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An Electric Conductive-Probe Technique for Measuring the Liquid Fuel Layer in the Intake Manifold

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Abstract

In order to investigate liquid fuel filming over the intake manifold wall, an electrode-type probe has been developed by ones of authors and this probe was employed in a single cylinder two and four-stroke cycle engine and in a four cylinder four-stroke engine operated by neat methanol fuel. The performance of the probe was dependent upon several parameters including the liquid fuel layer thickness, temperature, additive in the fuel, and electric power source (i.e., AC and voltage level) and was independent of other variables such as direction of liquid flow with respect to the probe arrangement.

Several new findings from this study may be in order. The flow velocity of the fuel layer in the intake manifold of engine was about 1/100 of the air velocity in the steady state operation, the layer thickness of liquid fuel varied in both the circumferential and longitudinal directions. In the transient operation of the engine, the temporal variation of fuel thickness was determined, which clearly suggests that there was difference between fuel/air ratio in the intake manifold and that in the cylinder. The variation was greatly affected by the engine speed, fuel/air ratio and throttle opening. And the variation was also very significant from cylinder to cylinder and it was particularly strong for different engine speeds and throttle opening.

1. Introduction

Since even a warm spark-ignition (SI) engine does not provide all the fuel introduced into the cylinder in the vapor phase, some liquid fuel in a starting engine off the carburetor or fuel injector is filming over the intake manifold walls. The presence of such liquid fuel layer over the intake manifold wall in the SI engines is known to cause adverse impacts on engine operation as well as hydrocarbon exhaust emission. One of the main impacts is the cyclic and cylinder variation in fuel delivery into the combustion chamber. It is reasonable to predict that the variation takes place in both the amount and the fraction of fuel vaporized in the mixtures. That is, the variation of fuel layer thickness taking place with changes in the engine operation and ambient condition suggests that the fuel/air ratio even in the same cylinder, from time to time, is different from that in the manifold. The temporal change in the condition of fuel induction into the cylinder also suggests that the fraction of fuel vaporized after the intake port varied with cycles and, if it is the case, also with cylinders. When the difference in distillation point of multicomponents in the fuel is considered, the variation is expected to be further involved(1). This is even more serious during the cold start and the transient engine operation, making its impacts greater. In order to reduce the amount of liquid fuel layer in the wall, the manifolds are often heated. For example, when the heating was changed from the engine coolant at 90 °C to the steam at 115 °C, its considerable reduction was realized (2), which was of course a function of intake manifold pressure and fuel/air ratio. Hire and Overington(3) proposed that the variation of in-cylinder fuel/air ratio caused by such changes in liquid fuel layer thickness may need compensation by throttle opening, at a characteristics time of the order of one second (4).

When a SI engine is fueled by methanol, in either neat or blends, the presence of the in-manifold liquid fuel layer is of far greater concern. This is because if its high latent heat of vaporization, almost eight times of gasoline per unit energy making the fuel hard be vaporized. Since methanol is a serious candidate as alternative fuel in SI engines, and the factors affecting the liquid film behaviors are multilateral and more serious, it will have to employ a special measure of achieving a constant fuel/air ratio at the intake port, which may be performed using a feedback method directly monitoring the amount of fuel in the liquid layer. In order to implement timely and accurate feedback according to the amount of liquid-layer fuel, the film layer thickness may be a proper choice to be determined as rapidly as possible, motivating the work to be discussed in this paper.

In order to carry out our goal of developing a sensor system that enables us to monitor the rapid change in methanol layer thickness in the intake manifolds, sensitivity of several design and operational parameters was studied. Included were those associated with design, material, electric current (frequency), fuel temperature, and fuel additives. Upon completion of device, it was tested on an actual stock engine to obtain several new findings as herein reported.

