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EXPERIMENTAL DETERMINATION OF FUEL FILM FLOWS IN MANIFOLDS

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ABSTRACT

The flow in the inlet system of a gasoline engine is complex, two-phase, stratified and multi-component. In addition, the gas stream flow itself can either promote or inhibit both the mixing and the formation of separated liquid streams. Any liquid fuel films which form on the walls of the manifold or ports can substantially influence the final air/fuel ratio received by the engine. This is particularly important for transient engine operation where good simulation models are not yet available and more experimental data are required for their development. The present paper reports experiments on a computer controlled rig for the determination of the fuel film velocities allowing their relationships to the air flow velocity to be established.

INTRODUCTION

Modelling of the flow in I.C. engine inlet manifolds and ports is important so that improved induction system design can occur. Depending on which part of the inlet system is being considered and the method by which fuel is introduced to the engine, the flow may consist of air only or be a mixture of air and fuel. In the latter case, the fuel may exist in the form of vapour, airborne liquid droplets and wall films which flow as separated but related streams and, as such, are instrumental in causing many of the air/fuel related excursions from the desired levels which are detrimental to engine performance, economy and emissions. Separated flows are associated particularly with transient operation whether of the long term, warmup type which exist following a cold start or the short term acceleration, deceleration or load change type which prevail under most normal operating conditions. Experiments to obtain details for and to calibrate the complex modelling process are of great importance.

Most of the fundamental modelling work to date has been related to studies of the base gas flow. Here a pulsating, piston driven flow applies for both steady state and transient engine operation. Pulsations may enhance or detract from the engine volumetric efficiency depending on the details of the design and the flow rates under study and are important for studies examining this effect. However, even if these pulsations are ignored, during transient operation both the air/fuel ratios and the fuel composition within the cylinders show time dependent variations due to the delays imposed by the separated fuel streams and the earlier evaporation of the lighter fractions of the multi-component fuels for a changed film extent. In order to model engine cycles during transient operation, the important factors differentiating them from the better understood steady cycles are the responses of the spark timing, emission control (in particular, exhaust gas recirculation where used) and the fuel systems, the last normally having the greatest impact and being the least understood. Hence, a fundamental knowledge of the transient effects stemming from the fuel introduction and its transport in the inlet manifold and ports to the cylinders is essential so that further improvements in the modelling and the design process can occur.

In addition, the inlet system plays the major role in engine control and, while modern techniques may by-pass the basic flow problems by using a closed-loop control system, a knowledge of the fundamentals is important to help optimise the system. This is likely to become even more relevant in the future with the introduction of alternative fuels of low volatility such as methanol and ethanol and the use of flexible fuel vehicles (FFVs) which will require automatic, on-board compensation of the engine control parameters at each fuel fill-up in order to cope with the noticeably different alternative fuel/gasoline blends which may be available from time to time or place to place. The present study provides background data for all the above aspects of the intake flow system.

FLOW IN INLET MANIFOLDS AND PORTS

During acceleration in a throttle body (single point) injection engine with an uncompensated fuelling system, various tests, using a step change in the throttle setting and measuring either maximum cylinder pressure (Tanaka and Durbin, 1977) or exhaust emissions (Hires and Overington, 1981), have shown that a considerable variation towards a leaner air/fuel ratio occurs rapidly. A deceleration will induce the opposite change. For both the steady state and transient cases, the flow in the manifold may be considered to be as shown on Fig. 1(a) for steady and 1(b) for transient engine operation. This is for fuel introduction upstream of the throttle valve (carburettor or throttle body injection) and a similar but more limited situation exists for downstream (port) injection. The liquid spray from the jet breaks up into droplets which are transported downstream in the air stream. Droplet breakup, evaporation, collision and coalescence occur and a proportion of the drops which move close to surfaces such as the throttle valve or duct walls are slowed and collect forming a film. This film is

