THE UNIVERSITY OF MICHIGAN
College of Engineering
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Cavitation and Multiphase Flow Laboratory

Report No. UMICH 03371-18-T

WET-STEAM TUNNEL FACILITY— DESIGN AND PROGRAM OF INVESTIGATIONS

by

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Typing and Reproduction Supported
by:
National Science Foundations
Grant No. GK-730

June 1972

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ABSTRACT

A new low-pressure wet-steam tunnel to be constructed and used in the Cavitation and Multiphase Flow Laboratory is described, and the research program for its future use is discussed.

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I. INTRODUCTION

Recently much attention has been paid to the problems of two-phase flow, such as wet steam, fuel droplet-oxidiser, etc.

Among others a certain amount of data has already been collected about the interaction between the gaseous phase and a relatively thick liquid layer along channels. Also the dynamics of individual droplets exposed to weak and strong pressure pulses in the gas was investigated. Extensive references may be found, e.g., in (Ref. 1) and (Ref. 2). Also at this university, a series of new experiments has been recently performed on the aerodynamic shattering of individual liquid drops exposed to shock wave impulse (Ref. 3).

However, there is still little known about the stability of thin water films on the surface submerged in transsonic and supersonic flows when surface tension and wettability comes into the picture. Also little has been done on droplet generation in the aerodynamic wake behind a body submerged in such a high speed two-phase flow.

In this particular case there is involved:

1. The flow of a thin liquid layer of thickness of the order of 100.10^{-6}m or less, with its stability and interaction with the transsonic and supersonic gas flow a question to be studied, and

2. The droplet stream generation, droplet shattering in the aerodynamic wake of a body submerged in transsonic and supersonic two-phase flow, which is proposed for study here, and particularly, the droplet stream structure.

These problems are of interest for many different reasons, and their solution could be applied to numerous fields of engineering, i.e., evaporation and dispersion of fluids, different types of heat and mass exchange, cooling and condensation. They are also of interest because of the erosion of fluid flow machines, particularly turbines operating on wet steam, metal vapors and vapors of low-boiling liquids. Recently, it has been shown that the structure of the droplet stream has not only significant influence upon the mean value of the droplet impact parameters in the turbine rotor blading (Ref. 4), but also the endurance of the material depends on the droplet stream structure (Ref. 5). Similar observations have been already reported, but the problem deserves further consideration.

The investigation of the structure of the droplet stream in the aerodynamic wake have been carried on in IFFM* for several years. Some of the results have been published, for instance, in (Ref. 6) and more recently in (Ref. 7). However, the investigations have been carried on using an air stream only. The lack of knowledge of the scaling lows of this complicated phenomena prevents drawing conclusions for other than air-water flows from this data. In particular the extrapolation of the available results for high-speed, low-pressure, wet-steam flow is not possible yet. There are urgently needed:

1. The formulation of the scaling lows for the phenomena under consideration and,

2. Collecting further experimental data as a basis of such generalizations.

The purpose of this report is to describe the design of a steam-tunnel facility, which would help to achieve these goals, being constructed in the Cavitation and Multiphase Flow Laboratory of the Mechanical Engineering Department of the University of Michigan. The wet-steam flow parameters have been chosen to be as close to the steam-turbine flow parameters in actual wet-steam turbine stage as possible. It will make possible:

1. The repetition of the IFFM experiments for significantly different Reynolds, Mach, and Weber number,

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2. The collection of the experimental data applicable directly to the theory of droplet impact in the steam turbine blading.

Joint use of the experimental data of IFFM and this laboratory will certainly contribute to the achievement of the ultimate generalization of the experiments. It will also contribute to the fruitful future cooperation between both groups.