2. Measurement Method of Liquid Fuel Layer Method

The basic idea of device(5) is to employ the simple relationship of resistance of an electric conductor to several variables, namely the length of the conductor, cross-sectional area of the conductor and the resitivity of material. The liquid fuel layer, therefore, represents a conductor that contains a minute amount of additive of which concentration determines the resitivity. The sensing probe is made of two electrodes placed flush with a wall (made of an electrically nonconductive material) over which the methanol fuel layer is covered, as schematically shown in Fig. 1. Performing several designs and bench testing, it was decided to have the distance of 5mm between the two electrodes with a simple Kohlrausen-bridge arrangement as indicated in the figure. The electrodes were made of stainless steel or platinum have a diameter of 2mm. It is noted that the electric source used in the experiment was AC instead of DC power in order to minimize polarization of the (electrically conductive) solution layer because its effects becomes stronger with a DC source affecting the resitivity of the solution.

A calibration step was taken prior to its application in an engine. Since the intake manifold is not necessarily square and flat, two different extreme cases were tested on the configuration of probe to the respective liquid pool with rectangular and cylindrical shape. Some of the test results obtained using a water-potassium solution with concentration of 0.1 grams/cc is shown in Fig. 1. The resistance between the electrodes was strong function of solution temperature and of course the layer thickness which was measured by using a micrometer. The results indicated that the geometry of the liquid pool did not affect the measurement. It was observed that the resistance was inversely proportional to the liquid thickness smaller than 1mm and almost its natural logarithm for greater thickness. This may be explained by the fact that when the layer thickness was changed the effective distance between two electrodes was also changed and when the thickness increased further the electric polarization effect and the surface impedance of the electrode with respect to the resistivity were no longer linear as mentioned next. Although some amount of current flow is realized through methanol fuel, which is too small to effectively monitor the rapid variations in fuel layer thickness, it was found that a minute amount of additives introduced into the fuel greatly helps to accurately determine the layer thickness. Five different kinds of additives were tested by varying the amount of the addition to find sodium acetate to be the most useful of all investigated. The choice of this additive was made on several considerations such as that it does not create noticeable corrosion when its content is a fraction of one percent. Nevertheless we investigated the effect of its concentration on the conductivity for ranges 0.01-1% as explained later.

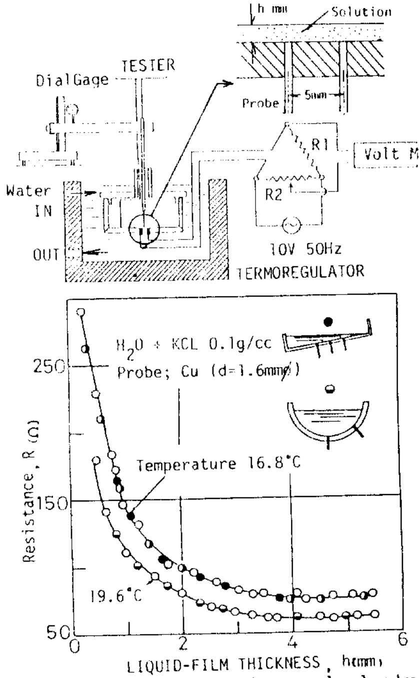

Fig.1 Calibration apparatus and electric resistance R and liquid-film thickness

Electric Current and Probe Installation As mentioned above, an AC current was used in order to minimize the polarization effect on the liquid resistivity. In general, the counter electomotive force, e and electric current, i under polarization is expressed by the following relationships.

$$e= \frac{1}{\omega RP} \cdot \frac{E_m}{\sqrt{1 + 1/\omega^2R^2P^2}} \cdot \sin(\omega t+\theta-\pi/2)$$

$$i= \frac{E_m}{R\sqrt{1 + 1/\omega^2R^2P^2}} \cdot \sin(\omega t+\theta)$$

From the equations, it is clear that i advances e by $\pi/2$ degree. The phase advance becomes insignificant for higher AC frequencies making the solution resistivity higher and the polarization effect, $1/\omega^2R^2P^2$ is smaller, when P is polarization constant. In the present case, however, the resistance of the solution is very high for obvious reasons the additive concentration is maintained as low as possible and the Deby-Falkenhagen effect becomes significant. One remedy measure taken for such a problem was to increase the polarization constant, P, which is achievable by either increasing the current flow or size of the electrode diameter.

Because of complexities of the problem the final design of the probe and mounting was determined through a lengthy trial and error approach along with parametric analysis, which included effects of frequency variation from 50 - 1,000 Hz, size of electrodes, distance between the electrodes, and additive and concentration. As a practical compromise, the frequency of AC current was chosen at 50 Hz and the probe was made of an electrode having a diameter of 2 mm and an electrode distance of 5mm as previously mentioned.

