering the test cell at 6.2 bar (90 psig), the air is filtered with grade three coalescing air filters to remove oil down to a concentration of 1 part per billion. A large surge tank is employed to damp out any abrupt changes in supply pressure. Downstream of the supply surge tank is a two-stage set of electrically operated valves that provide pressure and flow control for the intake air. A process-controlled 3500W electric heater is employed to heat and maintain the intake air at temperatures matching the production engine. Air flow is determined by measuring the pressure drop over a laminar flow element (LFE). The LFE is mounted downstream of the intake heater and before the inlet for the recirculated exhaust gas (EGR). A second smaller surge tank is used to damp out the pulsating intake flow into the single-cylinder engine to allow for accurate measurement of intake pressure. For accurate pressure measurements, the intake surge tank for a single-cylinder engine needs to be at least 50 times the displaced cylinder volume (Taylor and Taylor, 1962). The surge tank used for this test engine is 22.4 liters, or 53 times the engine displacement. Following the surge tank, the intake air joins the production intake system. The production intake system is retained from the port throttle/EGR valve unit through the intake manifold. A three millimeter thick blanking plate blocks the flow from the manifold to the cylinder ports of the three unused cylinders.

Exhaust System

The production engine exhaust manifold and turbocharger are not used on the single-cylinder engine. Instead, a short exhaust runner is employed and attached to a 7850cc (18.5 times the engine displacement) exhaust surge tank. This, like the intake surge tank, dampens the pulsating flow that occurs from a single-cylinder engine. Mounted downstream of the surge tank is an electrically actuated valve used to control the exhaust backpressure to match the production turbocharger settings, or, along with the boosting pressure, to turbocharger efficiency maps.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is used on the test engine. EGR is drawn off the main exhaust pipe immediately after the surge tank. An electrically actuated ball valve provides control over the amount of EGR flowing into the intake system, and a cooler is used to decrease the EGR temperature. Typical EGR coolers, including the cooler used on the production 4-cylinder version of this engine, cool the EGR by circulating engine coolant through a heat exchanger, but the EGR cooling setup on the single-cylinder engine uses a separate cooling system that is independent of the engine cooling loop. This allows for independent control over the temperature of the coolant, giving more flexibility in the EGR temperature. The cooling system is a simple one loop system similar in design to the oil and engine coolant systems. The coolant is a 50:50 mixture of ethylene glycol and distilled water.

EGR is fed into the intake system directly before the intake surge tank to allow for proper mixing to take place in the tank before the intake air goes into the engine.

The quantity of EGR inducted into the engine is computed by comparing the concentration of CO_2 in the intake stream to CO_2 concentration in the exhaust gas. The CO_2 in the intake stream is measured on a dry basis by a Siemens Ultramat 23 Infrared analyzer. This analyzer is mounted in a stand-alone sample cart with full gas conditioning including a sample pump, a filter to remove soot, and a chiller to remove the water from the sample gas. The sample port for the CO_2 measurement is in the intake manifold, immediately after the intake throttle where the EGR is normally introduced into the engine. By this point, the EGR and fresh intake air should be well mixed.

Engine Coolant System
The engine cooling system is a single loop with a 0.18 kW pump, an immersion heating element, and a heat exchanger. A process temperature controller monitors the coolant temperature and when the coolant temperature exceeds the desired setpoint, opens an electrically actuated ballvalve, allowing city water to flow through the heat exchanger. The city water cools the engine coolant and then is drained into the trench. This does not provide the same degree of stability as a two-loop simulated radiator system, but is a smaller and less complex system. The coolant is a 50:50 mixture of ethylene glycol and distilled water.

Lubrication System
A five quart wet sump oiling system provides lubrication and, with the piston oiljet, piston cooling to the test engine. Oil pressure is set at 4.2 bar (60psi) hot for all engine test conditions. Temperature control of the lubricating oil is achieved using a cooling system similar to the system used for the engine coolant system. The production Positive Crankcase Ventilation (PCV) system is not used. Instead, breather hoses to provide crankcase and valve cover ventilation are tied together and vented to atmosphere near the test cell's ventilation system exit.

Fuel System
Fuel is measured and supplied by a Max 710-100 Fuel Flow Measuring System. Fuel for the initial testing and combustion development was supplied from the Autolab fuel tanks, and is cooled and filtered before entering the test cell. The fuel comes into the test cell slightly pressurized from the static pressure head of the fuel tank, and having passed through a water separator and fuel filter. Fuels for later tests will be supplied from a pressurized five-gallon fuel can since the volume of fuel to be used is relatively small. In both cases, the fuel flows through a pneumatic emergency cutoff valve before being sent to the fuel measurement and supply unit, which consists of a fuel filter, variable pressure transfer pump, fuel cooler, and flowmeter. The unit supplies the fuel to the high pressure pump on the engine at 35psig.

The MAX model 213 positive displacement piston flowmeter determines the fuel quantity used by the engine by measuring the difference between the fuel supplied to the high pressure pump and the fuel that returns from the injector vent line.

Exhaust Emissions Measurement
Gaseous engine emissions are measured with a Horiba 200 Series emissions bench. This machine allows for steady state measurement of carbon dioxide (CO_2), oxygen (O_2), Carbon Monoxide (CO), and nitrogen oxides (NO_x). Hydrocarbon (HC) emissions are measured with a separate emissions bench.

The nitrogen oxide analyzer is a Horiba CLA-22A chemiluminescent analyzer. Both the carbon monoxide and carbon dioxide analyzers are Horiba AIA-23 Non Disruptive Infrared (NDIR) analyzers. The oxygen analyzer is a Horiba MPA-21A paramagnetic analyzer. A Horiba FIA-34A-2 heated flame ionization detector (FID) measures the hydrocarbon emissions.

Two separate ports for the emissions benches are located downstream of the variable exhaust backpressure valve. Heated remote sample filters remove particulates from the gaseous emissions samples before the gaseous exhaust sample flows to the emissions benches through heated lines operating at 190ºC.

Particulate emissions are measured with an AVL 415S particulate smokemeter. This compares the reflectivity of clean filter paper to filter paper where 500ml of exhaust have been flowed through it. The system outputs the Filter Smoke Number to an AVL 4210 Instrument Controller, and the data is logged manually. Filter Smoke Number (FSN) is defined as the function of post flow reflectivities for a set flow quantity through the filter paper (ISO, 10054).

High Speed Data Acquisition

Cylinder pressure is measured in the engine with a water-cooled Kistler 6041 piezoelectric pressure transducer. Filtered city water at 1.4 bar (20psig) is used to cool the transducer. The signal from the pressure transducer is sent to a DSP Technologies 1104CA charge amplifier, and then to the DSP technologies high-speed data acquisition system. The pressure transducer was calibrated before the engine tests using a dead-weight pressure calibration at six different pressures, with each point repeated three times for consistency. The calibration was done using the calibration program and procedure contained in the data acquisition software.

The high speed data acquisition system is a DSP Technologies CAMAC crate based system. A 100kHz model 2812 digitizer provides a sampling rate that, along with a BEI 1440 pulse per revolution optical encoder, allows for measurements every 0.25 crankangle degree up to the maximum engine speed of 4200rpm. A single 4325 TRAQ RTP real time processing unit provides real time calculation of pressure based parameters including Indicated Mean Effective Pressure (IMEP), the parameter used to monitor engine load.

The high speed data acquisition system software is DSP Red Line ACAP 5.0d. Since the piezoelectric cylinder pressure transducer measures gauge pressure fluctuations only, not absolute pressure, the pressure has to be referenced ("pegged") to a point in the cycle. During all tests, the software averages the cylinder pressure for the five degrees after bottom dead center of the intake stroke. The absolute pressure at this point in the engine cycle is pegged to the pressure in the intake manifold, as measured by the manifold absolute pressure (MAP) sensor.

Other signals measured on the high-speed data acquisition system include manifold pressure (used for pegging the cylinder pressure transducer), fuel injection line pressure, and injection driver signal. Fuel line pressure and injection driver signal are monitored to provide details of actual injector and injection behavior in the absence of a needle lift sensor which would directly measure the opening and closing of the injector needle. Needle lift sensors are not available for the Bosch injector used in the test engine.

Measuring the combustion noise is achieved using an AVL 450 Combustion Noise Meter. This instrument uses correlations based off a filtered version of the cylinder pressure to output an estimated engine noise level in decibels.

Dynamometer System
The engine is attached to a David McClure Ltd. 30kW AC dynamometer. The dynamometer is supported by trunion bearings at the front and rear to allow the dynamometer to float freely. Control of the dynamometer is by a Cussons manufactured control console that operates the dynamometer by means of a KTK 6P4Q30 thyristor drive system. The thyristor drive is contained in a cabinet in the test cell while the control console is in the control room next door. The dynamometer has speed control only; adjusting engine parameters controls load.

Torque Measurement
Torque is measured by a BLH Electronics load cell mounted 390mm from the centerline axis of the dynamometer. This instrument is calibrated before each test by a two point (zero/span) calibration. With no load on the dynamometer and the engine not spinning, the zero is adjusted at the control console. For the span calibration, a 51.3N mass is hung from the load cell (system measures a 20Nm torque) and the instrument span is adjusted by changing the signal multiplier in the low speed data acquisition system terminal for the torque signal.

APPENDIX B FLOWMETER EVALUATION FORM

The following is a flowmeter evaluation form provided by OMEGA Engineering Inc. to allow the systematic identification of suitable flow meters to measure exhaust gas velocity.