II. WET-STEAM TUNNEL FACILITY

It has been assumed that the desired flow parameters in the test section of the wet-steam tunnel facility should match as closely as possible the average steam parameter of the large steam turbines.[*] They are:

$p_4 = \sim 0.095 \frac{kG}{cm^2}$ abs (~1.35 psia)

$x_4 = \sim 0.970$

$t_4 = \sim 44.5^oC$ (~112°F)

$v_4 = \sim 15 \frac{m^3}{kG}$ ($\sim 243\ ft^3/lb$)

The rest of the parameters in the test loop depend upon the steam velocity in the test section and its cross-sectional area. Some of these parameters, such as the enthalpy drop h in the nozzle, the pressure, p_3, temperature t_3, specific volume v_3, quality x_3, as well as steam- and cooling-water demand, and also a schema of the facility are shown in Appendix A. It has been assumed that the steam expanding in the nozzle from (p_3, x_3) to (p_4, x_4) is a wet-steam, generated from saturated steam, suitably throttled and cooled. The steam is

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[*] The symbols are defined later in the report.

cooled by injecting the cooling water into the saturated steam line and if needed, into the silencer.*

Further details of the steam tunnel depend upon steam supply and the location of the facility. The pertinent argument has been considered in Appendix B. In Appendix C the drawings of the most important elements of the test facility are collected.

III. PROGRAM OF EXPERIMENTS

A. Minimum Program.

This should include the investigation of the size distribution function f_n of the droplet stream in the aerodynamic wake of a flat plate as a function of the steam velocity c_1. The distance z downstream between the trailing edge of the plate and the area of investigation should be about $z = 150$ mm.

The structure of the droplet stream should be defined by

$$f_n(r_*, c_1) \equiv \frac{1}{\Delta r_*} \quad \frac{n(r_*, c_1)}{N}$$

where

r_* - droplet size

Δr_* - the droplet size interval (in order to meet the conditions applied in IFFM take, if possible,

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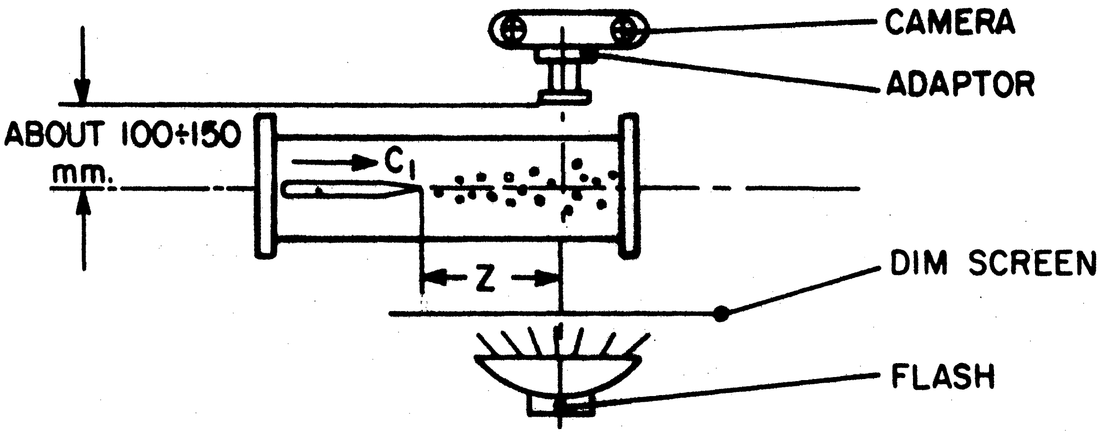
*As a matter of fact, the structure of the steam in the silencer should be similar to the structure of the steam expanding in the steam turbine. It means that the average droplet size of the liquid phase should be of the order 1.10^{-6}m or less. This condition may be realized when reducing the steam pressure in a special turbine-expander. Taking into account that the subject of the investigation is the dynamics of the water film and the droplets, it appears that the adopted method here for wet steam generation is adequate. In order to prevent the undesired heat and mass exchange in the test section, attention has been paid to the injection of water droplets: the injected droplets should be as small as possible. One may achieve this by maintaining the injection pressure of water as high as possible.

$\Delta r_* = 50.10^{-6}$ m or 100.10^{-6} m.)

$n(r_*, c_1)$ - the average number of the droplet of the given size r_* per unit area per given c_1.

N - the average number of all the droplets visible per unit area and c_1.