In view of compounded effects by various factors, the flow speed and direction of the fuel layer was of concern to see if it causes any change in the measurements. Fig.2 shows some test results on the question. The figure includes self-explanately notations indicating the experimental conditions. As expected the higher the concentration the greater the output (because of the smaller the resistance between the electrodes in the probe). Note that the results exhibit that the flow speed and direction with respect to the electrode arrangement do not affect the measurement.

Next, the effect of the temperature of the solution layer and the electric source voltage were investigated as shown in Fig.3. The temperature effect on the relationship was measurable, i.e., the higher the temperature of liquid film, the smaller the resistance between

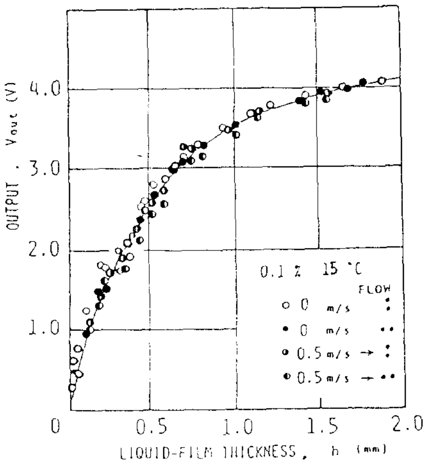

Fig.2 Effect of probe arrangement on the output

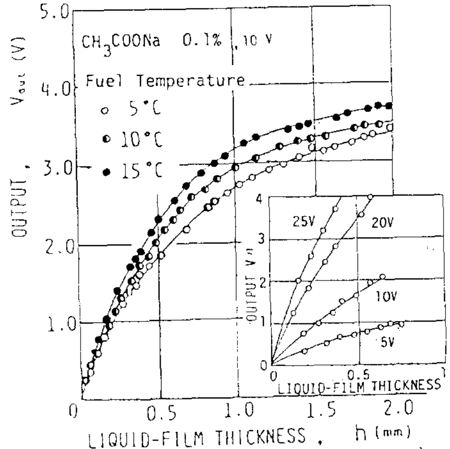

Fig.3 Effect of solution temperature and source voltage on the output

the electrodes. For fixed temperature level, the the output becomes higher(the resistance becomes lower) with higher source voltage, which may be explained by increased polarization of the solution and also by some increase in the temperature of film due to increased electric energy dissipation. The latter reason was confirmed by observating a small amount of bubbles formed within the film when a very high source voltage was used. Consequently, as a compromise in the experiment, we decided to employ the terminal voltage ranging 5 - 10 volts. In fact, despite the fact the impacts of the temperature increase in the fuel film of an operating engine were relatively small because the continuous flow of film over the electrode probes which was monitored through the experiment, a compensation method was not taken to eliminate the temperature effect.

Fuel Films over the Intake manifold The above discussion describes the basic relationship among several main variables associated with the measurement using the prove. The fuel film thickness in the intake manifold, however, varied in both longitudinal and circumferential directions. The thickness varies with time also. In order to take account the variations, two cases were considered. i.e., steady and transient conditions. When the engine speed was high and had an increased air velocity, the gravity effect on the film thickness variation in the circumferential direction was small so that the variation was relatively steady and small in both directions. When this is the case, the mean thickness, hm at a cross-section may be found form,

$$hm \doteqdot \frac{1}{\pi D}\int_0^{\pi D} h \cdot dZ \qquad (1)$$

The fuel flow rate at a cross-section of the intake manifold, Gfl, then can be calculated by

$$G_{fl} = \int_0^{\pi D}\int_0^{h} \rho_{fl} \cdot v_{fl} \cdot dh \cdot dz \qquad (2)$$

where, ρ fl is the density of fuel, vfl= is velocity. From the above definition, hm is introduced into the above relationship to obtain,

$$G_{fl} \doteqdot \pi D \int_0^{hm} \rho_{fl} \cdot v_{fl} \cdot dh_m \qquad (3)$$