Table 1: Flowmeter Evaluation Table

FLOWMETER	PIPE SIZE, in. (mm)	STEAM	Gases (Vapors) Clean	Gases (Vapors) Dirty	Gases (Vapors) Press High	Gases (Vapors) Press Low	Liquids Clean	Liquids Viscous High	Liquids Viscous Low	Liquids Dirty	Liquids Corrosive	Liquids Very Corrosive	Liquids Slurries Fibrous	Liquids Slurries Abrasive	Reverse Flow	Pulsating Flow	High Temperature	Cryogenic	Semi-Filled Pipes	Non-Newtonians	Open Channel	TYPICAL Accuracy, uncalibrated (Including transmitter)	TYPICAL Reynolds number ‡ or viscosity	TEMPERATURE °F (°C)	PRESSURE psig (kPa)
SQUARE ROOT SCALE: MAXIMUM SINGLE RANGE 4:1 (Typical)**																									
Orifice																									
Square-Edged	>1.5 (40)	✓	✓	X	✓	✓	✓	X	?	X	?	X	X	X	SD	?	✓	✓	X	?	X	±1-4% URV	R_D >10,000	Process temperature to 1000°F (540°C): Transmitter limited to -30-250°F (-30-120°C)	To 4,000 psig (41,000 kPa)
Honed Meter Run	0.5-1.5 (12-40)	✓	✓	X	✓	✓	✓	?	?	X	?	X	X	X	SD	?	✓	✓	X	?	X	±1% URV	R_D >10,000		
Integrated	<0.5 (12)	?	✓	X	✓	✓	✓	X	?	X	?	?	X	X	SD	?	?	X	X	?	X	±2-5% URV	R_D >10,000		
Segmental Wedge	<12 (300)	✓	✓	✓	✓	✓	✓	?	✓	?	?	X	?	?	SD	?	✓	✓	X	?	X	±0.5% URV	R_D >500		
Eccentric	>2 (50)	?	?	✓	✓	✓	?	X	?	?	?	X	?	X	SD	?	✓	✓	X	?	X	±2-4% URV	R_D >10,000		
Segmental	>4 (100)	?	?	✓	✓	✓	?	X	?	?	?	X	?	X	SD	?	✓	✓	X	?	X	±2-4% URV	R_D >10,000		
V-Cone	0.5-72 (12-1800)	✓	✓	?	✓	✓	✓	?	✓	?	?	X	?	?	X	?	?	?	X	?	X	±0.5-1% of rate	R_D: 8,000-5,000,000	700 (370)	≤600 (4,100)
Target***	<0.5(12)	?	✓	✓	✓	✓	✓	?	✓	✓	?	X	X	X	?	X	?	?	X	?	X	±0.5-5% URV	R_D >100	Process temperature to 1000°F (540°C): Transmitter limited to -30-250°F (-30-120°C)	To 4,000 psig (41,000 kPa)
Venturi	>2 (50)	✓	✓	?	✓	✓	✓	?	✓	?	?	X	✓	?	X	?	?	?	X	?	X	±0.5-2% URV	R_D >75,000		
Flow Nozzle	>2 (50)	?	✓	?	✓	✓	✓	X	?	?	?	X	X	X	X	?	?	?	X	?	X	±1-2% URV	R_D >50,000		
Low Loss Venturi	>3 (75)	✓	✓	X	✓	✓	✓	X	?	X	✓	X	X	X	X	?	?	?	X	?	X	±1.25% URV	R_D >12,800		
Pitot	>3 (75)	X	✓	X	✓	✓	✓	X	?	X	?	X	X	X	X	X	?	?	X	X	X	±3-5% URV	R_D >100,000		
Averaging Pitot	>1 (25)	✓	✓	SD	✓	✓	✓	X	?	SD	?	X	X	X	SD	X	?	?	X	X	X	±1-2% URV	R_D >40,000		
Elbow	>2 (50)	X	✓	?	✓	✓	✓	X	?	?	?	X	X	X	✓	X	?	?	X	?	X	±5-10% URV	R_D >10,000		
Laminar	0.25-16.6 (6-400)	?	✓	X	✓	✓	✓	✓	?	X	?	X	X	X	X	✓	X	X	X	X	X	±1% of rate	R_D <500	150 (66)	≤30 (225)
LINEAR SCALE TYPICAL RANGE 10:1 (Or better)																									
Magnetic*	0.1-72 (2.5-1800)	X	X	X	X	X	✓	?	✓	✓	✓	✓	✓	✓	✓	✓	?	X	?	?	?	±0.5% of rate	R_D >4,500	360 (180)	≤1,500 (10,800)
Positive Displacement																									
Gas	<12 (300)	X	✓	X	?	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	±1% of rate	-	250 (120)	≤1,400 (10,000)
Liquid	<12 (300)	X	X	X	X	X	✓	✓	?	X	?	X	X	X	X	X	?	X	X	X	X	±0.5% of rate	No R_D limit ≤ 8,000 cS	600 (315)	≤1,400 (10,000)
Turbine																									
Gas	0.25-24 (6-600)	SD	✓	X	✓	✓	X	X	X	X	X	X	X	X	SD	SD	?	?	X	X	?	±0.5% of rate	-	-450-500 (268-260)	≤3,000 (21,000)
Liquid	0.25-24 (6-600)	X	X	X	X	X	✓	X	?	X	?	X	X	SD	SD	SD	?	?	X	X	?	±0.5% of rate	R_D >5,000, ≤15 cS	-450-500 (268-260)	≤3,000 (21,000)
Ultrasonic																									
Time of Flight	>0.5 (12)	X	SD	SD	SD	SD	✓	?	?	X	✓	✓	?	?	✓	✓	X	?	X	X	?	±1% of rate to ff15% URV	R_D >10,000	-300-500 (-180-260)	Pipe rating
Doppler	>0.5 (12)	X	X	X	X	X	X	?	?	✓	✓	✓	✓	✓	✓	✓	X	X	X	?	X	±1% of rate to ff15% URV	R_D >4,000	-300-500 (-180-260)	Pipe rating
Variable-Area (Rotameter)	≤3 (75)	?	✓	X	X	✓	✓	X	?	X	?	?	X	X	X	?	?	?	X	X	X	±1% of rate to ff10% URV	No R_D limit, <100 cS	Glass 400 (200) Metal 1,000 (540)	Glass 350 (2,400) Metal 720 (5,000)
Vortex Shedding	1.5-16 (40-400)	✓	✓	?	✓	✓	✓	X	?	?	?	X	X	X	X	X	?	?	X	X	X	±0.75-1.5% of rate	R_D >10,000, <30 cP	400 (200)	≤1,500 (10,500)
Vortex Precession (Swirl)	<16 (400)	✓	✓	?	✓	✓	✓	X	?	X	?	X	X	X	X	X	?	X	X	X	X	±0.5% of rate	R_D >10,000, <5 cP	536 (280)	Pipe rating
Fluidic Oscillation (Coanda)	>1.5 (40)	X	X	X	X	X	✓	X	X	?	?	X	X	X	X	?	?	?	X	X	X	±2% of rate	R_D >2,000, <80 cS	350 (175)	≤720 (5,000)
Mass																									
Coriolis	0.25-6 (6-150)	?	?	?	✓	✓	✓	✓	✓	✓	?	?	?	✓	?	?	?	?	X	✓	X	±0.15-10% of rate	No R_D limit	-400-800 (-224-427)	≤5,700 (39,900)
Thermal Probe	<72 (1800)	X	✓	?	✓	✓	✓	?	✓	✓	?	?	?	?	X	?	?	X	X	?	X	±1-2% URV	No R_D limit	1,500 (816)	Pipe rating
Solids Flowmeter	<24 (600)	X	X	X	X	X	X	SD	X	?	X	X	SD	SD	X	SD	SD	X	✓	X	X	±0.5% of rate to ff14% URV	-	750 (400)	≤580 (4,000)
Correlation																									
Capacitance	<8 (200)	X	X	X	X	X	X	✓	✓	✓	✓	✓	✓	✓	X	?	?	X	?	?	X	No data available	No data available	300 (149)	≤580 (4,000)
Ultrasonic	>0.5 (12)	X	X	X	X	X	X	?	✓	✓	✓	✓	✓	✓	X	?	X	X	X	?	X	±6% of ??	No data available	-300-250 (-180-120)	Pipe rating

cP = centi Poise; cS = centi Stokes; SD = Some designs

? = Normally applicable (worth consideration); ✓ = Designed for this application (generally suitable)

URV = Upper Range Value; X = Not applicable

‡ According to other sources, the minimum Reynolds number should be much higher

* Liquid must be electrically conductive

** Range 10:1 for laminar, and 15:1 for target

*** Newer designs linearize the signal

APPENDIX C ENGINEERING CALCULATIONS FOR HEATING SYSTEM DESIGNS

Nomenclature Table

u_f	Mean Fluid Velocity
D	Pipe Diameter
ν_f	Kinematic Fluid Viscosity
Pr	Prandtl Number
k_f	Thermal Conductivity
L	Length
c_p	Specific Heat Capacity
Q	Volume Flow Rate
ρ	Density

Reynold's Number, $\mathrm{Re}_D = \dfrac{u_f D}{\nu_f}$

Nusselt's Number (Turbulent Flow), $\langle Nu \rangle_{D,t} = 0.023\,\mathrm{Re}_D^{0.8}\,\mathrm{Pr}^{0.4}$

Nusselt's Number (Transition Flow), $\langle Nu \rangle_{D,h}^{10} = \langle Nu_{D,l} \rangle^{10} + \left(\dfrac{e^{(2200-\mathrm{Re}_{D,h})/365}}{\langle Nu_{D,l} \rangle^2} + \dfrac{1}{\langle Nu_{D,t} \rangle^2} \right)^{-5}$

Conduction Resistance, $R_k = \dfrac{\ln\left(\dfrac{R_2}{R_1}\right)}{2\pi L k_f}$

Convection Resistance, $R_{ku,C} = \dfrac{D}{A_{ku} \langle Nu \rangle_D k_f}$

Total Resistance, $R_\Sigma = R_{ku,c} + R_{ku,h} + R_{k,c-h}$

Biot Number, $Bi = R_k / R_{ku}$

Stream Capacitance, $\dot{M}c_p = Q\rho c_p$

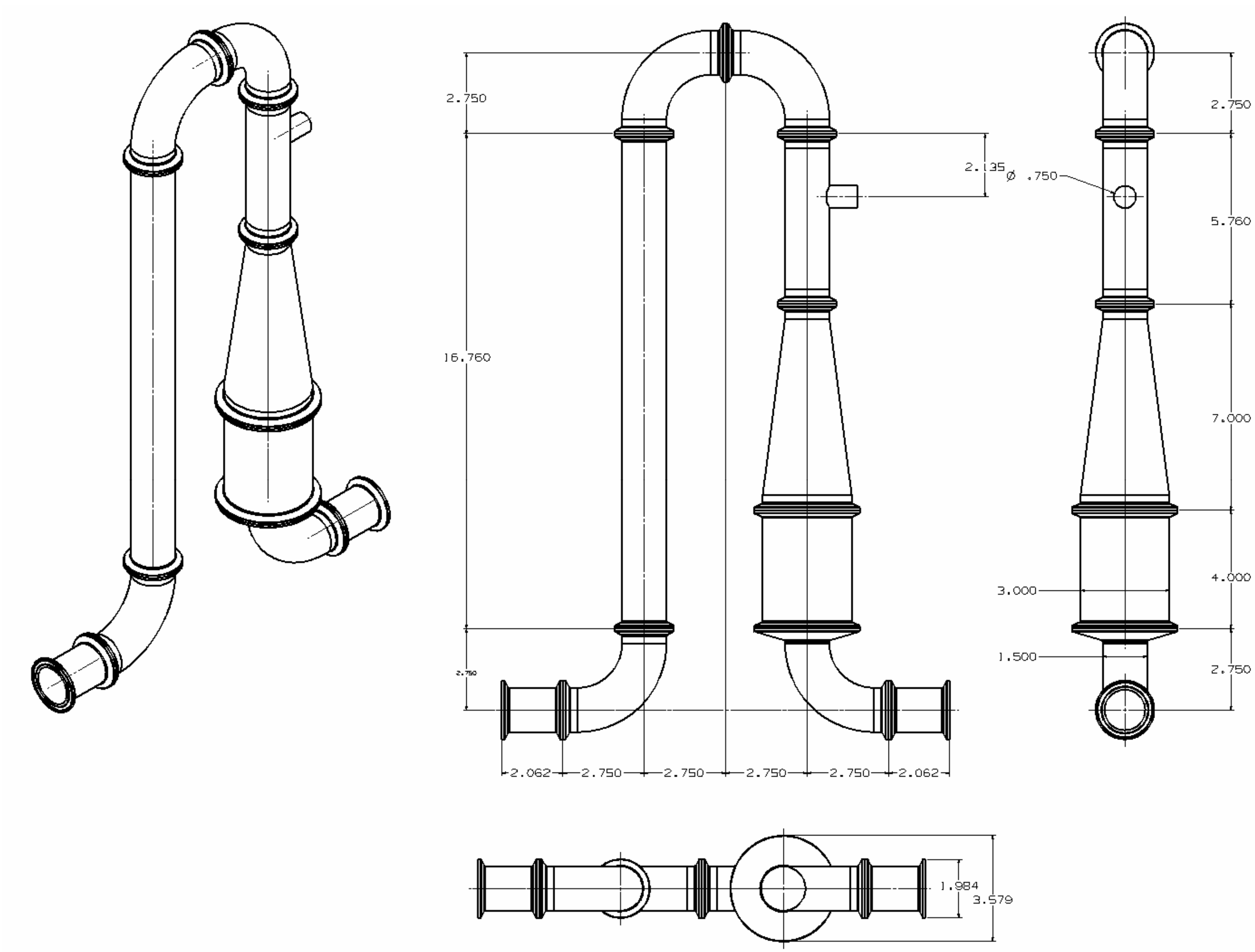
Ratio of Stream Capacitance, $Cr = \dfrac{(\dot{M}c_p)_{\min}}{(\dot{M}c_p)_{\max}}$

Number of Transfer Units, $NTU = \dfrac{1}{R_\Sigma (\dot{M}c_p)_{\min}}$

Heat Exchanger Effectiveness (Cross-flow), $\varepsilon_{he} = \dfrac{\Delta T \,|_{(\dot{M}c_p)_{\min}}}{\langle T_{f,h} \rangle_L - \langle T_{f,c} \rangle_0} = \dfrac{1 - e^{-NTU(1-Cr)}}{1 - Cr\left(e^{-NTU(1-Cr)}\right)}$

Heat Exchanger Effectiveness (Bounded flow), $\varepsilon_{he} = \dfrac{\langle T_f \rangle_0 - \langle T_f \rangle_L}{\langle T_f \rangle_0 - T_s} = 1 - e^{-NTU}$

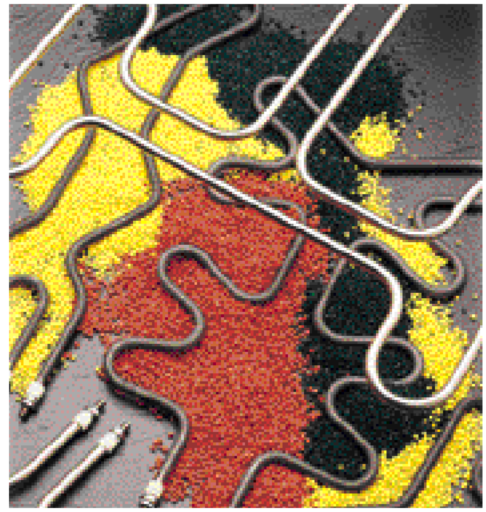
APPENDIX D DIMENSIONED DRAWING OF CAD MODEL (ASSEMBLED)



APPENDIX E HEATING SYSTEM

E1. WATROD Tubular Heater
E2. Dimensioned Drawing of Heater Installation

WATROD Tubular Heaters Provide Optimum Manifold Heating



Available in single- or double-ended termination styles, the versatile and economical WATROD tubular heating element lends itself to efficient heating of hot runner manifolds. The single-ended WATROD tubular design has both terminals at one end. The opposite end is sealed to resist contamination. Standard 305 mm (12 in.) flexible lead wires are crimp connected to the terminal pin and have silicone impregnated fiberglass oversleeves. With its round cross-section geometry, the double-ended WATROD is highly adaptable for bending – especially when bending is performed in the field.

