SOME CONSIDERATIONS REGARDING COMBUSTION OF HIGH PRESSURE SPRAYS

by

E. T. Vincent
Professor of Mechanical Engineering
University of Michigan

Prepared for the

Conference on Fuel Sprays
University of Michigan
Ann Arbor, Michigan
March 30-31, 1949

Sponsored by

The Air Materiel Command, USAF
and
The Engineering Research Institute
of the
University of Michigan

SOME CONSIDERATIONS REGARDING THE COMBUSTION OF HIGH PRESSURE SPRAYS

It must be admitted at once that the writer has little to offer to this gathering in the way of new theories or experimental results directly connected with the art of spray formation. However, due to some forty years contact with spray formations and characteristics for Diesel Engines, it is believed that a useful purpose would be served by presenting some of the experience gained in that field.

It is true that the Diesel field is totally different from that with which the majority of persons present are concerned since that field demands an intermittant spray of high frequency, accurately metered and controlled, particularly as regards the beginning and end characteristics. Interest today centers mainly on a continuous spray in which the starting and stopping periods are of negligible magnitude and of no influence on the resulting combustion process. This difference permits simplification of a number of design and construction problems when continuous injection is desired and is mainly associated with the effect of fuel compressibility which results in unatomised fuel at the starting and stopping periods together with the production of secondary sprays so harmful to fuel economy.

Let us examine some of the major requirements for the modern type of jet mechanism in order to approach the problem in a logical manner. It is believed that the following represent the more important requirements:

1. The spray should be finely and uniformly atomised at all rates of flow.

2. The atomised fuel should be uniformly distributed throughout the mass of air when operating at full load.

3. The products delivered by the combustion chamber should be at a uniform temperature, without stratification, at any load.

4. The combustion process should be capable of being maintained in an efficient manner in air streams of high velocity.

5. It should be possible to initiate and continue combustion at high altitudes where pressures and temperatures are low.

There are many other items which go to make up the overall performance characteristics of an injection and combustion chamber system. It will be observed that the injection system and chamber have been coupled together; this is believed necessary at the present time since the individual characteristics of each affect one another to an unknown extent. The same is true of the Diesel Engine combustion process, where there are advocates of high and low pressure injection systems, quiescent and turbulent chambers, etc. However, if the engine performance characteristics are studied, it will be found that despite the vast differences in the basic principles employed for the injection and combustion process, the output and specific fuel consumption remains comparatively unchanged, the advocates of high or low pressure injection, etc, turning out one HP for roughly the same amount of fuel in each case, in comparable engines. It is the combination of injection system and combustion chamber that matters, not one of the other despite the advertisements. It is believed the same will be true in the case of the jet engine. However, at the present time, combustion chambers for various jet applications bear a closer similarity to one another than is the case in the oil engine. In the early days of the oil engine all chambers were very similar to one another, thus the possibility of advance with considerable change in principle should not be ruled out.

Consider some of the above items. First, the question of atomisation on which considerable work has been done on engine sprays. The following represents the general observations: It appears necessary to divide the discussion into two parts, depending upon the type of nozzle employed in producing the spray, the plain hole nozzle, and centrifugal or whirling spray nozzle. The characteristics of these two seem totally different. Taking the plain orifice, the atomisation appears to be a function of pressure of injection which, in turn, could be considered one of relative velocity between the fuel and the air into which injection occurs. According to tests at the N.A.C.A. (Ref. Report #425), the main effect of pressure is to produce uniformity of atomisation; low pressure sprays have very small drops present, as small as high pressure sprays, but few in number. These are accompanied by larger droplets. The size of the largest droplet increases as the pressure is reduced. Increase of injection pressure has the effect of reducing the large drops and leaving the small ones almost unchanged. Thus a more uniform spray is produced, but not necessarily one which can be burned at a faster rate, since there is a relation between the drop size and the distance of travel from the nozzle. The gas density in the Diesel chamber is high and the effect of resistance to motion of the droplet results in an increasing de-celeration of the droplet as the size reduces. It follows that the length of travel must also reduce with drop size in quiescent air; it follows that fine atomization is not necessarily the one and only solution to a spraying problem. A large bore Diesel engine will definitely require a coarse atomisation to enable the fuel to travel from the nozzle to the outer reaches of the combustion chamber, unless some form of air motion is relied upon to carry the fuel droplet to the oxygen of the charge after it has lost its initial velocity resulting from the pressure difference of injection. Such a mixing process requires time which is usually not available, at least in high speed engines.