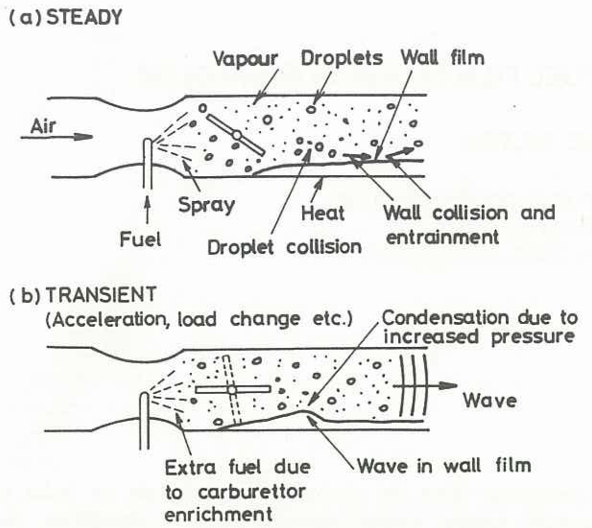

FIG. 1. Depiction of fuel flows for steady and transient conditions

driven downstream by the but, due to its greater inertia, it will travel with a velocity several orders of magnitude less than the gas. For an uncompensated transient when, for example, a rapid throttle opening occurs, the greater deposition into the film will result in a leaner airborne region between the downstream moving pressure wave and the thickened film of the new condition. The total extent of the flow induced part of the transient delay will be the difference between the times the gas stream and the film take to reach the cylinder. In between, the progressive evaporation and possible re-entrainment of the film into the airstream will reduce the initial lean excursion effect causing the gradual return noted to the desired air/fuel ratio settings. However, the additional evaporation will consist predominantly of the lighter fractions of the fuel leaving the heavier fractions in the film as shown in the computational studies of Boam and Finlay (1979) and Milton and Behnia (1989).

Gasoline consists of many components whose properties differ considerably. A typical sample might contain over 40 different components but these can vary for different samples obtained for a fixed fuel specification from different sources or indeed from the one source at different times. In the present research program, a typical winter grade Australian fuel was analysed and the results used for computational purposes in this research (Milton and Behnia, 1989). Of the large number of components identified, 15 were considered to be in proportions significant enough to influence the total fuel flow and combustion. It can be seen that, given the complexity of the flow and the fuel supplied, even steady state experiments and simulations present severe difficulties. The transient situation is considerably more complex as changes to the flow may occur due to opening or closing the throttle or increasing or decreasing the load and hence the engine speed over a wide range of rates. In general, both throttle position changes and engine speed variations occur simultaneously and a theoretically infinite number of combinations is possible. However, the basic cases can be limited to throttle movement at constant engine speed or change in engine speed at constant throttle setting. Transient experiments need to be performed for a better understanding of at least these basic cases.

PREVIOUS EXPERIMENTAL WORK

The concept that fuel from the spray may partially separate from the airborne flow to form wall films has been known from the early period of engine development. Mock (1920) discussed the necessary fuel compensation for carburettors and referred to experiments conducted on engines with glass windows in the manifold where films had been observed. The first attempt to determine the proportion of fuel existing in the film was carried out by Collins (1969) who used a traversing suction probe to draw off air and evaporated fuel. Kay (1978) used visual and photographic observations through small windows in the manifold of an engine. As part of a major program on engine intake flows, Finlay and Welsh (1978) photographed sprays from an air–valve carburettor. Hayashi and Sawa (1984) using conductive probes obtained typical film thickness values of 0.05 to 0.2 mm with methanol as the fuel. A recent experimental study by Hasson and Flint (1989), also on a fired, operating engine, examined the rate of droplet deposition onto the wall by trapping the liquid film flow. To obtain a better understanding of the flow by clearer visualisation and more accurate measurements over a wider range of operating conditions, an alternative approach is to decouple the manifold from the engine and simulate the required conditions by other means. An apparatus suitable for this approach has been developed for this project (Behnia and Milton, 1988) and preliminary transient results reported (Milton, 1986). It has also been used to calibrate the numerical simulations referred to previously (Milton and Behnia, 1989).