Both single- and double-ended WATRODs share many construction features that deliver long life—the resistance wire is centered in the heater sheath and electrically insulated with compact, high-grade magnesium oxide for superior manifold heating. Watlow's double-sided multicoil tubular elements offer various combinations of resistor coils and thermocouples inside one sheath. They have the ability to sense the heater's internal temperature accurately every time, or offer three-phase capability in one element.

Performance Capabilities

Single-Ended WATROD

- Watt densities to 6.9 W/cm² (45 W/in²)
- UL® and CSA component recognition to 240V~(ac)
- Incoloy® and stainless steel sheath temperatures to 650°C (1200°F)

Double-Ended WATROD

- Watt densities to 18.6 W/cm² (120 W/in²)
- UL® and CSA component recognition to 480 and 600V~(ac) respectively
- Inconel® sheath temperatures to 982°C (1800°F)

Features and Benefits

Precision wound nickel-chromium resistance wire

- Distributes heat evenly to the sheath for optimum heater performance

Silicone resin seals

- Protect against moisture contamination and manifold leakage and are rated to 200°C (390°F)

MgO insulation filled sheath

- Maximizes dielectric strength, heat transfer and life

Standard sheath materials include

- Copper, steel 316 stainless steel and Inconel®
- Optional materials, available on made-to-order, include 304 stainless steel, Inconel®, Monel® and titanium

36 standard bend formations

- Allows for exacting fit to the manifold
- Spirals, compound bends, multi-axis and multi-plane configurations

Resistance wire fusion welded to the terminal pin

- For a stronger, positive electrical connection

Stainless steel studs

- Fusion welded to terminal pins for mechanical strength with ceramic insulator

WATLOW

HAN-WRD-1001

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Moisture Resistance Seals

WATRODs MgO insulating material is hygroscopic. To prevent moisture contamination from entering the heater, an appropriate moisture seal must be used. Choosing the correct seal is important to the life and performance of the heater. Be sure the maximum continuous use temperatures is not exceeded at the seal location. Most end seals are applied with a small cavity in the end of the heater. The seal will also help prevent arching at the terminal ends.

Applications

- Hot runner molds

Bend Formations

Single-Ended WATROD

Watlow does not recommend field bending single-ended WATROD elements. The minimum radius of the bend and the straight length beyond the bend limits formation. The radius must be 76 mm (3 in.) or more for the heated length's end to be inside a bend.

Double-Ended WATROD

Double-ended WATROD heating elements can be formed into spirals, compounds, multi-axis and multi-planes from 36 common bend configurations. Custom bending with tighter tolerances can be made to meet specific application needs.

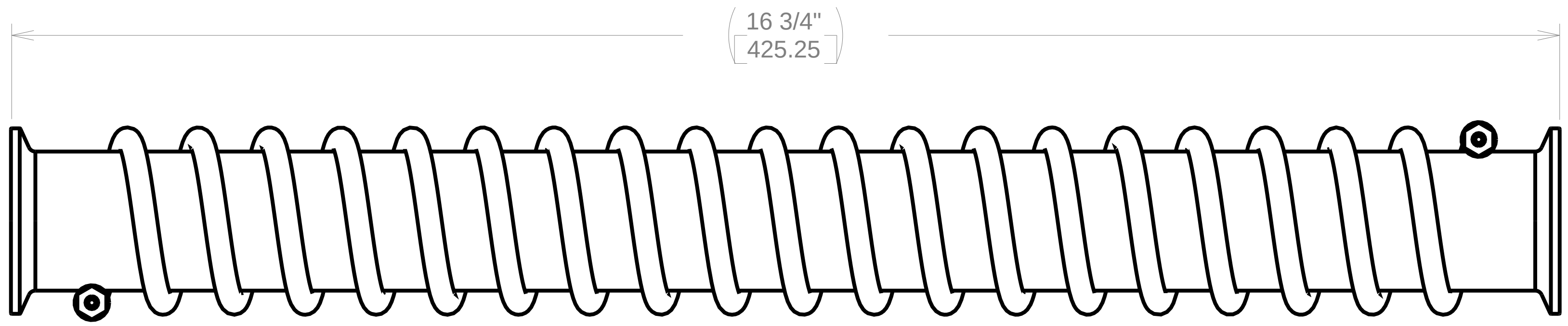
The minimum bend radius and the straight length required beyond the bend limits formation. In order to locate the end of a heated length within a bend, the radius must be 76 mm (3 in.) or larger. Additionally, overall length tolerances must be included in one or more of the straight lengths.

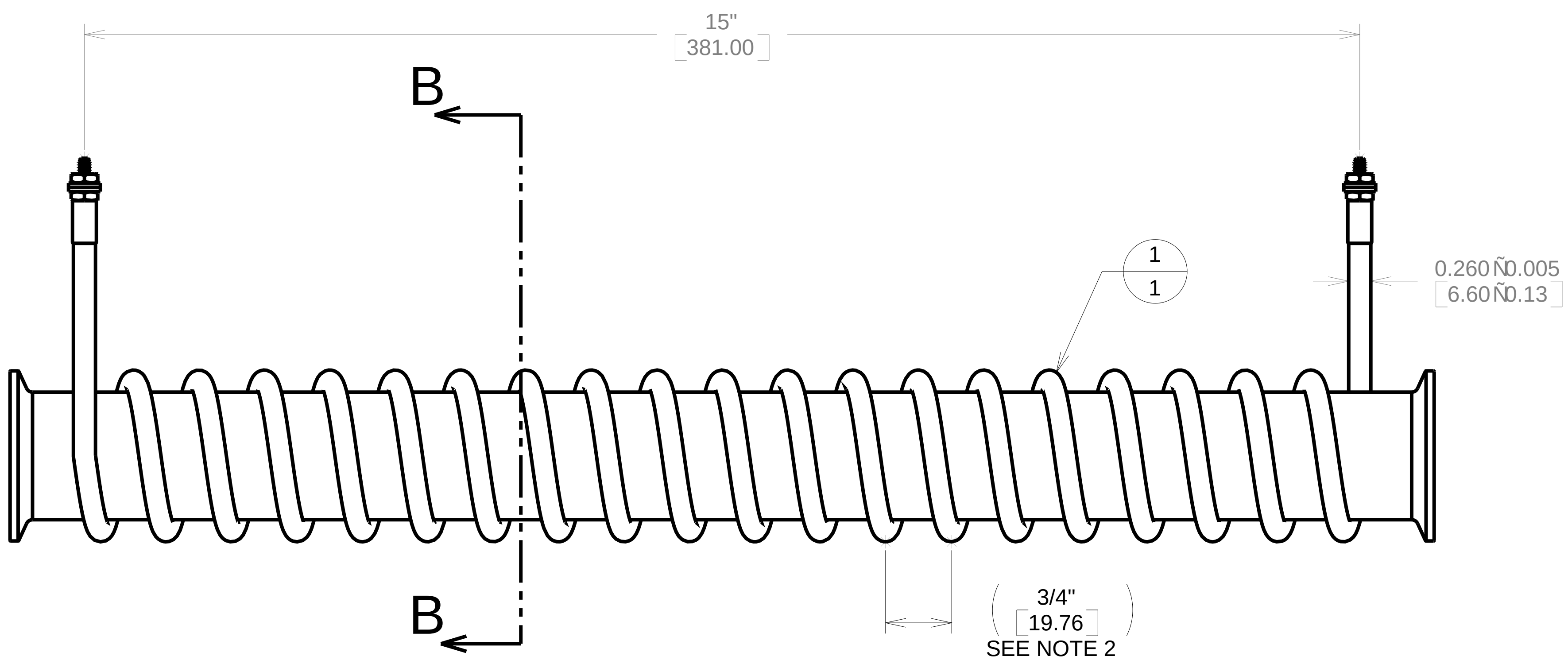
WATROD Termination Options

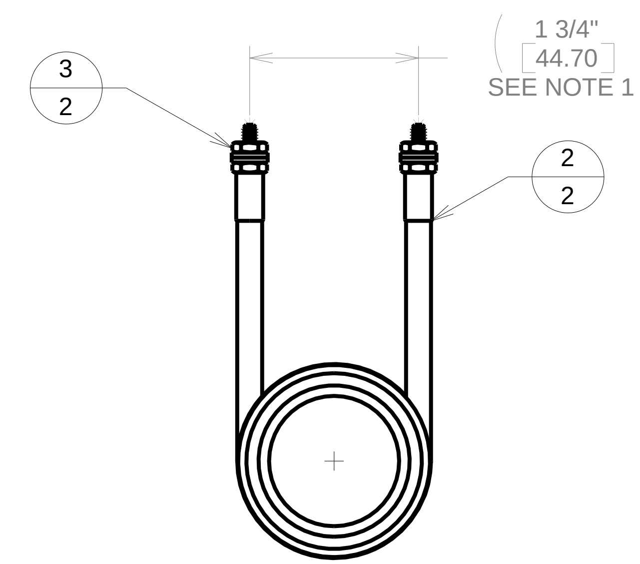
Double-ended WATROD elements are available with a variety of terminations. Single-ended WATROD elements are available with only flexible lead wires. The following table and illustrations detail the terminations available with double- or single-ended WATRODs – for each available sheath diameter.

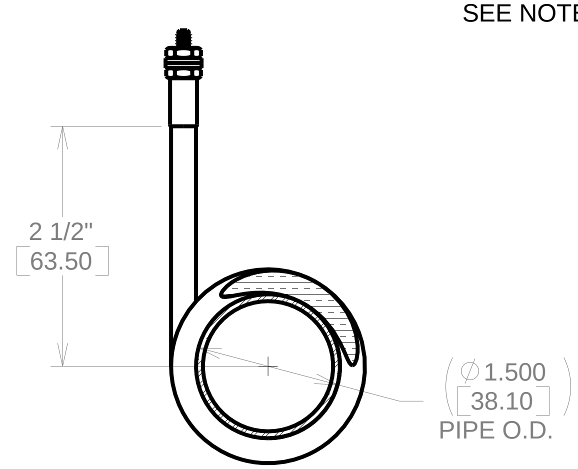
Standard flexible lead wires are 305 mm (12 in.) unless otherwise specified. Insulation options include TGGT (250°C/480°F) plus other temperature ratings. Consult factory for availability. Overmolds are available for flexible lead wires only and are available in silicone rubber (200°C/390°F), neoprene (90°C/212°F) and other materials. Consult your Watlow representative for details.

WATROD Element	Sheath Diameter		Threaded Stud[a]	Screw Lug (Plate)			Quick Connect (Spade)			Flexible Lead Wires	Lead Wire Overmolds
	mm	inch	A	B	C	D	E	F	G	H	J
Double-Ended	6.6	0.260	#6-32	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	8.0	0.315	#10-32	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	8.5	0.335	#10-32	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	9.5	0.375	#10-32	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	10.9	0.430	#10-32	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	12.0	0.475	#10-32	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	12.4	0.490	#10-32	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	15.9	0.625	#10-32	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Single-Ended	9.5	0.375	No	No	No	No	No	No	No	Yes	No
	10.9	0.430	No	No	No	No	No	No	No	Yes	Yes
	12.0	0.475	No	No	No	No	No	No	No	Yes	Yes
	12.4	0.490	No	No	No	No	No	No	No	Yes	No
	15.9	0.625	No	No	No	No	No	No	No	Yes	Yes









SECTION B-B
SCALE 1 : 2

NOTES:

1.) FORM ELEMENT ON CUSTOMER SUPPLIED PIPE.
ENDS OF ELEMENTS MAY NOT LINE UP AS SHOWN.
WHERE EVER ELEMENT LEGS LINE UP IS ACCEPTABLE.

2.) SPACE WRAPS AS EVENLY AS POSSIBLE. WRAP ELEMENT ON PIPE AS TIGHT AS POSSIBLE. WHATEVER SPRINGBACK OCCURS IS ACCEPTABLE.

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED

ITEM NO.	QTY.	UOM	PART NO.	DESCRIPTION	COMMENT
1	1	EA	A1-32-233-39	ELEMENT COMPONENT	
2	2	EA	309-74-4-1	INSULATION FLUID, (SEAL, ETC)	
3	2	EA	484-000-1-18	TERMINAL ASSEMBLY	
4	1	EA	381-60-9-1C	CUSTOMER SUPPLIED PIPE	

1-32-233-39	220	2000	
PRODUCT NUMBER	VOLTS	WATTS	CUSTOMER NUMBER

UNLESS OTHERWISE SPECIFIED
DIMENSION UNITS: INCHES [MILLIMETERS]
TOLERANCES:
.X = ± 0.1 in. [2.5]
.XX = ± 0.06 in. [1.52]
.XXX = ± 0.031 in. [.787]
.XXXX = ± 0.0050 in. [.1270]
ANGLES = ± 2 DEG.
FRACTIONS = ± 1/8 in. [3]
DIMENSIONS IN ( ) ARE REFERENCE ONLY

DSGN BY	MRC	DATE 04-13-07
DRAWN BY	MRC	DATE 04-16-07
ENGRG		DATE
Q.A.		DATE
MFG.		DATE

WATLOW ELECTRIC MANUFACTURING COMPANY
WATLOW HANNIBAL
#6 INDUSTRIAL LOOP ROAD
HANNIBAL, MO 63401
PHONE 573-221-2816, FAX 573-221-3723

TITLE: WATROD ASSEMBLY
FIG-34 FORMATION
TYPE A TERM, NO MTG

THIRD ANGLE PROJECTION

CUSTOMER: HI-WATT	SIZE: B	DRAWING NO.: 1-32-233-39	REV
MATERIAL: ALLOY 840	SCALE: 1:1	PART NO.: 1-32-233-39	SHEET: 1 OF 1

APPENDIX F THERMAL CONTROL SYSTEM

WATLOW Series SD Temperature Controller

SERIES SD Controllers Provide Value and Accurate, Cost-Effective Temperature Control

The SERIES SD family of PID temperature controllers utilizes today's advanced technology to provide the value, benefits and accuracy you've come to expect from Watlow. The features and performance offered by SERIES SD controllers make them ideally suited for a broad range of applications in temperature and process control.