The fuel flow in the intake manifold, in general, varies with time and location from that actually introduced from the carburetor Gf, which may be represented by (1-y(t))Gf(t), where y(t) indicates the difference caused by the local variation. When the vaporized portion of the fuel is taken into account, the mass flow rate in transient flow becomes (1-x(t))(1-y(t))Gf(t). The instantaneous flow rate,$dG_{fa}(t)/dt$ is calculated by

$$dG_{fa}(t)/dt = \{1-y(t)\}\{1-x(t)\}G_f(t) \qquad (4)$$

The flow rate, then can be found from

$$G_{fl}(t) = [y(t)+x(t)\{1-y(t)\}]G_f(t)+G_{fa}(t) \qquad (5)$$

The fuel flow rate, through the cross-sectional area where the probe is located, can be made by introducing the definition of hm and Gf,

$$G_{fl} = G_f(t) - \rho_{fl} \cdot \pi \cdot DL \cdot dh_m(t)/dt \qquad (6)$$

where Gf represents the flow rate off the carburetor.

In order to experimentally confirm the above relationship, eight pairs of electrodes were mounted on the intake manifold with equal spacing in the circumferential direction (Fig.4) and the individual output was connected in parallel to one end of the bridgecircit. The output hm, an averaged value of the individual probe measurements was compared with the geometric averaged from our actual measurements, hmc to find that the equation (6) well represents the concept as shown in Fig.4.

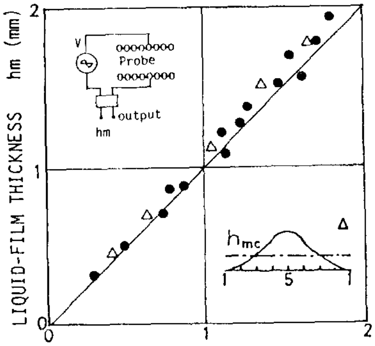

Fig.4 Measurement of mean thickness of fuel liquid-film

3. Experimental in an Engine

Test Engine A single cylinder two-stroke spark-ignition engine with crankcase-compressed induction system, a single cylinder four-stroke spark-ignition engine and a four-cylinder four-stroke spark-ignition engine were used in the experiment and Table 1 shows details of the engines.

Table 1 Test Engine Specifications.

Engine Type	Two stroke	Four stroke	Four stroke Four cylinder
BorexStroke	73 x 59mm	90 x 105mm	(75 x 70mm)x4
Compression Ratio	6.6:1	7.71:1	9.0:1
Max.Torque	2.63 kgf-m/6500rpm	3.9 kgf-m/1700rpm	10.2 kgf-m/3600rpm

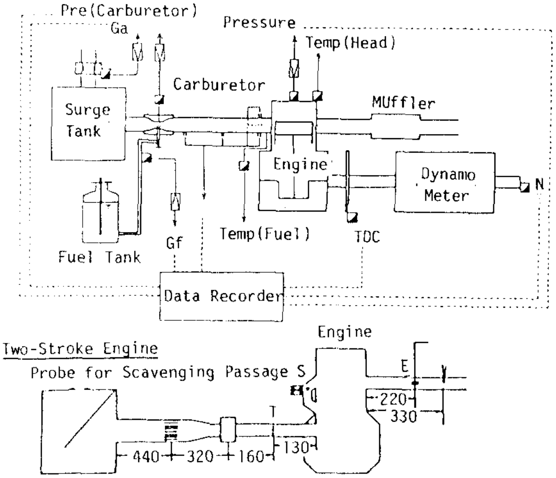

Fig.5 Experimental apparatus & prove location

The fuel was introduced through the intake manifold into the crankcase volume and the mixture was transported into the intake port through the scavenging passage, S. The intake manifold had a geometric configuration with respect to the engine as shown in Fig. 5. It is noted that the behaviors of fuel film over the intake manifold walls were very complex and it was decided to employ a photograhic method in order to obtain close observation under various engine design and operating conditions. For example, fuel film was observed at three different locations, a, b and c in the figure 6. In the figure, A/F represents air to fuel mixture ratio, Va denotes the air velocity in the duct and C shows the throttle opening. Since the probe were mounted at equally-spaced locations in the circumferential direction, namely location 1 through 8, the thickness film took place at location 5. When the engine speed was low, i.e., at 600rpm, fuel droplets were observable near the carburetor. Their amount increased and coagulated together with an increase in distance toward the engine producing a thin layer of fuel film. This layer was carried to the engine by the rushing air and gravitational force. Note that the thickness of the fuel layer decreased with the distance (from location a to b an to c) in large due to evaporation of fuel off the surface. When the engine was operated by a richer mixture such as A/F=5.0, as expected the above fuel behaviors were more obvious but the film thickness beyond 115mm from the carburetor (location b) did not increase with fuel/air ratio. Since the air velocity stayed the same, so was most likely the evaporation rate. The only main reason for having the same thickness downstream with richer mixtures is the increased fuel layer flow in the rich mixture.

