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Piezo-fluidic Gaseous Fuel MPI System for Natural Gas Fuelled IC Engines*

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A fast response piezo-fluidic gaseous fuel injector system designed for natural gas fuelled internal combustion (IC) engines is described in this paper. The system consists mainly of no moving part fluidic gas injector and piezo controlling interface. It can be arranged as a multi-point injection (MPI) system for IC engine fuel control. Both steady state and dynamic characteristics were investigated on a laboratory test rig. A comprehensive jet attachment and switching simulation model was also developed and reported. The agreement between predicted and experimental results is shown to be good.

Key Words: Fluidics, Piezo, Internal Combustion Engine, Natural Gas, Alternative Fuels, Fuel Injection

1. Introduction

Natural gas consists primarily of methane. As an alternative fuel, natural gas can produce significantly less harmful emissions. However, to meet the increasingly stringent vehicle emission legislation, the fuel metering system of natural gas engines must be capable of accurate control which requires a fast response gaseous fuel injection system and sophisticated engine management system. It is particularly true when stoichiometric air/fuel ratio combustion strategy incorporated with a three-way catalyst exhaust system is employed(1,2).

As an alternative internal combustion engine fuel, natural gas has much lower energy density and poorer lubrication than conventional liquid fuels. Therefore, for conventional solenoid type gas injectors, not only will the components be larger, with higher pintle lift than liquid fuel injectors to achieve a larger orifice to handle the large gas volume flow rate, but they also have to work in an environment with poor lubrication.

It is to meet these difficulties that the development of an alternative fluidic gaseous fuel injection system based on the use of mono-stable fluidic devices has been undertaken. The fluidic gas injector has the potential of handling the large gas volume flow rates required by natural gas engines and providing an accurate and fast response gas control. It can be arranged as a multi-point injection system. In this paper, both steady state and dynamic performances of the piezo-fluidic gas injector system are reported. A theoretical model developed for analysing the mechanism of fluidic injector dynamic switching is also introduced.

Notation

- \( a \): geometry constant
- \( J \): momentum flux of jet flow
- \( J_1 \): momentum flux of output jet flow
- \( J_2 \): momentum flux of returned jet flow
- \( J_{\text{main}} \): momentum flux of jet flow after being peeled
- \( J_{\text{peel}} \): momentum flux of jet flow peeled by splitter
- \( m_s \): gas mass in the attachment bubble
- \( m_c \): gas mass in the control port
- \( N_k \): characteristic number
- \( p \): pressure
- \( q \): volume flow rate
$R$: radius vector
$t$: time
$\dot{w}_c$: mass flow rate of control flow
$\dot{w}_{en}: mass flow rate of one side jet flow entrainment$
$\dot{w}_{re}: mass flow rate of returned jet flow$
$s$: jet flow axial distance from input nozzle
$s_0$: $s$ of the hypothetical origin of jet flow
$u$: velocity
$y$: distance perpendicular to the axis of jet flow
$y_{sp}$: splitter edge distance to the axis of jet flow
$\delta$: angle made by jet flow axis with radius vector
$\delta_m$: maximum possible value of $\delta$ (67°)
$\theta$: angle made by jet flow axis extended with attachment wall
$\rho$: density
$\alpha$: jet flow spreading parameter

2. Piezo-Fluidic Injection System

One of the important features of the fluidic device is the amplification characteristic (ratio of the operating pressure to the control pressure). It offers the possibility of using a very low energy consumption, and very fast response piezo interface to control the fluidic device to inject gaseous fuel into the engine inlet manifold.

2.1 Mono-stable fluidic injector

The fluidic device being used in the piezo-fluidic gaseous fuel injection system is a mono-stable fluidic amplification device based on the jet flow wall re-attachment Coanda effect. The biased geometric design is achieved by differing the wall angle on each side of the jet flow as illustrated in Fig. 1, i.e. $\alpha > \beta$. The wall with angle $\alpha$ is called stable side wall, while the one with $\beta$ is unstable side wall. It, therefore, has two different control ports, namely the positive control port and the vacuum control port. These are located on each side of the input jet nozzle. The output flow channel connecting with the positive control port is called the stable side output. The one connecting with the vacuum control port is called the unstable side output.

A vent is designed to open the jet flow channel to ambient on each wall, named as stable side vent and unstable side vent. These are used to limit the wall length which affects the jet flow switching response and to maintain the pressure drop across the jet nozzle by releasing the extra flow when the output is restricted.

If the pressure in the two control ports is atmospheric, and the pressure of the gas stream entering the input nozzle is higher, the jet flow issuing from the input nozzle will attach to the stable side output as indicated in the figure. This is because unbalanced jet flow entrainments at the stable and unstable sides due to the biased geometry design causes the unbalanced pressure at each side of the jet flow immediately after the jet flow being issued. The unstable side has wider opening to allow more fluid entrain the jet than that of stable side and results in high pressure at the unstable side than that at the stable side.