The SERIES SD single channel controllers include a universal sensor input with up to three outputs that can be programmed for heat or cool temperature control, or to operate as process or deviation alarms. Programming Inverse Scaling is also simplified with the user-friendly set-up menu, providing additional value without additional cost.

Advanced features of SERIES SD controllers include EIA-485 Modbus™ Serial Communications, Watlow's INFOSENSE™ sensor technology, Infrared Remote Communications operation, Watlow's patented User Definable Menu System and a "Save and Restore" feature that allows the restoration of either factory or user-defined settings.

The SERIES SD is available in FM Limit version and a four-profile, 10-step Ramping version that includes Ramp, Soak, Jump Loop, Link and End steps. The updated SERIES SD family includes a new Variable Burst Fire feature that saves wear and tear on heaters, thus prolonging heater life, reducing downtime and saving money. Two non-linear PID curves have also been added to improve performance in plastics extruder applications.

Available in 1⁄32, 1⁄16, 1⁄8 and 1⁄4 DIN panel mount sizes, Watlow's SERIES SD family is backed by an industry leading three-year warranty from Watlow Winona. The SERIES SD controllers are UL® and C-UL® listed, CSA, CE and NSF-2 certified and include the IP65/NEMA 4X seal.

Features and Benefits

TRU-TUNE+™ Adaptive Control Algorithm
- Tighter control for demanding temperature/process applications

Watlow's INFOSENSE™ sensor technology
- Thermal sensing technology improves sensor accuracy by a minimum of 50 percent

Watlow's patented User Defined Menu System
- Allows the user to assign up to 20 parameters in the operations menu
- Improves operational efficiency

"Save and Restore" feature for user settings
- Allows the user to save individual or factory settings
- Eliminates the need to contact the OEM or factory to restore settings

WATVIEW HMI (Human Machine Interface)
- Permits operation, configuration and data logging via a standard Windows® PC

Infrared Communications
- Allows easier controller setup, operation and monitoring

Up to three outputs (two for 1⁄32 DIN)
- Results in application versatility

Dual Displays for all models
- Provides better recognition of process changes

Ramp to set point
- Controls temperature rise

Variable Burst Fire
- Prolongs heater life

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Windows® is a registered trademark of the Microsoft Corporation.
Modbus™ is a trademark of Schneider Automation, Inc.

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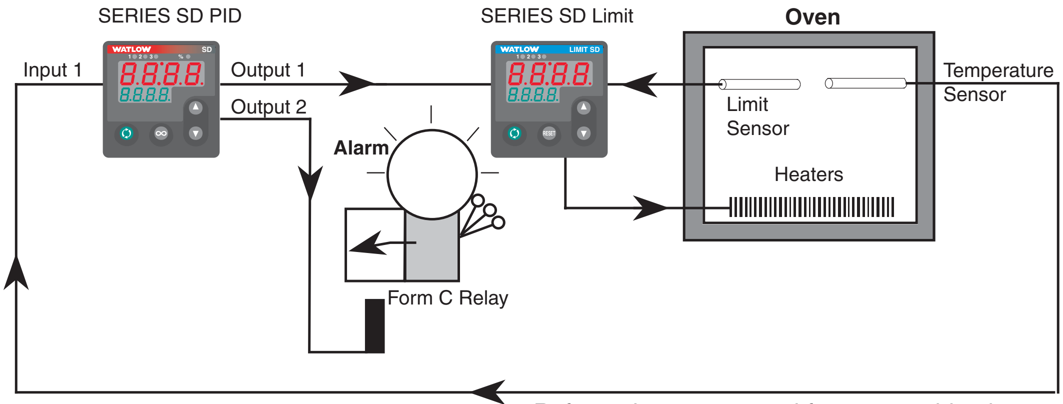
WIN-SD-0506

ISO 9001
Registered Company
Winona, Minnesota USA

Printed in the USA on Recycled Paper, 15% Postconsumer Waste

Typical Block Diagram



Refer to the user manual for proper wiring instructions

SERIES SD Limit Controllers

The SERIES SD family of limit controllers has been designed with the same microprocessor-based technology as the SERIES SD PID family of temperature controllers. The limits come with the FM (Factory Mutual) agency approval — the industry's most recognized designation for insurance concerns.

Limit controllers are typically added to thermal applications to monitor an over-temperature condition as a safety precaution. Limit controllers provide a redundant safety assurance to guard against instances where a high temperature runaway condition could result from a shorted input sensor, or from an output device that fails in a closed position.

Limits are recommended and are often required in applications where thermal runaway could result in costly operator safety concerns, product scrap, damage to capital equipment or a fire hazard.

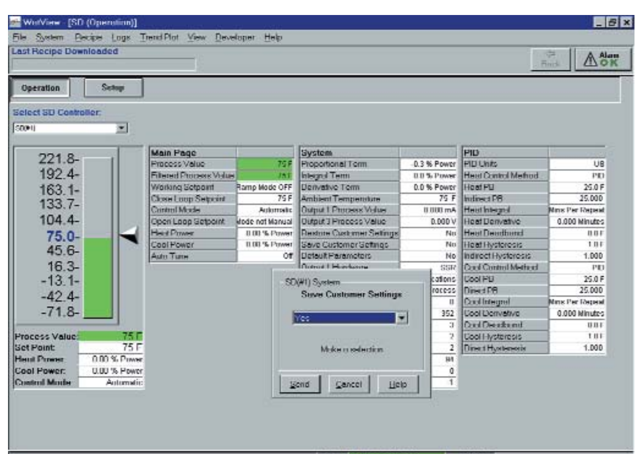
INFOSENSE™ Sensor Technology

Watlow's INFOSENSE™ sensor technology improves temperature sensing accuracy by 50 percent.

Each INFOSENSE "smart" sensor contains four numeric values located on tags attached to each sensor that are programmed into the SD controller memory. These values characterize Watlow sensors and allow the controller to provide enhanced accuracy.

WATVIEW HMI

WATVIEW, Watlow's Windows® based HMI (Human Machine Interface) software, supports the SERIES SD controllers. The software can be used to setup, monitor and edit the values of controller parameters, to monitor and manage alarms and to log and graph process data.

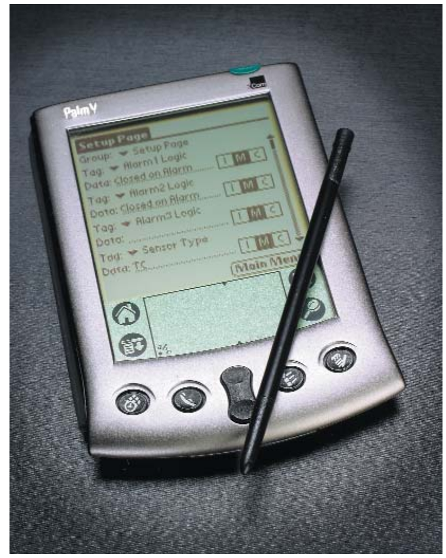


Infrared Communications

The Infrared Data Communications (IDC) option is available on all SERIES SD controller models except the 1/32 DIN and can support complete SERIES SD parameter configuration and operation. The IDC option supports wireless communications with PDAs (personal digital assistants) or other devices equipped with infrared communications that support the Infrared Data Association (IrDA) 1.0 Standard.

The actual user interface or configuration is dependent on the master device application software. A source for this software is Instant HMI from Software Horizons. For more information, visit www.instanthmi.com/watlow.

Advantages of IDC include automated logging of key process variables, increased accuracy and ease of use for recipe or configuration setups. Infrared data communications enhances controller data exchange in physically restricting environments (such as semiconductor clean rooms, governmental radio-active test labs or those hard to reach areas) and reduces the use of paper to record instrument information as well as human transposition errors.



Dimensions

DIN Size	Behind Panel (max.)	Width	Height
1/32 DIN	97.8 mm (3.85 in.)	52.6 mm (2.07 in.)	29.7 mm (1.17 in.)
1/16 DIN	97.8 mm (3.85 in.)	52.1 mm (2.05 in.)	52.1 mm (2.05 in.)
1/8 DIN Vertical	97.8 mm (3.85 in.)	52.8 mm (2.08 in.)	99.8 mm (3.93 in.)
1/8 DIN Horizontal	97.8 mm (3.85 in.)	99.8 mm (3.93 in.)	52.8 mm (2.08 in.)
1/4 DIN	101.1 mm (3.98 in.)	99.8 mm (3.93 in.)	99.8 mm (3.93 in.)

Specifications

Line Voltage/Power
- 100 to 240V~(ac), +10/-15 percent; (85-264V~[ac]) 50/60Hz, ±5 percent
- 24V≂(ac/dc), +10/-15 percent; 50/60Hz, ±5 percent
- 10VA maximum power consumption
- Data retention upon power failure via nonvolatile memory

Environment
- -18 to 65°C (0 to 149°F) operating temperature
- -40 to 85°C (-40 to 185°F) storage temperature
- 0 to 90 percent RH, non-condensing

Accuracy
- Calibration accuracy and sensor conformity: ±0.1 percent of span, ±1°C @ the calibrated ambient temperature and rated line voltage
- Calibration ambient temperature = 25°C ±3°C (77°F ±5°F)
- Accuracy span: 540°C (1000°F) minimum
- Temperature stability: ±0.1°C/°C (±0.2°F/°F) rise in ambient maximum

Agency Approvals
- UL® 3121, C-UL®, CSA, CE, IP65/NEMA 4X and NSF-2
- Limit version features FM approval

Controller
- Microprocessor based user-selectable control modes
- Single universal input, up to three outputs
- Control sampling rates: input = 6.5Hz, display = 10Hz, outputs = 6.5Hz

Operator Interface
- Dual 4 digit, 7 segment LED displays
- Advance, infinity and up down keys
- IrDA infrared port (not available on 1/32 DIN)
- Isolated EIA 485 Modbus™ serial communications

Wiring Termination -Touch Safe Terminals
- Input power and control outputs 12 to 22 AWG
- Sensor inputs and process outputs 20 to 28 AWG

Universal Input
- Thermocouple, grounded or ungrounded sensors
- RTD 2- or 3-wire, platinum, 100Ω @ 0°C calibration to DIN curve (0.00385 Ω/Ω/°C)
- Process, 0-20mA @ 100Ω, or 0-10V⎓(dc) @ 20kΩ input impedance; Scalable
- 0-50mV
- Inverse scaling
- >20MΩ input impedance
- Maximum of 20Ω source resistance

Specifications (con't)

Allowable Operating Range

Type J:	0	to	815°C	or	32	to	1500°F
Type K:	-200	to	1370°C	or	-328	to	2500°F
Type T:	-200	to	400°C	or	-328	to	750°F
Type N:	0	to	1300°C	or	32	to	2372°F
Type E:	-200	to	800°C	or	-328	to	1470°F
Type C:	0	to	2315°C	or	32	to	4200°F
Type D:	0	to	2315°C	or	32	to	4200°F
Type PTII:	0	to	1395°C	or	32	to	2543°F
Type R:	0	to	1760°C	or	32	to	3200°F
Type S:	0	to	1760°C	or	32	to	3200°F
Type B:	0	to	1816°C	or	32	to	3300°F
RTD (DIN):	-200	to	800°C	or	-328	to	1472°F

Process: -1999 to 9999 units

Control Outputs

Outputs 1, 2 , 3 (Output 3 not available on 1/32 DIN)

- User selectable for heat/cool as on-off, P, PI, PD, PID, or Alarm action. Not valid for limit controls
- Electromechanical relay. Form A, rated 2A @ 120V~(ac), 2A @ 240V~(ac) or 2A @ 30V⎓(dc)
- Switched dc non-isolated minimum turn on voltage of 6V⎓(dc) into a minimum 500Ω load with a maximum on voltage of not greater than 12V⎓(dc) into an infinite load. Maximum switched dc power supply current available for up to two outputs is 60mA
- Solid-state relay, Form A, 0.5A @ 24V~(ac) minimum, 264V~(ac) maximum, opto-isolated, without contact suppression
- Process output (Non Isolated)
  User-selectable 0-10V⎓(dc), 0-5V⎓(dc), 1-5V⎓(dc) @ 1KΩ minimum, 0-20mA, 4-20mA @ 800Ω maximum
- Electromechanical relay. Form C, rated 5A @ 120V~(ac), 5A @ 240V~(ac) or 5A @ 30V⎓(dc)
- Open collector 42V⎓(dc) @ 250mA maximum
- EIA 485 serial communications with Modbus™ protocol

Your Authorized Watlow Distributor Is:

Ordering Information

To order, complete the model number on the right with the information below.