THE CURRENT STUDIES OF MANIFOLD FLOWS

In general, experiments by other researchers have used manifolds on operating gasoline engines. However, many of the basic details of the flow are then difficult to obtain because of access problems for flow visualisation, pulsations from the intermittent cylinder motion which disturb the base flow and limitations on the air/fuel ratios which can be used. Two special rigs have therefore been constructed as detailed by Behnia and Milton (1988). The first used an engine driven by an electric motor to provide the flow. However, the flow both through the carburettor, which was a commercially available variable venturi (i.e. air–valve) type and past the butterfly valve could not be seen. This rig provided some important data on the

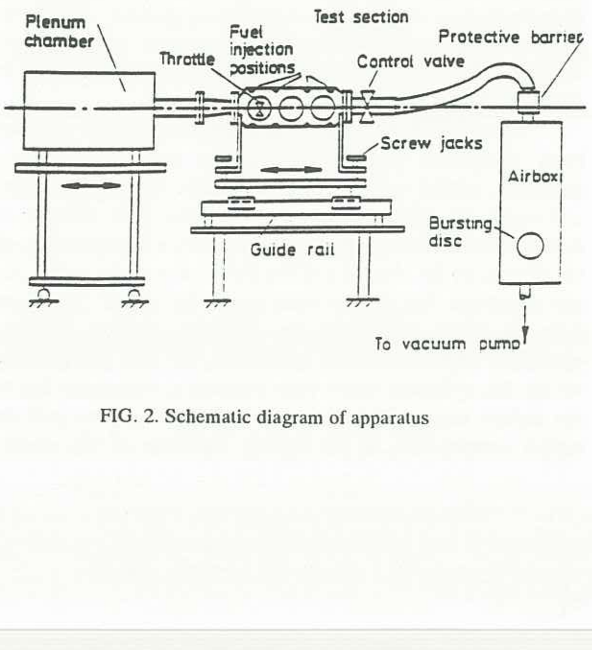

FIG. 2. Schematic diagram of apparatus

movement of the film towards the engine which was seen to occur during all steady operating conditions, in obtaining order-of-magnitude estimates of film depth and velocity and in confirming the fact that a wall film of different thickness to the original moved towards the engine during transients as a wave. However, the pulsating nature of the flow disturbed the surface with a superimposed, regular wave pattern which made accurate measurements of both the film depth and its velocity difficult. Re-assessment of the experiment suggested that a steady flow rig would not only reduce the measurement problems but would provide better calibration of the computer code under development which was based on a two-phase, separated stream, multi-component steady flow approach. The early experiments showed that the formation of the film required investigation and the region near the throttle valve needed to include both the throttle plate and the fuel injection region. This rig is shown in Fig. 2. The fuel injection can be located in several different positions along the manifold relative to the throttle valve and has top or bottom injection locations which can each be oriented to a series of different angles facing upstream, downstream or directly across the flow. High quality optical glass viewing sections show the complete fuel injection process and flow around the throttle plate. The manifold used in the rig retains the square cross-section of the earlier experiments but can be replaced with other cross-sections as desired. The rig is computer controlled allowing transient pressure waves of the desired shape to be generated using either the throttle valve or the downstream control valve individually or simultaneously. Maximum valve opening and closing rates are 45/sec. All data acquisition equipment is linked to the computer.

RESULTS AND DISCUSSION

The fuel film velocity and thickness are the primary factors determining the ultimate distribution of fuel both spatially and temporily to the cylinders. These depend on a range of manifold conditions which include the air stream velocity, the manifold pressure and temperature and the wall roughness. It is most important to examine the dependency on air stream velocity and manifold pressure as these must vary with normal engine operation and cannot be modified by independent control, design or manufacture to improved tolerance limits. Hence, in the present series of experiments, a smooth, generally unheated duct was used with measurements of the air mass flow rate (from which average gas stream velocities were determined), the manifold pressure and temperature at several stations along the test section and the total flow rate of the fuel injected into the system. In obtaining quantitative values for the film parameters, the air flow velocity and manifold pressures were adjusted independently of each other by varying the settings of either or both the throttle plate and the downstream control valve. All current measurements were taken under steady flow conditions.