The average $n(r_*, c_1)$, N or $n(r_*, c_1)/N$ should be established by means of a sufficient number of photographs. The arrangement for taking pictures is shown below:



The distance between the droplet stream and the lense should be about 100 ÷ 150 mm. The light source: Xenon flash light, the time of exposure: order of magnitude of 10^{-6} sec. (a spark-light source may be used). The results should be presented in the form of a curve $f_n = f_n(r_*, c_1)$, where r_* and c_1 is dependent variable and parameter, respectively.

For the interpolation of the experimental results, the Nukiyama-Tanassava function

$$f_n = N_1 r_*^{N_2} e^{-N_3 r_*}$$

should be used. The Weibul function

$$f_n = 1 - \exp(r_*^{N_4})$$

may also be used. $N_{1,2,3,4}$ are the sought experimental coefficients.

The establishing of the experimental relationship between these coefficients and c_1 is the first goal of the experiment.

In order to define and maintain chosen flow conditions of the steam expansion at least the following parameters should be measured:

$G_{ST}(t_2, p_2, \Delta p_{ST})$ - the steam flow,

$\left.\begin{matrix} p_2 \\ t_2 \end{matrix}\right\}$ - the pressure and temperature of the steam between the throttle valve and the orifice,

$G_{CW}(t_{CW}, p_{CW}, \Delta p_{CW})$ - the cooling water flow, this quantity may be measured either by means of a standard orifice or (better) by means of a flowmeter,

t_{CW} - the temperature of the cooling plate,

$\left.\begin{matrix} p_3 = p_2 - \Delta p_{23} \\ p_4 = p_3 - \Delta p_{34} \end{matrix}\right\}$ - the static pressure of the steam in the silencer, in the test section and in the condenser,

G_{PL} - the flow of water supplied onto the surface of the flat plate,

$\left.\begin{matrix} p_{PW} \\ t_{PW} \end{matrix}\right\}$ - the parameters of the water injected to the condenser,

p_{4C} - steam velocity distribution in the test section.

B. In the next stage of the experiments the variation of the following parameters may be considered:

1. the distance z
2. the static pressure p_4 in the test section
3. the water flux over the surface of the plate
4. the shape of the trailing edge of the plate

The results obtained may consitute a basis for considering a generalized dimensionless relationship between the parameters of the size distribution function f_n and a set of Reynolds, Mach, and possibly Weber numbers.

C. Application of the Fast Camera.

This may contribute to the understanding of the mechanism of liquid droplet shattering. Attention should be paid to the following questions:

1. What is the type of the droplet break-up (bag-type, strip-type), and its relationship to the flow parameters?
2. What is the mechanism of the water film break-up in the vicinity of the trailing edge of the submerged body; what is its relationship to the flow parameters and the shape of the body?
3. What is the influence of blowing-out or sucking-in of the water filament formed at the trailing edge of the plate?

D. Investigation of the Stability of the Water Film.

This should contribute to the understanding of the conditions of the flow, which stimulates the breaking-up of the continuous water layer into rivulets, the onset surface waves pattern etc. Of particular interest might be the influence of the wettability of the plate surface on the film flow pattern and droplet generation.

IV. ACKNOWLEDGEMENTS

This report has been prepared by the author to describe a large part of the work which he has accomplished during his stay at the Cavitation and Multiphase Flow Laboratory of the University of Michigan, and to help guide the future program resulting therefrom. The stay has been organized within the exchange program between the Polish Academy of Sciences, Warsaw, and the National Academy of Sciences, Washington, D.C. The author is grateful to his host, Professor F. G. Hammitt,

whose assistance made this design and the construction of the test facility possible. The author also trusts that the joint efforts of IFFM and this laboratory at UM will contribute to an effective and fast exploration of the problem. The results of the experiments of both laboratories will be complementary and will then be the subject of future periodical joint reviews.