S D _ _ - _ _ _ _ - _ A _ _

DIN Sizes
3 = 1/32 DIN[1]
6 = 1/16 DIN
8 = 1/8 DIN Vertical
9 = 1/8 DIN Horizontal
4 = 1/4 DIN

Control Type
C = PID Control Dual Display
L = Limit Control Dual Display [2]
R = Ramping Dual Display
E = PID Control with TRU-TUNE+™

Power Supply
H = 100 to 240V≈(ac/dc)
L = 24 to 28V≈(ac/dc)

Output 1
C = Switched dc
K = SSR, Form A, 0.5A
F = Universal process
J = Mechanical relay, Form A, 2A

Output 2
A = None
C = Switched dc
K = SSR, Form A, 0.5A
J = Mechanical relay, Form A, 2A
U = EIA 485 Modbus™ communications

Output 3 (Not available on 1/32 DIN)
A = None
C = Switched dc/open collector
K = SSR, Form A, 0.5A
F = Universal process
E = Mechanical relay, Form C, 5A

Infrared Comms Options (IrDA)
A = None (Default selection on 1/32 DIN)
R = IrDA ready (Not available on 1/32 DIN) [3]

Display Colors and Custom Options
RG = Red Green (Dual display units)
RR = Red Red (Not available on 1/32 DIN Dual Display)
XX = Custom options, special overlays, etc.

[1] An SD Single Display 1/32 DIN and a separate spec sheet are available.

[2] Not all options above are available on the SD limit controllers. Consult factory for proper configurations.

[3] IrDA communication not available if product is specified with TRU-TUNE+™ option.

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APPENDIX G GAS FLOW METERS

G1. Kanomax Anemomaster Model 6162
G2. Omni Instruments MiniAir 20 Mini Inox Vane Anemometer

KANOMAX
The Ultimate Measurements

ISO9001 ISO14001
JQA2790 JQA-EM1628

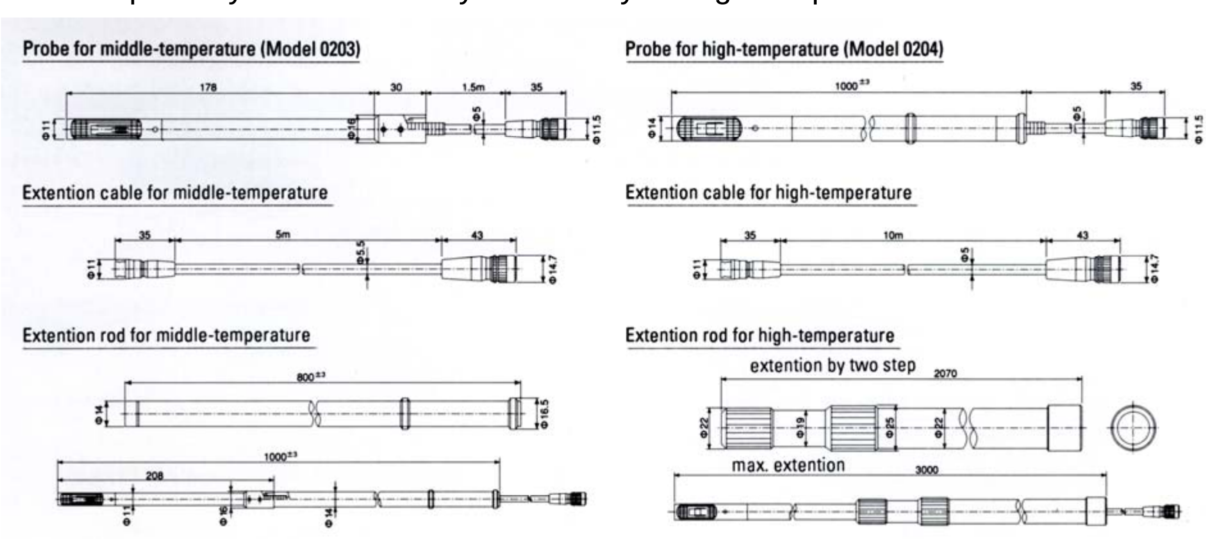
Middle and High Temperature Anemomaster

Probe Model 0203 (Middle temp. Up to 392ºF (200ºC))
Model 0204 (High temp. Up to 752ºF (400ºC))

EXCELLENT FIT for
High Temperature
Production
Environments in:
Sheet Forming
Container Production
Printing / Press
Steel
Atomic energy. etc

Simultaneous Measurement of Air Velocity and Temperature in High and Middle Temperature Environment

Features:
•Simultaneous display of air velocity and temperature
•Improved response time by the addition of secondary temperature compensation circuit
•Easy log review with graphic display
•Memory function of maximum 999 separate measurement data
•Built-in RS-232 C serial interface for connection to PC. Analog output and remote control terminal standard
•Probe Compatibility feature allows you to easily change the probe



Specifications

<table>
<tr><td>Model Name</td><td colspan="3">Main Body --- Model 6162
Probe --- Model 0203 (for middle temperature)
Model 0204 (for high temperature)</td></tr>
<tr><td>Measuring Functions</td><td colspan="3">Measurement of air velocity and temperature</td></tr>
<tr><td>Measuring Range</td><td colspan="3">Air velocity
40 – 9840fpm
(0.2 – 50m/s)
80 – 9840fpm
(0.4 – 50m/s)
138 – 9840fpm
(0.7 – 50m/s)
197 – 9840fpm
(1.0 – 50m/s)

Air temperature
32 – 212ºF
(0 - 99º C)
212 – 392ºF
(100 - 199º C)
392 – 572ºF (0204 only)
(200 - 299º C)
572 - 752ºF (0204 only)
(300 - 400º C)</td></tr>
<tr><td>Measuring Accuracy</td><td colspan="3">Air velocity: +/-3%
Air temp: +/-(1%rdg+1º C)</td></tr>
<tr><td rowspan="3">Temp. Compensation Accuracy (Air Velocity)</td><td></td><td>Model 0203
(32 – 392ºF)
(0 to 200º C)</td><td>Model 0204
(32 - 752ºF)
(0 to 400º C)</td></tr>
<tr><td>Less than 984fpm (4.99m/s)</td><td>+/-10%F.S.</td><td>+/-15%F.S.</td></tr>
<tr><td>More than 984fpm (5m/s)</td><td>+/-6%F.S.</td><td>+/-10%F.S.</td></tr>
<tr><td>Heat-resisting of Cable</td><td colspan="3">Teflon coating (Probe side): 392ºF (200º C)
Vinyl code (Extension cable): 176ºF (80º C)</td></tr>
<tr><td>Response</td><td colspan="3">Air velocity: Approx. 4 sec. (90% at air velocity of 984fpm (5m/s))
Air Temperature: Approx. 5 sec. (90% at air velocity of 984fpm (5m/s))</td></tr>
<tr><td>Display</td><td colspan="3">Digital (simultaneous display of air velocity and temperature)</td></tr>
<tr><td>Input/output Terminal</td><td colspan="3">Remote terminal: Start/Stop key
Analog output terminal: Output voltage 0 to 1V
Accuracy 0.5%F.S.
Output impedance 47Ω
Simultaneous output of air velocity temp.
Digital output terminal: RS-232C(serial interface)</td></tr>
</table>

<table>
<tr><td>Memory</td><td colspan="3">Max.999 data (only for the measurement in 1 page)</td></tr>
<tr><td>Power Supply</td><td colspan="3">Dry battery drive: U2 type (1.5V x 6 pcs = 9V)
Alkaline battery, Mn battery
AC adapter: 12.5V,450mA (AC100V+/-10%,50/60Hz)</td></tr>
<tr><td>Operating Temperature</td><td colspan="3">41 - 104ºF (5 - 40º C)</td></tr>
<tr><td>Battery Life</td><td colspan="3">Approx.8hrs (Alkaline Life, when operate continuously in air velocity 5m/s. This is a life time in case of the back light is OFF)</td></tr>
<tr><td>Dimensions</td><td colspan="3">8.7” x 3.3” x 5.9” (220 x 85 x 150 mm)</td></tr>
<tr><td rowspan="4">Probe</td><td>Model name</td><td>0203 (Middle temp)</td><td>0204 (High temp)</td></tr>
<tr><td>Dimensions</td><td>φ0.43”x8.2”
(φ11x208mm)</td><td>φ0.43”x39.4”
(φ11x1000mm)</td></tr>
<tr><td>Cable</td><td>Teflon coating: 4.9ft (1.5m)
Vinyl code: 16.4ft (5m)</td><td>Teflon coating: 7.5ft (2.3m)
Vinyl code: 32.8ft (10m)</td></tr>
<tr><td>Extension Rod (Option)</td><td colspan="2">0.65”(Max)x31.5” (middle temp)
(16.5(Max) x 800mm)
0.87”(Max)x81.5” (high temp)
(22(Max) x 2070mm)</td></tr>
<tr><td>Weight</td><td colspan="3">Main body: Approx. 4.0lbs (1.8kg)
Probe: Model 0203 Approx. 7.1oz (200g)
Model 0204 Approx. 17.6oz (500g)</td></tr>
<tr><td>List of Components</td><td colspan="3">Main Body (Model 6162)
Shoulder belt: 1pc, Dry battery (Size C Alkaline Batteries): 6pcs, AC adapter (DC 12V, 450ma): 1 pc, Analogue output cable: 2pc, Operation manual: 1pc
Probe for middle temp. (Model 0203)
Probe board: 1pc, Carrying case for probe: 1pc, Extension cable (Vinyl code: 5m): 1pc
Probe for high temp. (Model 0204)
Probe board: 1pc, Carrying case for probe: 1pc, Extension cable (Vinyl code: 10m): 1pc, reagent bottle, Beaker, Brush of bamboo: 1pc each</td></tr>
</table>

⚠ CAUTION	For safe and trouble-free operations, please read Operation Manual carefully before using the instrument.

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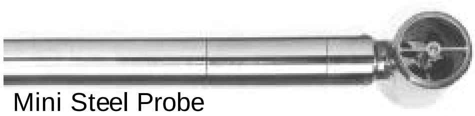
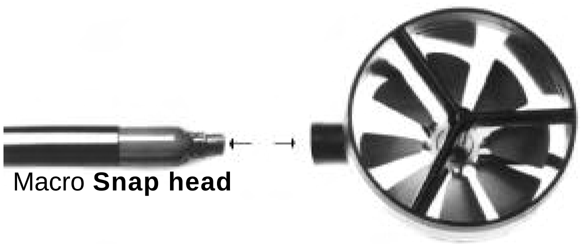
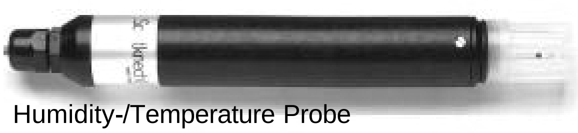
Micro **Snap head**



Mini Steel Probe



Macro **Snap head**



Humidity-/Temperature Probe

MiniAir®20

Multiprobe Anemometer

The universal MiniAir20 measures the velocity of gaseous and liquid media, temperature, relative humidity and revolutions. Accuracy and reliability are of the high standard expected from Schiltknecht Messtechnik AG.

- All MiniAir20 probes can be used
- Automatic probe recognition
- Easy handling, convenient keys
- Mean-, Minimal- and Maximal values
- Free selectable measurement time from 2s to 2h
- Analogue output 0-1 V
- Mini2Logger output
- Snap head principle features on-site serviceability

Types:

- **Indication unit MiniAir20**
- **Probe Micro (Æ 11x15 mm)**
- **Probe Mini (Æ 22x28 mm)**
- **Probe Macro (Æ 85x80 mm)**
- **Universal temperature probe**
- **Air temperature probe**
- **Surface temperature probe**
- **High temperature probe**
- **Humidity-/Temperature probe**
- **Revolutions probe**
- **Insertion device 4bar**
- **Insertion device 20bar**
- **Volume measurement system Micro**
- **Volume measurement system Mini**

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MiniAir20®

Multiprobe Anemometer

The vane anemometer MiniAir20 measures the velocity of gaseous or liquid media as well as temperature, relative humidity and revolutions. In anemometry, the accuracy achieved by a vane anemometer is acknowledged to be unmatched. The vane rotation is closely linear to flow velocity and is unaffected by pressure, temperature, density and humidity.
The probe MiniAir20, like other MiniAir models, features the unique Snap Head on types Micro, Mini and Macro, providing on-site serviceability, thus making it ideal for continual measuring.

Typical applications are measurements in ventilation, air-conditioning systems, building maintenance, general industrial research and laboratories.