When a gas flow at a sufficiently high pressure is initiated in the positive control port through an electro-fluidic interface, the jet will switch to the unstable side output and remain there. When this control flow is removed, the jet will shift back to re-attach to the stable side output. This switching control method is called the positive control method.

Alternatively, the electro-fluidic interface can be used to close off the vacuum control port. Because of the jet flow entrainment, a vacuum is created in the vacuum control port. This too, will cause the jet flow switching to the unstable side output from the stable side output till the vacuum control port is re-opened to atmospheric. This switching method is called the vacuum control method.

It can be seen that the fluidic device can control the jet between the two outputs by controlling the control flow through an electro interface.

2.2 Piezo interface

The total switching response of the fluidic injector is consisted of the response speeds of the electro interface and the jet switching inside the device. To achieve an overall fast control response speed, the development of a fast electro interface is essential.

Piezo-electrical material can produce an almost instantaneous deformation when an electric field is applied. This physical effect has been known for a long time, but is rarely used for engine fuel injection.
The major restriction is that the deformation is much too small and the required driving voltage is much too high.

Two potential methods can be used to increase the deformation. One is to stack the multi-layer piezo materials together to generate an accumulated deformation. This requires a high strength electric field and incurs high manufacture costs. The other solution is to bond two-layer-electrical material together by polarising in the opposite direction to generate a large bending deformation. This principle is well known in bimetallic strips. The piezo bending strip based on this principle can generate a relatively large deformation at a much lower driving voltage with a low manufacturing cost, but exerts a little force. Also, the strip bending response time is proportional to its geometric size and much slower than the multi-layer piezo stack. Therefore, if the piezo bending strip is used as a fast responding gas flow switching valve, it must be made small, work with a relatively low operating pressure and control a very small gas flow. Hence, it cannot be used as the gas injector directly.

However, since the fluidic gas injector can control a large gas flow through a relative small control flow due to its control flow amplification natural, the small gas flow controlled by the piezo bending strip can be then used as the control flow of the fluidic device. Figure 2 shows a schematic set-up of the piezo-fluidic combined unit where the piezo bending strip is used as the controlling interface and fitted on the vacuum control port.

2.3 Piezo-fluidic gas injector system

Figure 3 shows the schematic illusion of the piezo-fluidic gas injector system. The piezo-fluidic gas injector is arranged to be “sub-merged” in an encapsulated gas reservoir. A conventional three-stage gas pressure regulator is used to reduce the gas pressure from 20 MPa compressed natural gas storage pressure to atmospheric. It is by connecting the output from the regulator to the reservoir that the “submerged” pressure of atmospheric can be maintained.

Different from the unstable side vent which is connected to the reservoir to maintain an atmospheric pressure, the stable side vent is connected to the positive control port directly. This creates a pressure slightly above the atmospheric in the positive control port when the jet flow attaches to the stable side. This, in itself, will not be high enough to cause the jet flow to be switched, but improves the jet flow switching response from stable side output to unstable when vacuum control port is closed.

A low-pressure gas pump is connected to the gas reservoir and supplies a gas flow to the input nozzle of the fluidic device. When the piezo interface closes off the vacuum control port, the jet flow will attach to the unstable side output and be returned to the reservoir. In this state, the system is switched off. When the piezo interface is energised, the vacuum control port is opened. The control flow supplied to the piezo interface then flows into the vacuum control port. The jet flow will switch to the stable side output and so provide fuel to the engine inlet manifold. In this state, the system is switched on.

A diaphragm type isolating nozzle is used to connect the stable side output of the fluidic injector to the engine inlet manifold. The nozzle only contains a free moving diaphragm as illustrated in Fig. 4.
bottom of the diaphragm, around the outlet, is the gas pressure. At the top side, a reference orifice is opened to the atmosphere. Therefore, when the jet flow is switched to the stable side output, the gas pressure becomes higher than atmospheric. The diaphragm opens and the gas is injected into the engine manifold. When the jet flow is switched off, the gas pressure drops to atmospheric. The diaphragm closes and isolates the stable side output from engine inlet manifold. The vacuum in the manifold, then, cannot draw any gas from the fluidic injector.

3. System Development

The large mass flow rate of the gas and the dynamic responses of the piezo-fluidic injector system are essential requirements and central targets of the development. These were investigated by both theoretical and experimental studies in this research.

3.1 Gas flow rate of the system

The gas flow handling capability of the piezo-fluidic gas injector system was estimated by a steady state flow test operating on air. Figure 5 shows a schematic set-up of the laboratory test rig. The piezo interface was energised during the test. The jet attached to the stable output and was routed to a gas flow meter through the isolating nozzle.

