Application of Micro-Fuel Injection System by Thermal Bubble Inkjet Technology

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Abstract

This study uses the thermal bubble inkjet technology on the design of digital controlled micro-fuel injector. A micro-pulsation fuel injection system is composite by the arrays of the thermal bubble micro-fuel injectors, which could be operating in high ejection frequency and with fine fuel droplets into the intake pipe on engines by accurate control mode. The use of thermal bubble micro-fuel injector is able to reduce the air pollutions and the costs of product. Each single digital signal on the thermal bubble micro-fuel injector controls the individual atomization quality of fuel droplet. The advantages of digital control on fuel droplet atomization are active control of fuel ejection volume and optimization of combustion efficiency. This study redesigns the sizes and locations of heaters within the thermal bubble micro-fuel injector. The atomized fuel droplet volumes are controlled within 100 pl. ~ 500 pl. Up to now, the micro-pulsation fuel injection engine system runs smoothly to overcome disadvantageous factors compared to the inkjet printer, such as vibration, high temperature, and different working fluid.

Introduction

The tendency of modern automobile engine system results in increasing efficiency and decreasing fuel consumption. The fuel injection system is the core technology of the internal combustion engine. The working principle of injection is to provide fuel to the combustion chamber. The fuel will be atomized into small droplets then evaporating and mix with the surrounded hot air.

There are two types of inkjet printing technologies, i.e. the continuous-type and the drop-on-demand type. For the drop-on-demand device used electrical signals to control and actuate the ejection of each individual atomized fuel droplet. Typically, a drop-on-demand inkjet head consists of a fluid chamber with an exit called a nozzle from where droplets are to be generated under an electric current pulse to generate a thermal bubble with superheating phenomenon at a very short of time period. The instantly high pressure within thermal bubble ejects a column of liquid through a nozzle. The liquid ejected out the nozzle by the bubble growth further breaks into a sequence of droplets through the interaction between surface tension and inertial force. Based on the experience with thermal bubble drop-on-demand inkjet devices, which are capable of ejecting microscopic fluid drops of precisely uniform size and velocity, the concept of development was that if fuel is used instead of ink and some parameters are adjusted, a combustible fuel-air mixture will result at some distance from the printhead, which feeds a freely burning flame (Ederer et al, 1997). This study uses the thermal bubble inkjet technology on the design of digital controlled micro-fuel injector. A micro-pulsation fuel injection system is composite by the arrays of the thermal bubble micro-fuel injectors, which could be operating in high ejection frequency and with fine fuel droplets into the intake pipe on engines by accurate control mode. Tseng et al. (1996) revealed a promising method of using a droplet-on-demand thermal bubble jet to eject uniform liquid droplets for mixing enhancement, airflow control, and reduction of fuel evaporation time. The aforementioned micro-injector is used for the generation of commercial diesel fuel droplets for the first time. Ederer et al. (1997) developed a piezoelectric driven micro-pump for fuel dosing in automobile heaters with 5 kW peak power output. The ejection velocity of the droplets varied in the range of 4 to 7 m/s and droplet ejection frequency controls the ejection mass flow rate. Tseng et al. (1998) developed a monolithic silicon micro-injector by using MEMS technologies and successfully demonstrated the ability of single droplet ejection with water and ink as working fluids.

The use of thermal bubble micro-fuel injector is able to reduce the air pollutions and the costs of product. Each single digital signal on the thermal bubble micro-fuel injector controls the individual atomization quality of fuel droplet. The advantages of digital control on fuel droplet atomization are active control of fuel ejection volume and optimization of combustion efficiency. A combination of MEMS and emissions controlled power-train technologies has accomplished the pioneer of the digital injection system on the gasoline engine in this study. This paper introduced bench test, fuel spray characteristic, flow rate raise, and engine test, according to priority of development. This study redesigns the sizes and locations of heaters within the thermal bubble micro-fuel injector. The atomized fuel droplet volumes are controlled within 100 pl. ~ 500 pl. Up to now, the micro-pulsation fuel injection engine run smoothly to overcome disadvantageous factors compared to the inkjet printer, such as vibration, high temperature, and different fluid. An under-pressure stabilizer is also used in this technology to contribute negative pressure preservation and to achieve fuel circulation.