V. REFERENCES

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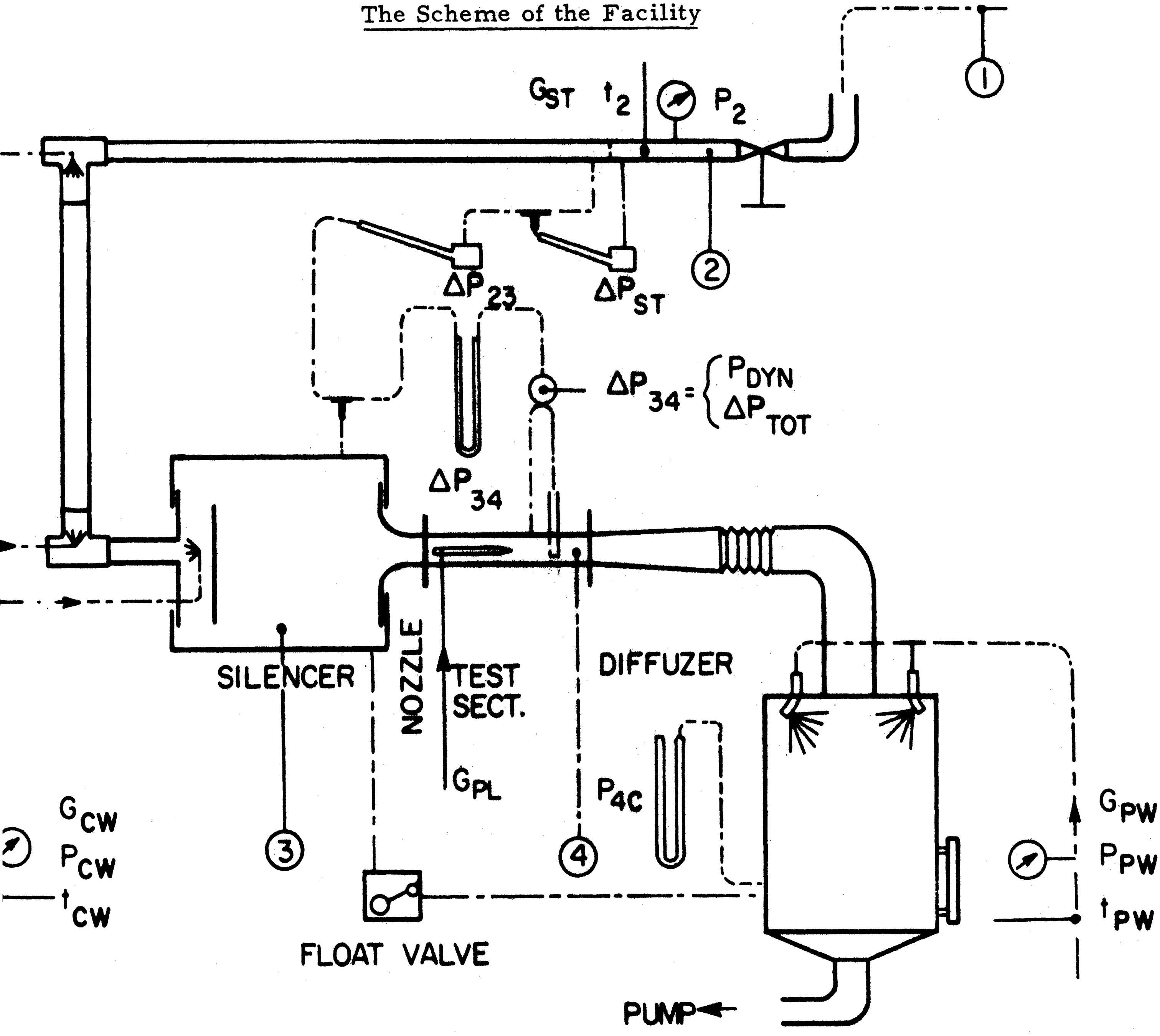
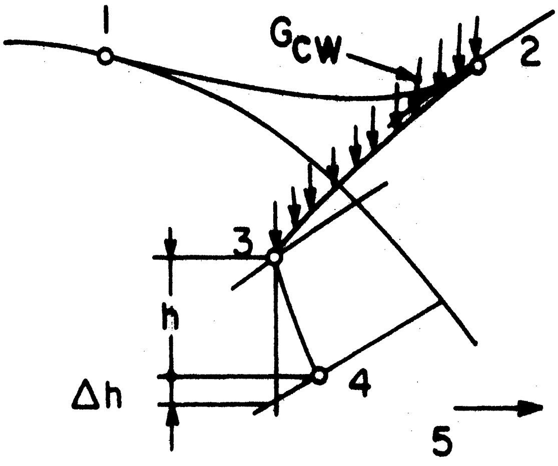
VI. APPENDICES