Measuring media	Synthetic probe:	non-aggressive gases or liquid media
	Steel probe:	aggressive media
Measuring ranges	**Flow:**	m/s
	Temperature:	ºC
	Humidity:	% rh
	Revolutions:	rpm
Indication	LED 4-digit	
Measuring rates	2 measurements / sec.	
Supply / Battery	Battery (1 x 9 V Leclanché LR22-9 V) or external mains adapter	
Current consumption	Approx. 15 mA	
Lifetime of battery	Approx. 12 h	
Output	**Flow/Humidity:**	0-1 Volt
	Temperature:	10 mV/ºC 0V = -20ºC
	High-Temperature:	2 mV/ºC 0V = 0ºC
	Output for **Mini2Logger** (interval 0.5 s)	
Case dimension	80 x 145 x 39 mm	
Case protection type	IP 40 (ABS synthetic)	
Weight	ca. 230 gram	
Operating temperature	0 to 50ºC	
Storage temperature	- 30 to 80ºC	
Air humidity	0 to 90% rh, non-condensing	
Working standard	Laser controlled wind tunnel (cert. in accord. with SN EN 45001)	

Air Probe	**MiniAir20 Micro**	**MiniAir20 Mini**	**MiniAir20 Macro**
Measuring range Flow	0.5 - 20 m/s	0.3 - 20 m/s	0.15 - 20 m/s
	0.7 - 40 m/s	0.5 - 40 m/s	0.3 - 40 m/s
Flow accuracy	1.0% fs	0.5% fs	0.5% fs
	3.0% rdg	1.5% rdg	1.5% rdg
Measuring range Temp.	-20 to +140°C	-20 to +140°C	-20 to +140°C
Accuracy	+/- 0.5°C	+/- 0.5°C	+/- 0.5°C
Operating temperature	-30 to +140°C	-30 to +140°C	-30 to +140°C
Head dimension	∅ 11 x 15 mm	∅ 22 x 28 mm	∅ 85 x 80 mm
Access opening	16 mm	35 mm	
Length of probe	165 mm	175 mm	235 mm
Length of cable	1.5 m	1.5 m	1.5 m
Storage temperature	-65 to +150°C	-65 to +150°C	-65 to +150°C

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Air Probe of stainless steel	MiniAir20 Mini up to 140°C Steel	MiniAir20 Mini up to 250°C Steel	
Measuring range Flow	0.3 - 20 m/s	0.3 - 20 m/s	
	0.5 - 40 m/s	0.5 - 40 m/s	
Flow accuracy	0.5% fs	0.5% fs	
	1.5% rdg	1.5% rdg	
Measuring range Temp.	-20 to +140°C	- - - -	
Accuracy	+/- 0.5°C	- - - -	
Operating temperature	-30 to +140°C	-30 to +250°C	
		Evaluation box up to 65°C	
Head dimension	∅ 22 x 28 mm	∅ 22 x 28 mm	
Access opening	35 mm	35 mm	
Length of probe	182 mm	182 mm	
Length of cable	1.5 m	2.0 m (250°C)	
		1.5 m from Box	
Storage temperature	-65 to +150°C	-65 to +250°C	
		(Box and Cable	
		up to 65°C)	

Water Probe	MiniWater20 Micro	MiniWater20 Mini	
Measuring range Flow	0.04 - 5 m/s	0.02 - 5 m/s	
	0.05 - 10 m/s	0.03 - 10 m/s	
Flow accuracy	2.0% fs	2.0% fs	
	3.0% rdg	3.0% rdg	
Measuring range Temp.	0 to +70°C	0 to +70°C	
Accuracy	+/- 0.5°C	+/- 0.5°C	
Operating temperature	-30 to +70°C	-30 to +70°C	
Head dimension	∅ 11 x 15 mm	∅ 22 x 28 mm	
Access opening	16 mm	35 mm	
Length of probe	165 mm	175 mm	
Length of cable	5 m	5 m	
Storage temperature	-65 to +150°C	-65 to +150°C	

Temperature Probes	Universal temperature probe	Air temperature probe	Surface temperature probe
Measuring range	-20 to +140°C	-20 to +140°C	-20 to +140°C
Resolution	0.1°C	0.1°C	0.1°C
Accuracy	at 0 – 70°C 0.2°C	at 0 - 70°C 0.2°C	at 0 - 70°C 0.2°C
	outside 0.5°C	outside 0.5°C	outside 0.5°C
Operating temperature	-30 to +140°C	-30 to +140°C	-30 to +140°C
Head dimension	∅ 3 x 100 mm	∅ 3 x 100 mm	∅ 3 x 100 mm
Shaft	∅ 10 x 80 mm	∅ 10 x 80 mm	∅ 10 x 80 mm
Access opening	∅ 4 mm	∅ 5 mm	
Length of probe	180 mm	180 mm	180 mm
Length of cable	1.5 m	1.5 m	1.5 m
Storage temperature	-65 to +150°C	-65 to +150°C	-65 to +150°C

Temperature, Humidity and Revolutions Probes	Universal high temperature probe	Humidity and temperature probe	Revolutions probe
Measuring range	-20 to +600°C	0 to 99.9% RH	0 to 9'999 rpm
Resolution	1°C		
Accuracy	at 0-70°C 0.5°C outside 1.0°C		
Calibration accuracy		+/-1.5%rh at 10 - 95%rh	
Reproducibility		0.5%rh	
Temperature range		-10 to +60°C	
Calibration accuracy		+/-0.35°C at -10 - +50°C	
Reproducibility		0.1°C	
Operating temperature	-30 to +600°C	-20 to +60°C	0 to +60°C
Head dimension	∅ 3 x 230 mm	∅ 22 x 32 mm	∅ 13x40/45 mm
Shaft dimension	∅ ca. 22 mm	∅ 25 mm	∅ 15 x 120 mm
Access opening	∅ 4 mm	∅ 26 mm	∅ 14 mm
Length of probe	350 mm	195 mm	180 mm
Length of cable	1.8 m	1.8 m	1.5 m
Storage temperature	-65 to +150°C	-65 to +150°C	-65 to +150°C

Volume measuring system for water	Volume measuring system 4bar for MiniWater20	Volume measuring system 20bar for MiniWater20	
Measuring range	0.04 to 5 m/s	0.04 to 5 m/s	
Accuracy	0.5% fs 1.5% rdg	0.5% fs 1.5% rdg	
Operating temperature	-10 to +95°C	-10 to +200°C	
Length	288 mm	560 mm	
Insertion length	200 mm	360 mm	
Pressure-resistant up to	4 bar	20 bar	
Tube size	G ¾" - max. 200 mm	G ¾" - max. 200 mm	
Clear insertion width for probe	min. ∅ 15.75 mm	min. ∅ 15.75 mm	
Connection thread	G ¾" for ball valve	G ¾" for ball valve	
Length of cable	5.0 m	2.0 m (200°C) 1.5 m from Box (65°C)	
Storage temperature	-65 to +150°C	-65°C to +200°C (Box and Cable up to 65°C)	

Volume measuring system for air	Volume measuring system Micro (PSU)	Volume measuring system Mini (Steel)	
Measuring Range	0.4 to 40 l/min. 1.0 to 100 l/min.	2.5 to 250 l/min. 5.0 to 500 l/min.	
Accuracy	1.0% fs 3.0% rdg	0.5% fs 1.5% rdg	
Operating temperature	-30 to +140°C	-30 to +140°C	
Length	150 mm	300 mm	
Diameter	out ∅ 14 mm in ∅ 9 mm	out ∅ 22 mm in ∅ 18 mm	
Hose connector or	∅ hose 14 mm	∅ hose 18 mm	
Threaded connector	G ¼"	G ¾"	
Length of cable	1.5 m	1.5 m	
Storage temperature	-65 to +150°C	-65 to +150°C	

Snap head only replaceable with same range and diameter **Specification subject to change without notice**

APPENDIX H PIPE INSULATION

H1. KNAUF 1000° Pipe Insulation
H2. KANUF Proto PVC Fitting Covers

Knauf Data Sheet

PE-DS-1 04-06

1000˚ Pipe Insulation

1000° Pipe Insulation

Description

Knauf 1000° Pipe Insulation is a molded, heavy-density, one-piece insulation made from inorganic glass fibers bonded with a thermosetting resin. It is produced in 3' lengths with or without a factory-applied jacket. The jacket is a white-kraft paper bonded to aluminum foil and reinforced with glass fibers, and the longitudinal lap of the jacket is available with or without a self-sealing adhesive. A butt strip is furnished for each section.

Application

Knauf 1000° Pipe Insulation is used in power, process and industrial applications and in commercial and institutional buildings where maximum fire safety, resistance to physical abuse and a finished appearance are desired. Additional weather protection is needed outdoors.

Features and Benefits

Energy Conservation

- Offers excellent resistance to heat loss or gain, which saves energy and lowers operating costs.
- A low thermal conductivity of .23 at 75°F (24°C).

Low-Cost Installation

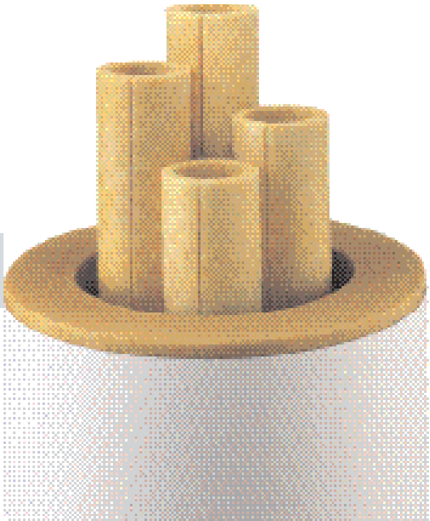
- Available with self-sealing lap, which eliminates need for staples, additional material and tools.
- Fast, easy installation reduces labor costs.

Condensation Control

- Installed properly, the foil vapor retarder and pressure-sensitive lap assure a positive vapor seal.

UL Classified

- All Knauf Pipe Insulation, plain or jacketed, meets the fire and smoke safety requirements of most federal, state and local building codes.



Easy Size Identification

- Pipe size, wall thickness and Proto 25/50 Rated PVC fitting cover size are printed in a repeat pattern along the longitudinal lap.
- Easy identification at job site.
- Simplifies restocking.
- After application, print is covered by the lap for a neat appearance.

Specification Compliance

In U.S.:

- ASTM C 547; Type I, Grade A; Type IV, Grade A
- ASTM C 585
- ASTM C 795
- ASTM C 1136 (jackets); Type I, II, III, IV
- HH-B-100B (jackets); Type I and II
- HH-I-558C; Form D, Type III, Class 12; Class 13 (to 1000°F, 538°C)
- MEA 325-83-M (City of New York Dept. of Buildings)
- MIL-I-22344D
- MIL-I-24244C (ships)
- NFPA 90A and 90B
- NRC Reg. Guide 1.36
- USCG 164.109/4/0 (plain, unjacketed only)

In Canada:

- CAN/ULC S102-M88
- CCG F1-304 (plain only)
- CGSB 51-GP-9M
- CGSB 51-GP-52M (jacket)

Technical Data

Surface Burning Characteristics

- UL Classified.
- Does not exceed 25 Flame Spread, 50 Smoke Developed when tested in accordance with ASTM E 84, CAN/ULC S102-M88, NFPA 255 and UL 723.

Temperature Range

- Pipe operating temperatures from 0°F to 1000°F (-18°C to 538°C). Water Vapor Transmission (ASTM E 96, Procedure A)
- Jacket has a water vapor permeance of .02 perms or less.

Corrosiveness (ASTM C 665)

- No greater than sterile cotton.
- Complies with ASTM C 795, MIL-I-24244C and NRC 1.36.

Puncture Resistance (TAPPI Test T803) (Beach Units)

- Jacket minimum rating of 50 units.

Alkalinity (ASTM C 871)

- Less than 0.6% as Na_2O.
- pH between 7.5 and 10.0.

Microbial Growth (ASTM C 1338)

- Does not promote microbial growth.

Water Vapor Sorption (ASTM C 1104)

- Less than 0.2% by volume.

Linear Shrinkage (ASTM C 356)

- Negligible.

Product Forms amd Sizes

Produced in 3' (914 mm) sections:

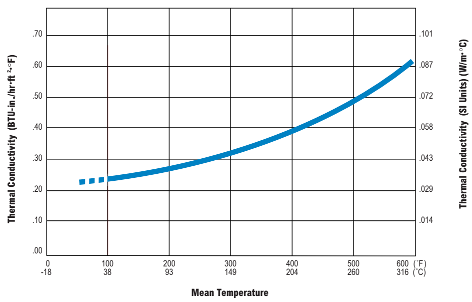
- For iron pipe from ½" to 24" nominal pipesize (13 mm to 610 mm).
- For copper tube from ⅝" to 6 ⅛" (16 mm to 156 mm).
- Wall thicknesses from ½" to 6" (13 mm to 152 mm) in single layer (for most sizes).
- All insulation inner and outer diameters comply with ASTM C 585.