The one-dimensional computer program (Milton and Behnia, 1989) requires either the film velocity or thickness as an independent variable. Film thickness is subject to substantial error as it may not be uniform at any one duct cross-section and, indeed may not extend fully around the periphery. Hence, film velocity was chosen as the independent variable and an appropriate measurement system was developed. The criterion for selection of a system was that measurments could be taken as accurately as possible using a simple, non-intrusive method. While previous investigators (Hayashi and Sawa, 1984 and Hohsho et al, 1985) used conductive or hot wire probes, optical or thermcouple based methods were considered here to be preferable because they best fulfilled this criterion while at the same time being simple and robust. Several systems were examined and compared for consistency, reliability and rapidity of response, the last being extremely important for transient measurements. The first system evaluated was optical, with two sensitive photodiodes spaced 114 mm apart flush mounted in the floor of the test section on the duct centreline with light sources, also flush mounted, in fittings placed directly opposite. The latter used a pre-focused flashlight bulb illuminating its paired photodiode through a small aperture drilled into the bulb mount fitting so as to collimate the light and prevent it affecting any other photodiode/light pair. An identifiable marker (bearing blue dye) produced a pulse as it passed through the time of traverse then giving the velocity.

This was compared with a film front method using spaced thermocouples as detectors. Here, the manifold was run without fuel and, at the appropriate moment, the fuel was injected causing a fuel film with a distinct leading edge to move down the duct, the leading edge of the fuel film front becoming the measurement datum. This method is much quicker, cleaner and simpler than "dye" injection and has better potential for adaptation to transient operation if the fuel flow is commenced simultaneously with throttle repositioning. Also, there was no need to mask the windows and simultaneous measurement and visualisation were possible.

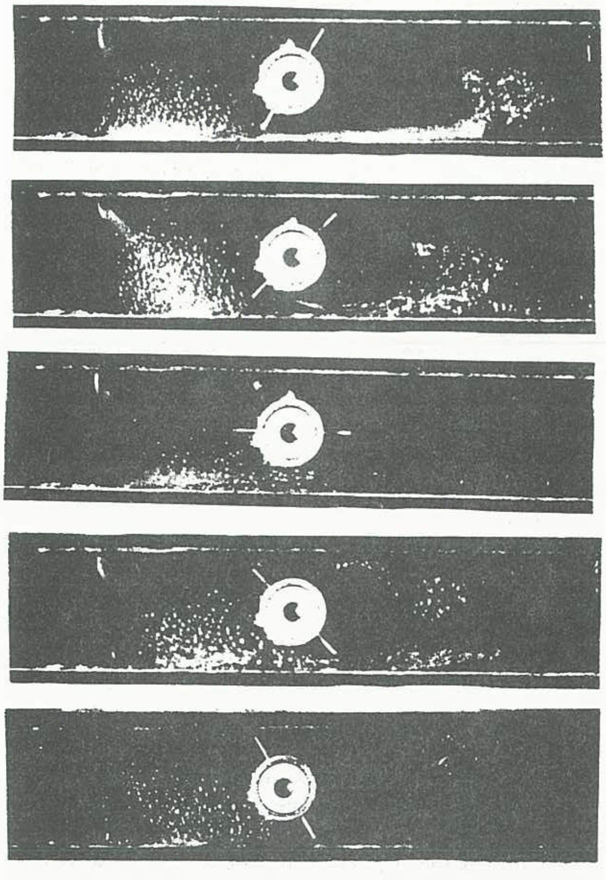

FIG. 3. Typical flow patterns, $\theta = +30^{o}, +45^{o}, 90^{o}, -45^{o}, -30^{o}$