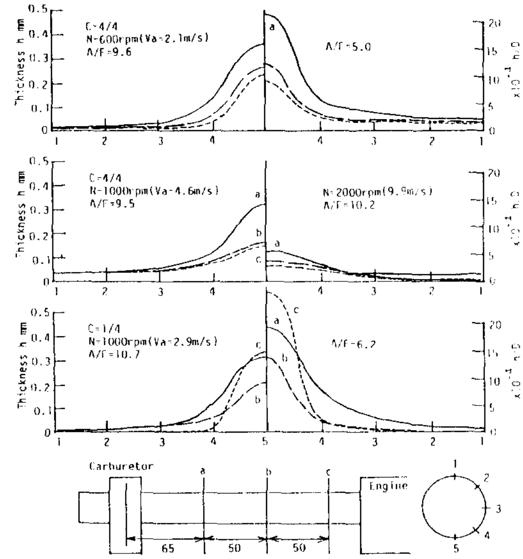

Fig.6 Circumferential distribution of fuel liquid-film thickness

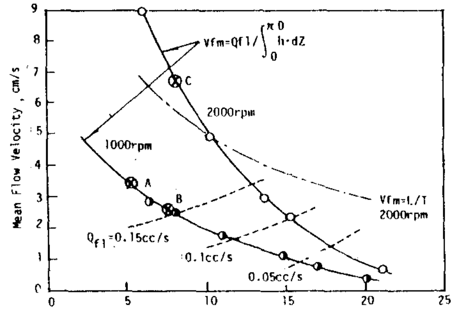

Fig.7 Mean flow velocity of fuel liquid-film (Vfm) and air fuel ratio

On the other hand, when the engine speed was increased(so was the air velocity), the fuel layer thickness became uniform in the circumferential direction particularly at location c, 165mm from the carburetor. Note that at the high speed the initial location where fuel droplets bombarded was moved nearer the engine, suggesting that not only the fuel layer flow speed but also the evaporation rate increased.

According to Eq.(1), the typical value of hm varied from 0.05 to 0.15mm. Since the average fuel flow, Vfm was calculated using hm and Gfl to plot in Fig. 7 against air/fuel ratio, the velocity of fuel layer flow was determined by measuring the arrival time [T] of fuel layer at respective probes located a, b and c within the distance L (Vfm=L/T): the measurements indicated by A in the figure were obtained using the respective signal from the probes by starting the engine (from the rest condition), and those indicated by B and C were acquired by suddenly allowing the fuel issued out of the carburetor while the engine was operated at the corresponding speed. Among important findings obtained from these measurements was Vfm was an order of Va/100 for the condition studied.

Fuel Layer under Transient Operation The relationship of hm and Vfm to Gfl in the steady state engine condition seems justified as demonstrated in the above discussion. If it is the case, it is reasonable to predict that the relationship may similarly prevail in transient engine operation conditions. Eq.(6) suggests that it is possible to monitor the real-time change in both the amount of fuel issued by the carburetor and the actual amount of fuel introduced into the combustion chamber. For example, we expected that Gfl(t)>Gf(t) if dhm>0 and vice versa, which may be quantified for proper compensation to achieve an unchanging in-cylinder fuel/air ratio. Unlike in the steady-state measurement, the timed variation in mixture condition was investigated in both the intake manifold and scavenging passage. Fig. 8 shows time lag measured at both ducts according to definitions made by the notations at respective engine speeds. The measurements of course were obtained using the same probes at S and T indicated in the Fig.5. The results indicate that except for operations with partial throttle opening at high engine speeds, the variations of mixture condition at both ducts fairly well compared with each other. The discrepancy at the partial throttle opening is considered to be contributed by the random gas motion with in the crankcase.