Packaging

- Four convenient carton sizes for easy ordering, inventory tracking and storage.
- Unique sesame tape reinforced carton hand holds for superior strength and easy handling.
- Color-coded labels to easily identify pipe sizes by wall thickness.
- Easy to access butt strips.

Thermal Efficiency (ASTM C 335)

Mean Temperature	k	k (SI)
75°F (24°C)	.23	.033
100°F (38°C)	.24	.035
200°F (93°C)	.28	.040
300°F (149°C)	.34	.049
400°F (204°C)	.42	.061
500°F (260°C)	.51	.074
600°F (316°C)	.62	.089



Minimum Pipe Insulation (In.)[a] (to meet ASHRAE 90.1 Requirements)

Insulation Conductivity			Nominal Pipe Diameter (in.)					
Fluid Design Operating Temperature Range, °F	Conductivity Range BTU-in./(hr·ft²·°F)	Mean Temperature Rating, °F	Runouts[b] up to 2	1 & less	1 ¼ to 2	2 ½ to 4	5 & 6	8 & up
Heating Systems (Steam, Steam Condensate and Hot Water)								
Above 350	32-34	250	1½	2½	2½	3	3½	3½
251-350	29-31	200	1½	2	2½	2½	3½	3½
201-250	27-30	150	1	1½	1½	2	2	3½
141-200	25-29	125	½	1½	1½	1½	1½	1½
105-140	24-28	100	½	1	1	1	1½	1½
Domestic and Service Hot Water Systems[c]								
105 and Greater	24-28	100	½	1	1	1½	1½	1½
Cooling Systems (Chilled Water, Brine, Refrigerant)[d]								
40-55	23-27	75	½	½	½	1	1	1
Below 40	23-27	75	1	1	1½	1½	1½	1½

a For minimum thicknesses of alternative insulation types, see 9.4.8.2, ASHRAE 90.1.
b Runouts to individual terminal units not exceeding 12 ft. in length.
c Applies to recirculating sections of service or domestic hot water systems and first 8 ft. from storage tank for non-recirculating systems.
d The required minimum thicknesses do not consider water vapor transmission and condensation. Additional insulation, vapor retarders, or both, may be required to limit water vapor transmission and condensation.

Precautions

Hot Pipe

- May be installed while the system is in operation, at all temperatures up to 1000°F (538°C).
- Knauf recommends, for insulation thicknessesgreater than 6” (152 mm) the temperature must be increased from 500°F (260°C) to maximum temperature at a rate not exceeding 100°F (56°C) per hour.
- During initial heat-up to operating temperatures above 350°F (177°C), a slight odor and some smoke may be given off as a portion of the bonding material used in the insulation begins to undergo a controlled decomposition.
- If natural convection is not adequate in confined areas, forced ventilation should be provided in order to protect against any harmful fumes and vapors that might be generated.
- Care must also be taken when using sealants, solvents or flammable adhesive during installation.
- A maximum of 6” (152 mm) wall thickness is recommended.

Cold Pipe

- Use a continuous vapor retarder on piping operating below ambient temperatures.
- Seal all joints, surfaces, seams and fittings to prevent condensation.
- On below-freezing applications and in high-abuse areas, the ASJ jacket shall be protected with a PVC vapor retarding outer jacket. In addition, exposed ends of insulation shall be sealed with vapor barrier mastic installed per the mastic manufacturer’s instructions. Vapor seals at butt joints shall be applied at every fourth pipe section joint and at each fitting to isolate any water incursion.

- On chilled water systems operating in high-humidity conditions, it is recommended that the same guidelines be followed as listed above for below-freezing applications.
- Exterior hanger supports are recommended.

Outside Application

- Do not expose pipe insulation to weather. It must be covered with appropriate jacketing, mastic or vapor retardant adhesives.
- All exposed surfaces must be protected. Proto® Indoor/Outdoor PVC Jacketing is recommended. See Knauf Guide Specifications for recommended PVC jacketing application guidelines.
- Apply jacketing, mastics or vapor retardant adhesives per manufacturer's instructions. For metallic jackets, factory-applied and condensate retarders are recommended.

ASJ-SSL

- Keep adhesive and contact surfaces free from dirt and water, and seal immediately once adhesive is exposed.
- Apply when ambient and insulation temperatures are between 0°F and 130°F (-18°C and 54°C).
- If stored below 0°F or above 130°F, allow insulation cartons to stand within recommended temperature range for 24 hours prior to application.
- Do not store product below -20°F (-29°C) or above 150°F (66°C).
- When using Knauf's SSL closure system, make sure the longitudinal and circumferential joints are properly sealed by rubbing the closure firmly with a squeegee. Use of staples is not recommended.
- When using Knauf SSL Pipe Insulation, the surface temperature of the insulation should be between -20°F and 150°F (-29°C and 66°C) during the life of the insulation.

Fittings and Hangers

- Use Proto 25/50 Rated (ASTM E 84) PVC Fitting Covers, applying PVC fittings per Proto's Data Sheet.
- Fittings should be insulated to same thickness as the adjoining insulation.
- Apply fittings per manufacturer's instructions.
- When required by specification, a hard insert of sufficient length should be used to avoid compression of the insulation.

Caution

Fiber glass may cause temporary skin irritation. Wear long-sleeved, loose-fitting clothing, head covering, gloves and eye protection when handling and applying material. Wash with soap and warm water after handling. Wash work clothes separately and rinse washer. A disposable mask designed for nuisance type dusts should be used where sensitivity to dust and airborne particles may cause irritation to the nose or throat.

Application Guidelines

Storage

- Protect insulation from water damage or other abuse, welding sparks and open flame.
- Cartons are not designed for outside storage.

Preparation

- Apply only on clean, dry surfaces.
- Pipe or vessel should be tested and released before insulation is applied.

General Guidelines

- All sections should be firmly butted.
- Seal circumferential joint with a minimum 3" (76 mm) wide butt strip.
- Jackets, coating and adhesives should have a comparable F.H.C. rating.
- Factory-applied jacket can be painted with latex or water-based paint. Solvent-based paints should not be used.
- Do not expose factory-applied jacket to chemicals or liquid water.
- All piping should have continuous insulation.
- Position longitudinal lap downward to avoid dirt and moisture infiltration.
- Do not expose pipe insulation to excessive vibration or physical abuse.
- Faced insulation should not have a facing temperature above 150°F (66°C).

Recommended Thicknesses

The minimum thicknesses (see chart on page 5) are based on ASHRAE 0.1-1989 standards and do not necessarily represent the Economic Thickness of Insulation or the thickness required for proper condensation control. Rather, they serve as minimum recommendations for commercial applications. For recommended Economic Thickness, install according to Knauf or NAIMA ETI programs or as specified.

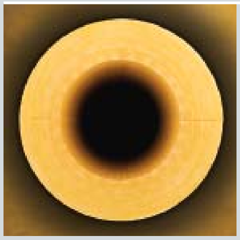
Fiber Glass and Mold

Fiber glass insulation will not sustain mold growth. However, mold can grow on almost any material when it becomes wet and contaminated with organic materials. Carefully inspect any insulation that has been exposed to water. If it shows any sign of mold it must be discarded. If the material is wet but shows no evidence of mold, it should be dried rapidly and thoroughly.

If it shows signs of facing degradation from wetting, it should be replaced.

Notes

The chemical and physical properties of Knauf 1000° Pipe Insulation represent typical average values determined in accordance with accepted test methods. The data is subject to normal manufacturing variations. The data is supplied as a technical service and is subject to change without notice. References to numerical flame spread ratings are not intended to reflect hazards presented by these or any other materials under actual fire conditions. Check with your Knauf sales representative to assure information is current.



- The Knauf rotary manufacturing process produces insulation with concentric inside diameters and consistent wall thicknesses.

- Knauf 1000° Pipe offers an extended temperature range—the best thermal performance in the industry.

- Knauf's "wind-up" forming mandrel process prevents gaps and inconsistent densities, while making it easy to cleanly notch out sections.

- Knauf 1000° Pipe's superior compressive strength allows for fast installation and a neat finished appearance.

- Installed properly, the foil vapor retarder with a pressure-sensitive lap assures a positive vapor seal.

Facts at a glance

- For all applications from 0°F to 1000°F.
- Excellent thermal performance.
- Superior fabrication properties.
- Manufactured in ISO 9001:2000 certified plant.

Knauf Insulation GmbH
One Knauf Drive
Shelbyville, IN 46176

Sales and Marketing	(800) 825-4434, ext. 8283
Technical Support	(800) 825-4434, ext. 8212
Customer Service	(866) 445-2365
Fax	(317) 398-3675
World Wide Web	www.KnaufInsulation.com

LEED Eligible Product
Use of this product may help building projects meet green building standards as set by the Leadership in Energy and Environmental Design (LEED) Green Building Rating System.
Credit 4.1 - 4.2 Recycled Content
Credit 5.1 - 5.2 Regional Materials

Proto PVC Fitting Covers

Submittal MSDS

Description

The Proto® Fitting Cover System consists of one-piece, pre-molded, high-impact PVC fitting covers with fiber glass inserts and accessories. Accessories are elbows, tee/valves, end caps, mechanical line couplings, specialty fittings, jacketing, tacks, and PVC tape.

Application

The Proto Fitting Cover System is used to insulate mechanical piping systems at fitting locations. It provides PVC jacketing for straight run piping and gives a quality appearance and excellent durability.

Features and Benefits

Fire and Smoke Safety

- Proto PVC Fittings do not exceed 25 Flame Spread, 50 Smoke Developed.
- Roll jacketing is available in 25/50-rated or indoor/outdoor grade.
- The 25/50 products meet most fire and safety requirements of federal state and local building codes.

UV Resistant

- Use indoors or outdoors.
- Paint outdoor fittings to enhance UV and colorfast protection.

Excellent Appearance

- Bright high-gloss white coloring adds a distinct quality appearance to the system.

Easy to Clean

- The smooth high-gloss surface cleans easily with soap and water.
- Ideal system for food and drug facilities.

Low-Cost Installation

- Significant cost savings vs. conventional cement, molded sections and mitered sections.

Fast and Easy

- At fitting locations, the fiber glass insert is wrapped around the pipe fitting, the Proto PVC Fitting is applied over the insert and then tacked or taped.

Wide Temperature Range

- For mechanical piping systems operating to 500°F (260°C)

Long Lasting

- Can be used more than once on retrofit projects, general maintenance.

Excellent Thermal Value

- Low thermal conductivity value of 0.26 at 75°F (0.037 W/m^2•°C) mean temperature.
- Better thermal efficiency than conventional cement fittings.

Resistant to Fungi and Bacteria

- Does not promote growth of fungi or bacteria.

Specification Compliance

In U.S.: Federal (Polyvinyl Chloride)

- LP-1035A; Type II Grade GU and Type III
- LP-535E; Type II Grade GU and Type III
- New York City MEA 243-84-M, Chicago, Los Angeles
- ASTM C 585 (Sizes)
- United State Department of Agriculture

In Canada:

- AC 774.1K82

Physical Properties (PVC)

Specific Gravity (ASTM D 792)

- 1.41

Tensile Modulus (ASTM D 638)

- 381,000 psi

Tensile Strength (ASTM D 638)

- 6,000 psi

Flexural Strength (ASTM D 790)

- 1,175 psi

IZOD Impact (0.25") ft. (ASTM D 256)

- 16.8 lb. per inch of notch

Heat Deflection (ASTM D 648)

- 159°F (70°C) @ 264 psi

Water Vapor Transmission
Mocon Permatran W-1 Method (ASTM E 96 (Equiv.)) (U.S. Perms)

- 100°F (38°C) & 90% relative humidity:
  .007" (.177 mm) thick = .19
  .009" (.228 mm) thick = .15
  .022" (.558 mm) thick = .07
- 73°F (23°C) & 50% relative humditiy:
  .006" (.152 mm) thick = .19
  .010" (.254 mm) thick = .13
  .022" (.558 mm) thick = .09

Puncture Resistance(TAPPI Test T803) (Beach Units)

- .006" (.152 mm) thick = 78
  .015" (.381 mm) thick = 221

THERMAL EFFICIENCY OF INSERT (ASTM C 177)

Mean Temperature	Mean Temperature (SI)	k	k (SI)
100°F	38°C	.28	.040
200°F	93°C	.38	.055
300°F	149°C	.52	.075
400°F	204°C	.70	.101
500°F	260°C	.90	.130

PROTO FITTING COVERS

25/50 RATED
PER ASTM E-84 — LoSMOKE® PVC

SUBMITTAL SHEET

Effective: 05/01/03

Submitted Date: ____________

PROTO REGULAR PVC & LoSMOKE® PVC JACKETING

25/50 RATED (Up to .035" Thk.)

PROTO CORP.
10500 47th Street North
Clearwater, FL 33762-5017
Tel: (727) 573-4665
Fax: (727) 572-6823

PVC FITTING COVERS, PRE-MOLDED, INSULATED
WHITE GLOSS FINISH — INDOOR OUTDOOR GRADE

SUBMITTAL SHEET DOES NOT SUPERCEDE WRITTEN SPECIFICATIONS OR OWNER AGREEMENT.