Appendix A: Some Selected Parameters of the Test Facility

The Scheme of the Facility





Some Parameters of the Expansion:

ASSUMPTION I

1. Nozzle Cross-Sectional Area: 0.1 x 0.1 m
2. Steam parameters in ④ :

$p_4 = 0.095 \frac{kG}{cm^2}$ abs (1.35 psia)

$x_4 = 0.970$

$t_4 = 44.5^{o}C$ ($112^{o}F$)

$v_4 = 15 \frac{m^3}{kG}$ (243 ft.^{3}/lb.)

c_4	$\frac{m}{s}$	300	200	100	Remarks
h	kcal/kG	10.70	4.80	1.20	$h = c_4^2 / 8380$
	Btu/lb	19.25	8.64	2.16	
Δh	kcal/kG	0.43	0.19	0.048	$\Delta h = (\frac{1}{\varphi^2} - 1) \frac{c_4^2}{8380}$
	Btu/lb	0.77	0.34	0.086	
p_3	kG/cm^2	0.1335	0.1088	0.0983	
	psia	1.90	1.55	1.40	
x_3	—	0.984	0.976	0.972	
t_3	^{o}C	51.10	47.04	45.09	
	^{o}F	124.0	116.0	113.0	
v_3	m^3/kG	11.30	13.57	14.67	$v_3 \cong x_3 \cdot v_3''$
	ft^3/lbs	181	217	235	
G_{ST}	kG/s	0.20	0.13	0.067	
	lb/h	1590	1030	523	
G_{PW}	kG/s	10.0	6.50	3.40	$G_{PW} = \sim 50\ G_{ST}$ for surface cond.
	lb/h	79300	51500	26900	

ASSUMPTION II

1. Nozzle Cross-Sectional Area: 0.08 x 0.08 m
2. Steam Parameters in ④ :

$p_4 = 0.105 \frac{kG}{cm^2}$ abs (1.5 psia)

$x_4 = 0.970$

$t_4 = 46.7^{\circ}C$ ($116^{\circ}F$)

$v_4 = 14.1 \frac{m^3}{kG}$ (226 ft^3/lb)

$G_{PW} = 3.47 \frac{kG}{s}$ (27500 lb/h) (55 GPM)

c_4	$\frac{m}{s}$	100	150	200	250	300	350
G_{ST}	kG/s	0.0454	0.0681	0.0909	0.1135	0.136	0.159
	lb/h	360	540	720	900	1080	1260
$\frac{G_{ST}}{G_{PW}}$	1	76	51	38.2	30.6	25.4	21.8
h	kcal/kG	1.19	2.68	4.77	7.45	10.7	14.55
	Btu/lb	2.14	4.83	8.60	13.40	19.25	26.20
p_3	$\frac{kG}{cm^2}$ abs	0.1075	0.1120	0.1205	0.1295	0.1400	0.1605
	psia	1.54	1.60	1.72	1.84	2.00	2.30
v_3	m^3/kG	13.9	13.4	12.5	11.75	10.97	9.60
	ft^3/lb	222.8	214.2	200.3	188.2	174.1	153.7

ASSUMPTION III

1. Nozzle Cross-Sectional Area: 0.08 x 0.08 m

2. Steam Parameters in ④ :

$p_4 = 0.211 \frac{kG}{cm^2}$ abs (3.0 psia)

$x_4 = 0.970$

$t_4 = 50^\circ C$ ($142^\circ F$)

$v_4 = 7.32 \frac{m^3}{kG}$ ($117\ ft^3/lb$)