The spraying characteristics of an injection system are of secondary importance, combustion is the primary objective. Here some discussion of the elementary factors controlling efficient combustion can be considered as a starting point. When considering the combustion of a sprayed liquid fuel with air it is generally believed that the phenomena is a surface characteristic, the surface liquid producing a vapor which can then react with the oxygen of the air, releasing heat. It follows that the resulting envelope of combustion gases must be removed from the surface of the drop if combustion is to continue at a rapid rate, i.e., some relative velocity is necessary between the fuel particles and the air. It is believed to be immaterial whether the fuel is moving faster than the air or vice-versa, the object being to tear away the surrounding gaseous envelope, bringing oxygen into intimate contact with the vaporizing fuel.

The Diesel engine industry provides plenty of evidence to substantiate these observations, since the combustion has been effected in so many different ways.

1. <u>The quiescent open combustion chamber</u>

In this, the common chamber for slow to moderate speed engines, the air during the combustion phase of the cycle has little motion but gives excellent output. In general, good specific fuel consumptions are secured, accompanied with excellent smokeless exhaust. In this design the injection system and its spray characteristics become of dominant importance. The degree of atomisation, spray pattern, penetration, etc., must be matched accurately with the chamber shape, and thus the subject of this conference is seen in perhaps its most important phase.

2. <u>The whirlpool chamber of the single sleeve valve engine</u>

Due to Ricardo, this design is perhaps the exact antithesis of the above open chamber engine. In this case, the fuel is added in practically a non-atomised state at one local point of the chamber, but the air, through the action of the admission ports in the sleeve valve, can be given a tremendous whirl about the axis of the engine cylinder. Speeds of whirl up to 30,000 RPM have been recorded in an engine cylinder of about 5" in diameter, which probably means a minimum tangential velocity of the air of some 450 to 500 f.p.s. It follows that, in this case, the air sweeps past a more or less unatomised column of fuel, combustion occurs on the surface of the fuel droplets, and the combustion products are swept away by the air stream, exposing a fresh surface of fuel to the continued action of a stream containing oxygen.

The mistaken idea is often expressed that the air flow carries the fuel drops along with it, thus mixing the fuel and air together. This is very definitely not the case, since, with such a coarse spray, the large drops travel in a straight line, due to their high kinetic energy, and are deflected but little by the air motion. This is apparent by examining the piston top which shows the mark of the extreme outer fringe of the spray almost directly under the nozzle, which seems to confirm the above expressed scheme of combustion.

The power output and specific fuel consumption achieved with this method of combustion are comparable with the previous combustion system. Maximum efficiency is, in general, secured with an air velocity somewhat less than the above 450 to 500 f.p.s., i.e., about 350 f.p.s.

In the case under discussion, the engine performance characteristics are claimed to be practically independant of the spray characteristics, as regards atomisation, dispersion, etc. There are many other intermediate types of oil engine combustion chambers, employing air velocities of the order of 300 to 350 f.p.s. or higher, in which good combustion characteristics can be secured; this means complete combustion in a time interval of 0.003 to 0.004 sec. Translating this to the flow combustion chamber of the present jet mechanism, if similar conditions can be secured, the chamber need not be longer than about 1.5 to 2 feet, much shorter than present demands, which would enable considerable reduction of space and weight to be effected. True, the initial state of the air into which the fuel is injected in the oil engine is considerably different from that of the present jet engine, being at a pressure of some 450 to 550 p.s.i. and 1100 to 1200° F, but the speeds of flight under discussion in some of the advanced thinking of today do not rule out the possibility of employing such values in the jet engine of the future.

Applying the above type of thinking to the problem at hand, i.e., the jet engine fuel system and combustion chamber, it raises the question of whether the present day components of such injection systems and combustion chambers are the best combination. Is it not possible that the future will result in varying the principle in as many ways as was the case in the oil engine? What those principles may be the author cannot forecast; it remains for future developments to chart the course. There are indications that the future may demand a considerable increase in combustion chamber velocity with reduction of external drag, etc., in the case of the ram-jet type of engine. Calculations made at this University, Ref UMM 1 & 7 and EMG 12, have shown that the overall performance of a ram jet can be expected to improve with increase of entrance combustion chamber velocity to at least 600 f.p.s., approx., if efficient combustion can be secured simultaneously.