In order to obtain further insight into the fuel layer behaviors, the engine was operated by changing the throttle opening from 1/4 to 4/4 (full) at different engine speeds. Fig.9 shows a example of the experimental results. The throttle opening is represented by the pressure-time history plotted on the same plane where the film thickness variations are shown by h1 and h5 (subscription corresponds to the circumferential locations indicated in the figure) measured at different locations, a, b and c. When the engine speed was low such as 500rpm, the fuel layer thickness was high and varied much with both circumferential and longitudinal direction. When the throttle valve opened suddenly, the layer thickness measured by circumferential position 5 at b became thicker, i.e., dhm/dt>0, and thinner and followed by rather constant thickness. According to Eq.(11), the fuel at the intake-port was the opposite of this trend, that is, upon the sudden throttle opening, the mixture was, sequentially, compared with the carburetor fuel/air ratio, leaner and richer and steady. And same tendency was appeared with averaged liquid-fuel thickness hm as shown in the Fig.10. Such fuel behavior will obviously affect the engine power output as well as emission. The same tendency was also observed with four-stroke spark ignition engine as shown in Fig.11. Namely, The rapid movement of a large bulk of accumulated fuel(about a second to travel a distance of 5cm) in the direction of flow during the transient period. Again, such change in dhm/dt will clearly affect the in cylinder fuel/air ratio history during the period.

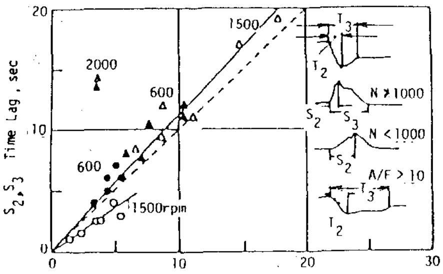

Fig.8 Mutual relation between behavior of fuel liquid-film thickness in inlet pipe and that in scavenging passage

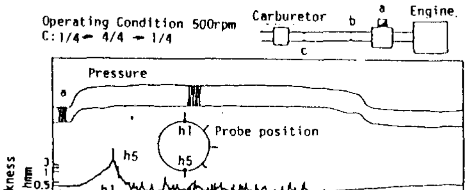

Fig.9 Behavior of fuel liquid-film thickness during transitional operation

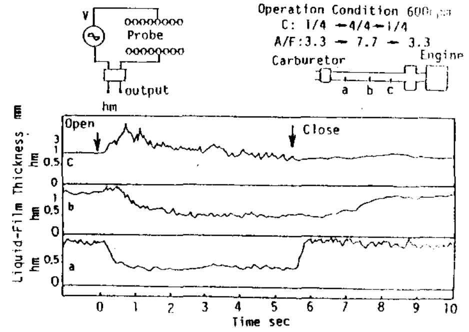

Fig.10 Behavior of mean fuel liquid-film thickness during transitional operation

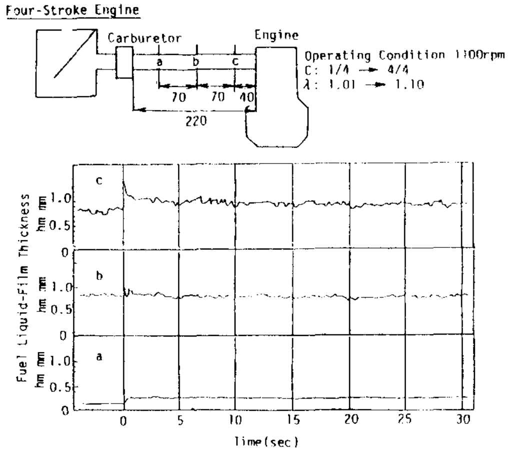

Fig.11 Behavior of mean fuel liquid-film thickness during transitional operation (four stroke engine)

However, with two and four stroke engine, the liquid layer thickness at high speeds exhibited that the variation is relatively small but there was a sudden decrease of thickness followed by rapid recovery to steady state layer thickness.