$G_{PW} = 3.47 \frac{kG}{s}$ (27500 lb/h) (55 GPM)

c_4	$\frac{m}{s}$	100	150	200	250	300	350
G_{ST}	kG/s	0.0875	0.1311	0.1750	0.2190	0.2620	0.3060
	lb/h	695	1040	1390	1735	2080	2430
$\frac{G_{ST}}{G_{PW}}$	1	39.5	26.5	19.8	15.8	13.2	11.3
h	kcal/kG	1.19	2.68	4.77	7.45	10.7	14.55
	Btu/lb	2.14	4.83	8.60	13.40	19.25	26.20
p_3	$\frac{kG}{cm^2}$ abs	0.217	0.220	0.227	0.237	0.248	0.262
	psia	3.10	3.15	3.25	3.40	3.55	3.75
v_3	m^3/kG	7.26	7.10	6.86	6.58	6.33	5.98
	ft^3/lb	116.3	114.0	110.0	105.6	101.5	95.8

Estimation of the Quantity of Cooling Water G_{CW}

Assumptions:

$p_4 = 0.211 \frac{kG}{cm^2}$ abs (3 psia)

$p_3 = 0.246 \frac{kG}{cm^2}$ abs (3.5 psia)

$i_2 - i_3 = 33.3$ kcal/kG (~60 Btu/lb)

$r = 556$ kcal/kG (~1000 Btu/lb)

$G_{ST} = 0.177$ kG/s (~1400 lb/h)

$$G_{CW} = G_{ST} \frac{i_2 - i_3}{r} = 0.0106 \text{ kG/s}$$
$$= 10 \text{ GPH}$$

Characteristics of a Free Flow Spray Nozzle*

Injection Pressure	psi	30	40	60	100
Water Flow	GPH	5.1	5.9	7.2	9.2

In view of expected small efficiency of mass and heat exchange between the steam and water, 3 nozzles 1/8" (61.61) have been chosen.

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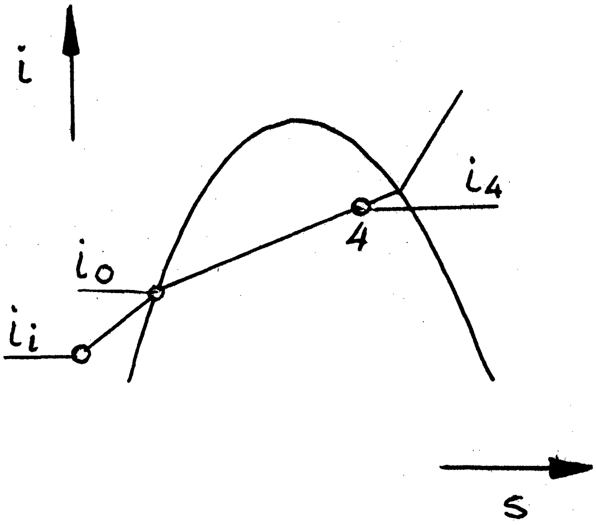
*McMaster-Carr Catalog, p. 696

Estimation of the Pressure in the Mixing Condenser

Assumptions:



$$i_4 - c_p t_o = n\, c_p (t_o - t_i)$$

$$i_4 = \sim 615 \ \text{kcal/kG} \ (\sim 1110 \ \text{Btu/lb})$$

$$t_i = \sim 15^\circ\text{C} \ (\sim 59^\circ\text{F})$$

$$G_{PW} = 3.5 \ \text{kG/s} \ (27500 \ \text{lb/h})$$

$$G_{ST} = 0.177 \ \text{kG/s} \ (1400 \ \text{lb/h})$$

$$h = \frac{G_{PW}}{G_{ST}} = 19.6$$

$$t_o = \frac{i_4 + n\, c_p t_i}{c_p (1+n)} = 44.5^\circ\text{C} = 112^\circ\text{F}$$

$$p_o = p_4 = \sim 0.10 \ \frac{\text{kG}}{\text{cm}^2} = 1.35 \ \text{psia}$$

Estimation of the amount of air sucked into the loop:

1. According to: Dubbel-Technische Taschenbuch, V. 2, 1953, one has to take into account 2-3 liters air/s per 1 kG steam/s. Hence, the amount of air sucked into the loop of the test facility

$$G_{AIR} = G_{ST} \ (2 \div 3) \ \text{liters/s} = (4.4 \div 6.5) \cdot 10^{-4} \ \text{kG/s}$$