Figure 6 shows the measured steady state flow rate under varying supply pressure of the system within the interested range. With supply pressure lower than 25 kPa, the flow rate is much too low to be used for gaseous fuel injection purpose and to be measured accurately with current test rig though the system is still switchable. While with pressure much higher than 150 kPa, it is not practically applicable neither since a high load will have to be applied on the pump. It can be seen that the flow rate of the system is linearly proportional to the supply pressure. At 150 kPa, the gas flow rate is about 100 SLPM (standard litre per minute). This flow rate is equivalent to the fuel requirement of a 2-litre natural gas engine.

3.2 Theoretical study

The gas control function of the fluidic gas injector is achieved by the natural of jet attachment. There is no moving part inside the injector. Therefore, the jet flow switching performance depends seriously on the geometry design of the injector. Traditionally, its improvement is somewhat uncertain since the fluidic device geometry design is largely based on “try and error” approach. In order to analyse the jet switching mechanism, simulate the switching response, identify some critical parameters responsible for the speed of switching and improve the fluidic injector design, a comprehensive jet dynamic switching dynamic simulation model has been developed during the research.

The model is based on the following assumptions with details shown in Fig. 7:

- The fluidic device is assumed to be two-dimensional.
- The jet flow is assumed to be a free jet having the Gortler's velocity profile:

\[
    u = \left[\frac{3\sigma_{g}}{4\rho(s+s_{0})}\right]^{1/2} \sech\left(\frac{\sigma_{g}y}{s+s_{0}}\right) \tag{1}
\]

- The momentum flux peeled off by the splitter is assumed to be determined by the relative position of the assumed velocity profile with the splitter.

![Fig. 5 A schematic set-up of the piezo-fluidic gaseous fuel injector system](image1)

![Fig. 6 Steady state gas flow rate of the piezo-fluidic](image2)

![Fig. 7 Geometric relations of the jet attachment](image3)
\[ J_{\text{reel}} = \int_{-\infty}^{+\infty} \rho u^2 dy \quad \text{and} \quad J_{\text{main}} = \int_{-\infty}^{+\infty} \rho u^2 dy \] (2a, b)

- The momentum is assumed to be conserved in the control volume surrounding the attachment point.
- The average angle of the momentum flux of the jet is assumed essentially to be the same as the angle made by the centreline extended with the attachment wall.

\[ J_{\text{main}} \cos \theta = J_1 - J_2 \] (3)

- The attachment line of the jet is assumed to be a Sinusoid function \( R = a \sin \left(\frac{\pi}{2} \frac{\rho}{\rho_m}\right) \) (4)

- The jet deflection angle due to the control flow is assumed as \( \beta \).

To maintain a stable attachment of the jet flow, there is an equilibrium state of mass flow rate across the attachment bubble.

\[ w_{\text{ent}} = w_{\text{in}} \] (5)

If a control flow is applied on the positive control port, the control flow is introduced into the attachment bubble, and a new mass flow equilibrium will be established

\[ \frac{dm_s}{dt} + w_{\text{ent}} + w_c = w_{\text{ent}} \] (6)

Rearrange this equation, the dynamic response time of bubble mass change due to the addition of the control flow can be obtained

\[ dt = \frac{w_{\text{ent}}}{w_{\text{ent}} + w_{\text{in}} - w_c} \] (7)

By using the quasi-steady assumption, the dynamic response time of the attachment bubble can then be obtained.

Between the jet flow and the controlling interface, it is inevitable that there is a nominal length of the control port. The control pressure issued from controlling interface, therefore, has to travel through it until reaches the attachment bubble to switch the jet flow. It is clear that there is a response delay due to the existence of the 'dead volume' of the control port. This pressure propagation was analysed by the method of characteristics by changing the partial derivative of the momentum and the continuity equations to total derivatives under certain conditions.

\[ N_e \frac{dy'}{dt'} \pm \frac{dy''}{dt''} + q' = 0 \] (8a)

\[ \frac{dx'}{dt'} = \pm 1 \] (8b)

where prime denotes normalising.

Since the existence of the control port 'dead volume', it will take some time to build up the pressure in the control port after the control flow is available in the electro interface. This delay can be obtained as

\[ \frac{dm_c}{dt} = w_c \] (9)

By using the quasi-steady method, the dynamic response time to rise the control port pressure can also be obtained.

3.3 Experimental study

Figure 8 shows the test rig for the dynamic response measurement of the fluidic injector and the entire injector system. Four pressure transducers manufactured by "Entran Sensors" were employed to monitor responses of the piezo interface (by transducer 1), the two outlets of the fluidic injector (by transducer 2 and 3), and the outlet form of the isolating nozzle (by transducer 4) respect to driving signal. The supply pressure from the second stage of the three-stage pressure regulator is 550 kPa which is required to control the fluidic injector. The outlet pressure from the gas pump supply to the fluidic gas injector is 150 kPa.