In addition, the cylinder-cylinder variation was studied using a four-cylinder four-stroke engine. Fig.12 shows the design of the intake manifold and the location of the probe. Fig.13 shows the effects of engine speeds and throttle openings on the liquid layer thickness. The variation was strongly affected by both throttle opening and engine speed. Among the findings from this measurement are that the higher the engine speed the smaller the variation and that the throttle opening effects, which warrants further study.

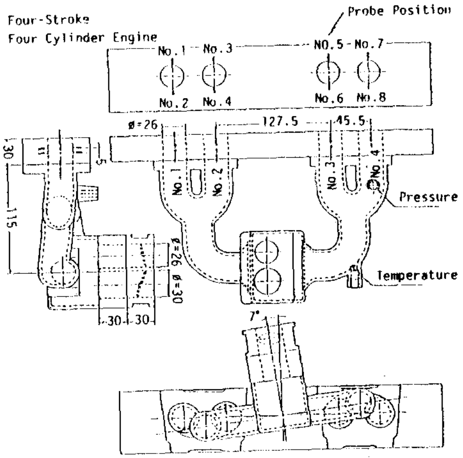

Fig.12 Intake manifold configuration of four cylinder engine

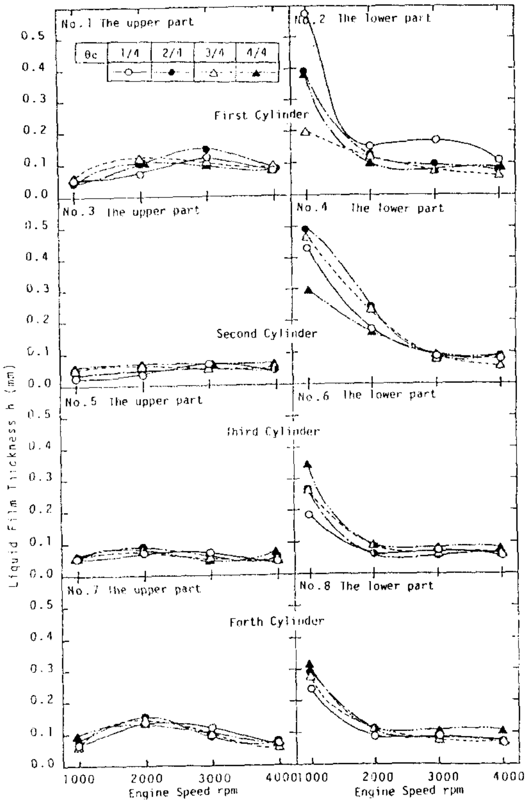

Fig.13 Effect of engine speed on the fuel liquid film thickness with four cylinder engine

4.Conclusion

A electrode-type probe was used to investigate the variations in amount of liquid fuel layer in the intake manifold of single cylinder two and four stroke engine and multi-cylinder four stroke engine. After the probe was tested to find its valuable performances, measurements of fuel layer films in the intake manifold were conducted in both steady and transient state operation for an engine operated neat methanol. The results are followings:

(1) The probe design concept was investigated to find its usefulness for investigation of instantaneous behaviors of the liquid fuel layer in the engine intake manifold.

(2) The probe exhibited consistent measurements for layer thickness under one millimeter and some nonlinear performance for thicker layers.

(3) The temperature of the liquid layer affected the output from the probe so that compensation was need in order to achieve correct measurements.

(4) The flow velocity of fuel layer in the intake manifold was measured. It was about 1/100 of the air velocity in the duct.

(5) In the steady state operation, the thickness of fuel layer varied both in the circumferential and longitudinal direction of the intake manifold. The lower the circumferential angle with respect to the ground level at a fixed longitudinal location, the thicker the layer. The layer in the manifold was thicker near the carburetor and thinner near the engine.

(6) In a transient operation, there were some amount of fuel temporarily accumulated within the intake manifold which was measured by the fuel film thickness history indicating the corresponding change in the in-cylinder fuel/air ratio. The variation was greatly affected by the engine speed, fuel/air ratio and throttle valve opening.

(7) The above tendency is common with four-stroke engine. And the liquid layer thickness significantly varied at multi-cylinder engine, and even so when the engine speed and throttle opening were changed.

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