2. According to Hoefer K.-Die Kondensation bei Dampfmaschinen, Springer Verl., Berlin, 1925,

$$G_{AIR} = \left(0.02 \ \frac{G_{PW}}{1000} + \mu \ \frac{G_{ST}}{1000}\right) \ \frac{B}{760}$$

where

G_{AIR} - the quantity of water $\left(\frac{\text{kG}}{\text{h}}\right)$

$\frac{G_{PW}}{1000}$ - volumetric flow of cooling water $\left(\frac{\text{m}^3}{\text{h}}\right)$

$\mu = 1.8 + 0.01\ L$

L - the length of the steam line (m)

G_{ST} - the quantity of steam $(\frac{kG}{h})$

B - the barometric pressure (mm Hg)

Assuming:

$G_{PW} = 3.5$ kG/s $= 12500 \frac{kG}{h}$

$L = 5$ m

$G_{ST} = 0.177$ kG/s $= 637 \frac{kG}{h}$

$B = 760$ mm Hg

One obtains:

$$G_{AIR} = 1.43 \text{ kG/h} = 4.15 \cdot 10^{-4} \text{ kG/s}$$

In order to remove this amount of air out of the condenser the water ejector PENBERTHY, size No. 184 A may be used.

Appendix B: Steam Supply and Location of the Test Facility

The following location for the test facility has been considered:

A. The location in the G. G. Brown Laboratory, University of Michigan, North Campus,

B. The location in the Automotive Laboratory, University of Michigan, North Campus.

The advantages of the variant A are:

Abundance of space,

Steam supply from the boiler house (the boiler parameters: $p_1 = \sim 125$ psia, $t_1 = \sim 344\,^{\circ}\mathrm{F}$, saturated steam flow $= \sim 10.042$ lb/h; when assuming the return of the condensed steam into the boiler, the steam flow in the test section is limited only by the capacity of the condenser,

Existing steam and condenser installation; the condenser capacity: 2,000 lbs steam/h with $70\,^{\circ}\mathrm{F}$ cooling water and vacuum about 2 inches Hg. abs.

The disadvantages are:

Higher steam parameters demand relatively sophisticated equipment for pressure/temperature reduction (large quantities of water have to be injected into the fresh-steam line),

The troublesome moving of a fast camera from the Cell 252 at the Automotive Laboratory to G. G. Brown. Moreover, the fast camera is used in Cell 252 for other experiments,

The problems with the efficient organization of the experiments and maintenance of the stand by the personnel of the Cavitation and Multiphase Flow Laboratory.

With regard to these disadvantages, it has been decided to locate the facility in the Automotive Laboratory.

The advantages of this location are:

Convenient operation of the fast camera,

Smooth organization of the experiments,

Steam supply from the boiler house (the boiler parameters: $p_1 = \sim 20$ psia, $t_1 = \sim 228^\circ F$, saturated steam flow ~ 8.750 lb/h; the usable quantity of steam is restricted by the mixing condenser. In view of the discharge of condensed water into the sewer, the quantity of steam has been restricted to about 1,400 lb/h).

The disadvantages are:

The need of the design and construction of a mixing condenser,

The need of discharge of cooling water and condensed steam into the sewer,

The limitation of the time of the operation of the stand to approximately one hour per run because of the waste of water in the boiler,

The relatively low reliability of the prototype design of the mixing condenser,

In further considerations it has been assumed as realistic to maintain in the mixing condenser the vacuum of the order $p_4 = 1.5 \div 3$ psia. The relevant parameters in some selected points of the test facility are presented in the Appendix A. The calculations have been performed for c_4 varying between 100 and 350 m/s.

Appendix C: The Drawings of the Most Important Parts of the Test Facility[*]

1. The Installation of the Steam-Tunnel Facility in the Cell 252 of the Automotive Laboratory.
2. The Silencer Chamber and Nozzle.
3. The Silencer's Inlet Part
4. The Nozzle
5. The Transparent Test Section and Flat Plate
6. The Diffuser Section
7. The Condenser

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[*] Originals on file in the Cavitation and Multiphase-Flow Laboratory, University of Michigan.