The experiments are aimed at determining the relationship between the film velocity and the throttle angle, the injector location, the air stream velocity and the manifold pressure. Results reported here are for upstream injection only. The throttle positions shown in the photographs are measured from the vertical up position with clockwise rotation, the fully closed positions being + or − 15°. The gas stream velocity was measured at inlet to the test section. The equivalence ratio, φ, was held within the range 0.95 to 1.05. Typical fuel flow patterns for different valve angles are shown on Fig. 3. The difference in the recirculation zone behind the valve for positive and negative throttle angles is apparent, the wake showing more uplift in the negative case. The fuel injector directs the spray towards the floor and a film forms immediately. This is broken up and re-entrained as it passes through the gap created by a partially closed throttle and then re-formed by deposition from the wake region. Fuel carried from the spray onto the throttle plate also makes a contribution in this region. The film therefore tends to be thicker in the positive throttle angle case where this contribution is greater and the re-entrainment into the wake is less.

The gas stream and film velocity relationships are compared on Figs. 4 and 5. In both cases, the film velocity increases almost linearly with airstream velocity reaching a maximum of around 0.35 m/s when the air velocity is 35 m/s. At airstream velocities of between 5 and 10 m/s, the film velocity reduces to zero. The value at which this happens cannot be precisely defined because, at these values, the film was not always fully complete. The negative angles show only a small variation in the film velocity with throttle setting but there is a noticeable difference with the positive angles. Here, greater throttle closure lowers the film velocity and there is some indication that there is departure from linear at the low velocity end of the range. This throttle dependence is most likely due to the fact that the film is substantially formed in the upstream region by direct spray impingement and also deposition from the plate, with subsequent breakup and reformation at closed throttle in the wake region. For negative angles, the downstream film is formed to a much greater extent by direct deposition from the throttle.

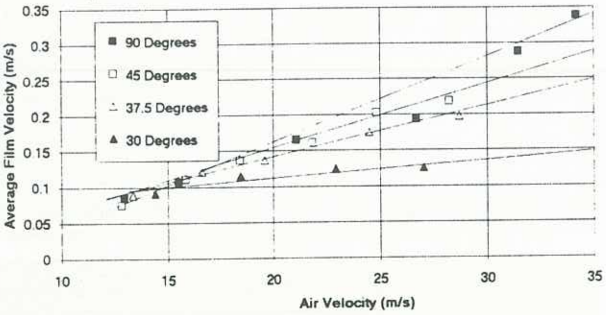

FIG. 4. Film velocity relationships to average gas stream velocity (positive throttle angles)

CONCLUSIONS

An experimental rig has been developed for fundamental studies of the two-phase, separated, multi-component, evaporating flow in the inlet manifold of a gasoline engine. The flow is stratified, a high proportion of the fuel being carried in a fuel film. The remainder is in the form of airborne droplets and vapour. The film velocity increases with airstream velocity reaching values of about 1% that of the airstream. A significant variation occurs in film velocity with throttle angle (+ve angles), a more closed throttle giving a lower film velocity while −ve angles gave film velocities largely independent of throttle position. This appears to be due to the more significant re-formation process and influence of the wake region in the former.

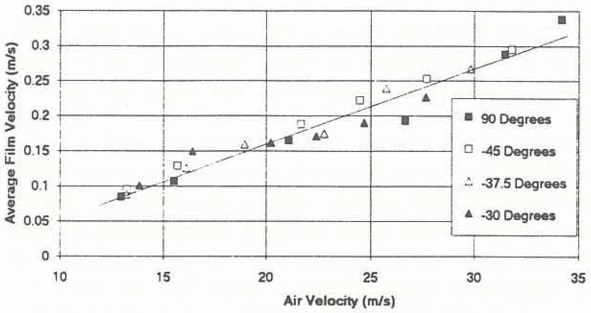

FIG. 5. Film velocity relationships to average gas stream velocity (negative throttle angles)

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