DESCRIPTION

The Proto Fitting Cover System consists of one piece and two piece pre-molded high impact LoSMOKE® PVC fitting covers with fiberglass inserts and accessories, which include elbows, tee/valves, end caps, mechanical line couplings, specialty fittings, white and color jacketing, Protop® Tank End Panels, Aluminum Faced PVC supported jacketing, tack fasteners, tapes and specialty items.

APPLICATIONS

The Proto Fitting Cover System is used to insulate mechanical piping systems at fitting locations, and provide a PVC Jacketing for straight run piping which gives a quality appearance, and excellent durability.

FEATURES AND BENEFITS

25/50 Rated. All Proto PVC Fittings are made of LoSMOKE® grade PVC. Roll Jacketing is available in either 25/50 rated or regular PVC Grade (not 25/50 rated). The 25/50 products meet fire and smoke safety requirements of federal, state and local building codes.

Excellent Appearance. Bright high-gloss white coloring adds a distinct quality appearance to the system. Both LoSMOKE® PVC and regular PVC are designed for outdoor use. Regular PVC Jacketing costs less than LoSMOKE® PVC Jacketing, and has excellent fire resistance for outdoor use, with a flame spread of 10 and smoke development of (.020") approximately 150. The standard line of Proto Fitting Covers are all made in LoSMOKE® PVC only (no regular PVC). Virtually all sizes pass 25/50 when made of LoSMOKE® PVC.

Easy To Clean. Due to the smooth high gloss finish on Proto PVC Fittings, the product cleans easily with soap and water. This makes the system ideal for food and drug facilities.

Low Cost Installation. Significant cost savings vs. conventional cement, molded sections, and mitered sections.

Fast and Easy. At fitting locations, wrap the fiberglass insert around the pipe fitting, apply the Proto PVC Fitting over the insert and tack or tape in place.

Wide Temperature Range. May be used for mechanical piping systems operating from -20°F to +140°F surface temperature of insulation. Variety: LoSMOKE®, Indoor/Outdoor, Exod®, Exotuff®. Proto products are also available in LoSMOKE® Indoor colors. Exod® is CPVC, GOOD TO 225° F.

Long Lasting. Can be used more than once on retrofit projects, general maintènance.

Excellent Thermal Value. K value of .26 at 75°F (.037 W/m °C at 24°C) of fiberglass insert, mean temperature assures better thermal efficiency than conventional cement fittings.

Resistance To Fungi and Bacteria. (ASTM C 665) Does not promote growth of fungi or bacteria.

U.V. Resistant. Can be used on indoor or outdoor applications, for both (White) LoSMOKE® PVC and Regular PVC. Extra thick fitting covers should be used outdoors. (All Std. Proto Fitting covers are made of LoSMOKE® PVC.)

TECHNICAL PHYSICAL PROPERTIES OF PVC LoSMOKE® MATERIALS

Specific Gravity (ASTM D-792) 1.41
Tensile Modulus, PSI (ASTM D-638) .... 361,000 (25,380 kg/cm²)
Tensile Strength, PSI (ASTM D-638) 6,011
Flexural Strength, PSI (ASTM D-790) 9,396
Izod Impact (1/4") ft. lb./in (ASTM D-256) 3.7
Heat Deflection Temp. (ASTM D-648) .... 157°F (70°C)
at 264 PSI (8.95 kg/cm²), °F
VICAT Softening Temp. (ASTM D-1525) .... 198°F (92°C)

Water Vapor Transmission
ASTM E 96-95
70°F & 50% Relative Humidity
.015" thick = .058
.020" thick = .047
.030" thick = .027

Surface Burning Characteristics of All Fitting Covers and Jacketing
LoSMOKE® PVC .... passes 25/50 ASTM-E 84
Up to .035" Thk. (The best rated PVC we know of)
Puncture Resistance (ASTM D 781) ... .006" thick = 178 Beach Units
.015" thick = 221 Beach Units

FEDERAL SPECIFICATIONS COMPLIANCE— POLY VINYL CHLORIDE — ASTM 1784-92

LP-1035A Type II Grade GU and Type III

LP-535E Type II Grade GU and Type III

United States Department of Agriculture Authorized
Agriculture Canada Authorized
New York City MEA 243-84-M, Chicago, Los Angeles ASTM C-585-76 (sizes)
Canada CAN/CGSB - 51.53-95

TECHNICAL PROPERTIES OF FIBERGLASS INSERT MATERIAL

Thermal Conductivity (ASTM C 177)

Mean Temperature –	°F	"k" — BTU in/hr. Ft.2 °F
HH-I-558 Form B	75° 1(24°C)	.26 (.037 W/m. °C)
Type 1 Class B	150° 1(66°C)	.33 (.048 W/m. °C)
	250° (121°C)	.44 (.063 W/m. °C)

APPLICATION AND SPECIFICATION GUIDELINES

A. STORAGE

Protects cartons from water damage or other abuse. Proto Fitting Cover cartons are not designed for outside storage.

B. PREPARATION

Proto Fitting Covers should be applied on clean dry surfaces.

C. APPLICATION

1. **General** The matching fiberglass insert shall be wrapped completely around the metal fitting leaving no voids. Loose wrappings of twine is helpful in shaping difficult surfaces. The Proto Fitting Cover shall then be applied over the fitting and insert, and the throat secured by either tack fastening or taping. Seal all laps with caulk adhesive, outdoors.

2. **Cold Pipe** Fitting systems below ambient temperature must have a continuous vapor retarder, either with Proto PVC tape, Butt Strips, Proto PVC Adhesive, or a vapor retardant mastic as specified by the engineer. When using Proto PVC Tape, a 2" (51mm) minimum downward overlap is recommended for optimum performance. Care should be taken not to stretch the last 2" (51mm) of Proto PVC Tape, to avoid stretching or creeping.

3. **Hot Pipe** Insulate as per General Instructions given above. Due to PVC softening point at approximately 159°F (70.6°C), care should be taken to ensure sufficient insulation thicknesses are applied.

For hot piping which requires Pipe Insulation over 1 1/2" (38 mm) wall thickness, an extra fiberglass insert shall be applied for each additional inch of pipe insulation wall thickness. Proto recommends the surface temperature of the Pipe Insulation and PVC to be no higher than 125°F (52°C). To complete application of Proto PVC Fittings on hot piping, the throat seam shall be tack fastened or taped. Seal all laps outdoors and in wash down areas.

CAUTION: During initial heat-up to operating temperatures above 350°F, (177°C) an acrid odor and some smoke may be given off as a portion of the bonding material used in the insulation begins to undergo a controlled decomposition. If natural convection is not adequate in confined areas, forced ventilation should be provided in order to protect against any harmful fumes and vapors that might be generated.

4. **Outdoor Pipe:** Insulates as per above instructions. When installing Proto PVC Fittings outdoors, add one layer aluminum foil or saran wrap over the fiberglass insert applied, making sure the aluminum foil is extended over the adjacent pipe insulation and sealed with adhesive or tape.

Minimum Proto PVC Jacketing thickness for outdoor application should be .030" (.7 mm). The PVC Jacketing shall be overlapped a minimum of 2" (51 mm) on the down side so as to shed water. All long and round joints shall be completely weather sealed with caulk adhesive. Piping insulation up to 3 1/8" O.D. can be .020" Thk. PVC.

On all piping, insulation shall be of sufficient thickness to keep the surface temperature below 125°F (52°C). Additionally, a slip type expansion joint of 8" (202 mm) minimum width shall be applied at least every 25 lineal feet (6.1 lineal meters) and within 10 feet between fittings.

Painting: Painting must be done only after priming the PVC surface with X-1-M 400W Primer (X-1-M Products, Inc., Westlake, Ohio 44145, Telephone (440) 871-4737 or (800) 262-8469.

Outdoors Painting: Only over White Exotuff® 195°F deflection temp. (modified PVC) or EXOD™ 225°F deflection temp. CPVC after X-1-M primer. Use PVC compatible paints without strong solvents. Test paint a section before proceeding.

5. **CAUTION:** Fiberglass may cause temporary skin irritation. Wear long-sleeved, loose-fitting clothing, head covering, gloves and eye protection when handling and applying material. Wash with soap and warm water after handling. Wash work clothes separately and rinse washer. A disposable mask designed for nuisance type dusts should be used where sensitivity to dust and airborne particles may cause irritation to the nose or throat.

D. HEAVY INDUSTRIAL APPLICATIONS OUTDOORS

Use .030" or higher PVC Jacketing. Use "heavy duty" two piece fitting covers made from minimum .030" thick to .050" thick PVC sheet depending on size of fitting cover. Jacketing to be cut and oven precurled

E. FIRE TEST RESULTS: PROTO LoSMOKE® — PVC

USA: E-84 25/50 Rated up to .035" thick (The Best Rated PVC)

CANADA: Passes CAN 4-S102.2

LoSMOKE® fitting covers confirm to virtually all city, state and federal codes, for use in hotel, commercial and industrial buildings.

LoSMOKE® fitting covers will be labeled on the box "Passes ASTM E-84." Flame spread 25; smoke developed 50".

All E-84 ratings shown here were tested on flat sheets from which fitting covers are made. (Our .035" thick tested out at 13 flame spread and 25 smoke.)

Virtually all Proto LoSMOKE® fitting covers will pass E-84 25/50 flame spread and smoke development rating requirements.

SUGGESTIONS

Slide Joints: Do not apply PVC Jacketing too tightly. Slide joints plus PVC thickness must work together to prevent cracks and puckering.

Caulk/Adhesives:

Use: Celulon® (Red Devil Inc.) water base "Ultra Clear".
Service temp. -25°F to +175°F
Dow #739 silicone plastic adhesive.
Service temperature of -65°F to +350°F
Over 350°F use appropriate Dow silicone. (Grease on Slide Joints)

PVC Cement: Avoid use if possible. Heavy application can cause puckering and cracks. Learn how to use it sparingly.

Vapor Barrier Foil: Use .001" thick kitchen type aluminum foil, over the insulated fitting, outdoors and on all chilled 50°F to below freezing pipe temperatures, prior to PVC cover. Kitchen saran wrap can also be used. This doubles waterproof protection, and assures a good vapor barrier.

Outdoor Fitting Covers: Use extra thick, two piece heavy duty covers.

Outdoor and Indoor Washdown Areas: Use EXOD™ (CPVC) by Proto, for its higher deflection temperature (225°F). It is light grey.

PVC Outdoor Thickness (Reg. PVC Jacketing): Use .030" thick cut and oven precurled jacketing. Use "heavy duty" two piece fitting covers formed from minimum .030" to .050" thick PVC sheet depending on size of fitting cover. On pipe insulation larger than 15" O.D. use .040" thick PVC.

PVC Indoor Thickness: Use white or color LoSMOKE® on piping. Use .020" thick with standard one piece fitting cover, .030" jacketing can also be used.

Vessels and Tank Tops: Use .050" thick tank panels, and .050" thick Protop® segments for tank heads. (Only Proto Corp. has them.) Made of LoSMOKE® PVC.

Pipe Insulation End Caps: Use on all outdoor, indoor washdown areas, and all vapor sealed systems. End caps will be PVC, metal, or gasket materials appropriate for the metal pipe temperatures. Silicone rubber (500°F) can be applied (min. 1/16" thick) as an end cap outdoors.

Seal to pipe and jacketing with Dow #739, or Celulon®. Described above — in Caulk/Adhesives. Indoor hot piping need not be sealed to the end cap. Cap will be sealed or taped, to the jacket.

Two-Ply Waterproofing System: Use .010" thick PVC with self-sealing long lap tape, as the first waterproof layer. Overlap ends 3" and PVC tape over. Caulk all openings with Celulon® or Dow #739 then apply staggered joint next heavy layer of PVC, or your choice of jacketing. Recaulk again over last layer. Install slide joints every 25', caulk shut all other seams, openings, or end overlaps with PVC tape or caulk. Use vapor seal jacketing (instead of .010" thick PVC first layer) where a vapor seal system is required.

CPVC-High Chem, Resis. and High Deflect. Temp.: Use "Exod®" CPVC jacketing and fitting covers for 225°F deflection temperature and maximum chemical resistance. Offered only by Proto Corp. as a substitute for stainless steel at 1/2 to 1/3 the price of stainless steel.

Regular PVC Jacketing Outdoors: Use regular PVC jacketing outdoors. It is less expensive, does the same job as LoSMOKE® PVC. Regular PVC has very good fire (self-extinguishing) properties — not as good as the LoSMOKE® PVC used in confined people areas (buildings), however much better than common plastics used outdoors.

Vessels with ends 24" O.D. or larger: Use .040" thick jacketing up to 48" O.D. On sides of vessels larger than 48" O.D. See Protop® brochure for instructions requiring a suspended band system, to hang panels from, (Gerrard & Company or equal). Use thick PVC panels on Outdoor Tanks not PVC Roll Jacketing. See Tank Tops above for end segments.

PROTO PVC CORP™

10500 47th Street North
Clearwater, FL 33762-5017
Tel: [727] 573-4665
Fax: [727] 572-6823

05/01/2003