Bringing the above observations down to the spray patterns and atomisation of the fuel, there is ample evidence that at the opposite end of the scale a well-dispersed spray from a low pressure injection system can be carried along by a high velocity air flow before combustion is complete, consequently requiring a long chamber for efficient combustion and good temperature distribution.

Sprays such as those in common use at present, such as the whirling spray, using a few hundred pounds per square inch injection pressure, would fulfill the above conditions since such sprays lack penetrating power, are rather uniformly atomised but of large drop size with low absolute velocity and are thus easily capable of being carried along by an air current. Complete combustion will then depend upon the relative velocity between the oil and air. If this is low, a long length of travel is necessary to bring sufficient oxygen in contact with the fuel for complete combustion.

Looking at the alternatives, there is the case of high pressure injection with greatly decreased drop size, of increased velocity of travel, which is hardly affected by any reasonable air velocity up to about 500 f.p.s. Such a spray could be formed in an air stream, the oxygen passing across the stream at any desired rate, exposing the fuel to the maximum burning rate. The length of travel from the jet to the tip of the spray can be made almost anything desired, to suit the air velocity involved. Such sprays have usually been formed by the use of small holes and high injection pressures. The resulting spray, compared with the whirl type, has very little dispersion. It follows that, for complete coverage of any area, multiple orifices would be necessary. Good filtration would be an essential, and a suitable high pressure pump would require development. Again, the present low density medium into which injection occurs would perhaps produce some complications regarding length of spray path due to lowered resistance to motion. Altogether, these are some rather difficult conditions to fulfill at the present time for existing types of chambers, but time will undoubtedly contribute to easing the condition which, together with the advancing skills and knowledge available to handle the problem, will contribute to its solution.

Secondly, it is possible to produce high pressure sprays of fine atomisation, coupled with wide dispersion, by the use of impinging orifices. Such jets have proved to possess sufficient penetration for high density air despite their wide dispersion and will thus withstand the action of high velocity air currents, giving high rates of relative velocity between fuel and air, thus, possibly, quick and efficient combustion. The orifice size in this case is not so critical, and in addition the injection pressures are not excessive.

A comprehensive spray investigation should cover all phases of the problem, both high and low pressures, types of nozzles, etc., so that the spray pattern, atomisation, etc., will be capable of prediction for any desired combination. This is a very desirable state that still remains to be achieved. So far as the writer is aware, it cannot be too strongly urged that the attainment of such a goal means absolutely nothing so far as the final end state is concerned. The desired end is efficient combustion in the smallest combustion chamber, under the widest variations possible among operating conditions, Whether this is achieved by high or low pressure, atomised or non-atomised fuel, etc., is purely incidental. As a result, the writer believes that a spray investigation as such means little without its associated combustion study. This has been proved the case many times in the past, in the oil engine industry, where large sums of money have been expended on spray investigations. The final result is still a trial and error solution for each engine, so far as efficient combustion, which is the main object, is concerned.

In conclusion, it can be stated that combustion is possible in high velocity air streams in very short time intervals without the aid of flame holders, if given suitable initial conditions, spray formations, etc. That spray pattern itself is no measure of the resulting combustion process; similarly air velocity is no criterion for success or failure. The overall result achieved is a combination of velocity, spray pattern, chamber shape, and state of the air.

Regarding the actual application to particular problems, it will be necessary to solve the rather complicated combination presented by all the above variables, if it is desired to be able to design and put on paper a combination capable of operating over the range presented by modern flight requirements from sea-level to possible 80,000 ft. altitude.

It can be reported that in addition to its spray investigation this University is conducting some fundamental and applied research in the field of combustion for the Ram-Jet and similar jet mechanisms. It is hoped that it will be possible to coordinate these two programs in such a manner that answers to some of the problems outlined above can be secured.

Again it is emphasized that efficient combustion is the goal. Spray characteristics is one step along the path, but there are many other steps to be taken before reaching the desired objective.