A vacuum chamber equipped with a relieving valve and driven by a vacuum pump was used in the test rig to simulate the engine inlet manifold. Different manifold conditions were obtained by adjusting the relieving valve.

Figures 9 and 10 show the switching-on and off responses of the piezo interface with respect to the driving signal monitored by pressure transducer (1) from 500 consecutive cycles. Each dot in the figure represents a response in millisecond (ms) of a switching cycle, and the test data were collected at 45 kHz frequency. The average response times among these 500 cycles are 0.31 ms and 0.72 ms for switching-on (opening the vacuum control port and supply control flow to the control port) and off (closing the vacuum control port, the control flow is vented back into the gas reservoir), respectively.

Figure 11 shows the response pressure traces of control port (measured by pressure transducer 1) and the two outlets (measured by pressure transducers 2
and 3) in comparison with the calculated results obtained from the simulation model developed in Section 3.2. The good agreements are achieved by adjusting the jet flow spreading parameter \( \sigma \). The value used in the model is 35.5.

It is worth noting that this value is much higher than the value of 7.5 chosen for the Golertler's free jet flow assumption. The possible reason may due to the 2-dimensional assumption\(^9\) when Golertler's equation was initially introduced. In practice, the fluidic injector is 3-dimensional where the aspect ratio (ratio of the device depth to width of the jet nozzle) limits the area available for jet flow entrainment, therefore reduces the quantity of entrained fluid which is directly responsible to jet flow switching responses. The jet flow spreading parameter \( \sigma \) is inversely proportional to the jet flow entrainment, therefore, it should be increased when the aspect ratio decreases. Further research is needed to investigate such relationship.

In the current calculation, the aspect ratio of the fluidic gas injector is 2, much different from the 2-dimensional assumption where aspect ratio is infinite. In spite of lacking sufficient model to analysis the relationship between the jet flow spreading parameter \( \sigma \) and device aspect ratio, it was found that a good correlation between tested results and calculation can be obtained by increasing \( \sigma \) to a value of 35.5. Smaller value gave faster response prediction while larger value predicted slower than experimental results.

Figure 12 shows the pressure traces from the pressure transducer (2) and (4) with atmospheric pressure in the vacuum chamber.

Figures 13 and 14 show the switching response results of the fluidic injector measured by the pressure transducer (2) from 500 consecutive cycles. Again, each dot in the figure represents a response in millisecond (ms) of a switching cycle, and the test data were collected at 45 kHz frequency. The average response times of switching-on and off with respect to
Fig. 13 Switching-on response of fluidic injector

Fig. 14 Switching-off response of fluidic injector

Fig. 15 Switching responses of the system under varying outlet pressure

driving signal of these 500 cycles are 1.15 ms and 0.98 ms, respectively. If the response delays of the piezo interface (0.31 ms and 0.72 ms for switching-on and off, respectively) are deducted from these results, the response delays of the fluidic injector itself are merely 0.84 ms and 0.26 ms for switching-on and off, respectively.

Figure 15 shows the average entire system switching responses under different vacuum chamber pressure (absolute pressure) measured by pressure transducer (4) with respect to driving signal. It can be seen, when the chamber pressure drops to vacuum both switching-on and off responses increase slightly. This is because when the pressure in the chamber drops to vacuum, the pressure of the gas surrounding the outlet of the isolating nozzle has to take some time to build up to overcome the force acting on the diaphragm due to the suction of the vacuum. However, since the size of the outlet nozzle is relatively small, the suction force is limited. Therefore, as vacuum increases, the system switching response delays do not increase seriously.

Conclusions

1. A gaseous fuel injector system based on the fluidic and piezo technologies was developed and investigated. The system consists mainly of no moving part fluidic gas injector and fast response piezo interface.

2. The system is able to handle the large gas flow rate required by natural gas engines. A steady state flow rate of 100 SLPM has been achieved by the current system. Higher flow rate can be achieved by stacking the fluidic injectors.

3. It was demonstrated that the system is able to achieve the fast responses required by natural gas engines. The typical switching-on and off response times of the entire system are 1.65 ms and 1.85 ms under vacuum pressure condition inside the engine inlet manifold, respectively.

4. A simulation model for analysing the jet flow switching mechanism has been developed. The model is based on 2-dimension assumptions. It can predict the jet flow switching performance by adjusting the jet spreading factor.

5. Good agreement between simulated and measured jet flow switching results has been obtained by 'tuning' the jet spreading parameter to 35.5. Smaller value gave faster response prediction while larger value predicted slower than experimental results. Further theoretical study is needed on 3-dimensional scale to investigate the effect of aspect ratio on jet flow spreading parameter.

References