Fabrication and Packaging of Micro-Fuel Injector

The micro-fuel injector was made on a N-type <100> silicon wafer and growing the silicon dioxide as a thermal barrier layer by thermal oxidation method. Then the heater metal and conduction line metal was deposited by sputter, respectively, and was defined by photolithography. After the deposition and definition of heater and conduction line, the passivation layers (silicon nitride and silicon carbide) were deposited by PECVD. Another of the passivation layer of tantalum (Ta) was deposited by sputter and defined by photolithography. Finally, the contact holes were etched by RIE, and the contact pad metal TiW/Au was also be deposited and defined. The micro fluid channel was defined by thick photoresist and the nozzle plate was fabricated by electroforming. Due to low surface tension of the fuel property, this study applies the hydrophobic treatment on nozzle plate to avoiding the puddling effects on the nozzle plate surface. The contact angle is improved from less than 10 to 49.5 degrees. In the fuel injector assembling process, the nozzle plate was bonded with the chip of fuel injector by accurate alignment and bonded with the bonding pad of chip and the leads of TAB (Tape Automated Bonding) tape. A unit of the fabricated micro-fuel injector is shown in Fig. 2. Inside the chip structure of micro-fuel injector, the geometry of firing chamber is 300, 120, and 60 μm in length, width and fluid channel thickness, respectively. The heater size within the chip is 105×105 μm^2. The diameter of nozzle is 80 μm and thickness of the nozzle plate is 50 μm.

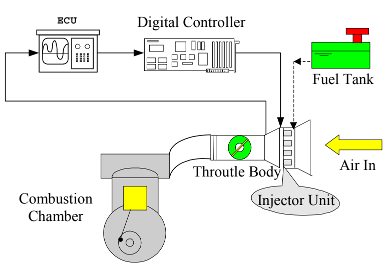

Figure 1. micro-fuel injector system

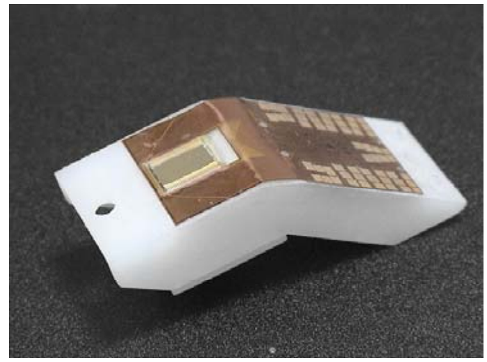

Figure 2. Unit of thermal bubble micro-fuel injector

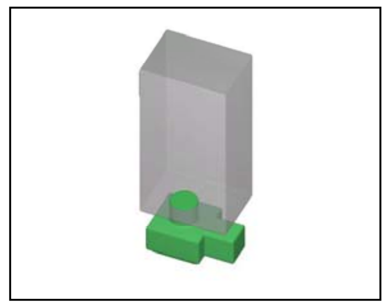

Figure 3. Computational domain and fluid channel solid model

Simulation on the Ejection Performance

The physical properties such as surface tension and viscosity of the working fluid are important factors that affect the droplet ejection behavior. It is necessary to simulate on the ejection performance of the micro-fuel injector with working fluid of gasoline. Theoretically, the ejection of droplet phenomenon is governed by Navier-Stokes equations with appropriate boundary conditions describing fluid interface motions. Volume of fluid (VOF) method resolves the transient motion of the gas and liquid phase using the Navier-Stokes equations, and accounts for the topology changes of the interface induced by the relative motion between the gas and liquid phase. Therefore, the complex fluid dynamic process during drop ejection is simulated with CFD package FLOW-3D that employs the VOF method to track effectively the transient fluid interface deformations and disruptions. To provide the physical insights for establishing general design rules in device development, the primary attention here is paid to variables of immediate practical importance such as the volume and speed, as well as shape evolution of ejected droplets.

The VOF method utilizes a finite difference to represent the free surfaces and interfaces that are arbitrarily oriented with respect to the computational grids. There exists a free surface interface while the value of F is between zero and unity in a cell. The time dependence of F is governed by

$$\frac{\partial F}{\partial t} + F\nabla \bullet \vec{V} = 0 \qquad (1)$$

The mass and momentum equations can be considered to be conservation and homogeneous, which can be expressed as

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \vec{V}) = S_c \qquad (2)$$

$$\frac{\partial \vec{V}}{\partial t} + (\rho \vec{V} \bullet \nabla)\vec{V} = -\nabla P + \nabla \bullet \tau_{ij} + S_m \qquad (3)$$

where ρ is the density, t is the time, P is the pressure, $\vec{V}$ is the velocity vector, F is the volume fraction function, τ_{ij} is the viscous stress tensor, and S_c, S_m are the source terms.

In this study, physical properties of gasoline are 0.756 g/cm^3, 0.7 cps, and 20.5 dyne/cm for density, viscosity, and surface tension, respectively, while 1.0 g/cm^3, 1.0 cps, and 73 dyne/cm for the water liquid. The micro-fluid channel geometry model and computational domain setup in this study is shown in Fig. 3. Figure 4 compares the numerical results of water and gasoline droplet ejected at different instants of 10, 20, 30, 40, and 200 µs. It reveals that the ejection speed of gasoline is larger than that of water because of the density of gasoline of smaller than water liquid. The difference of the ejection volume flow rate for water and fuel flying through the top section of computational domain is shown in Fig. 5. The result shows that the volume flow rate of gasoline is about the same with the water for the same driving force.

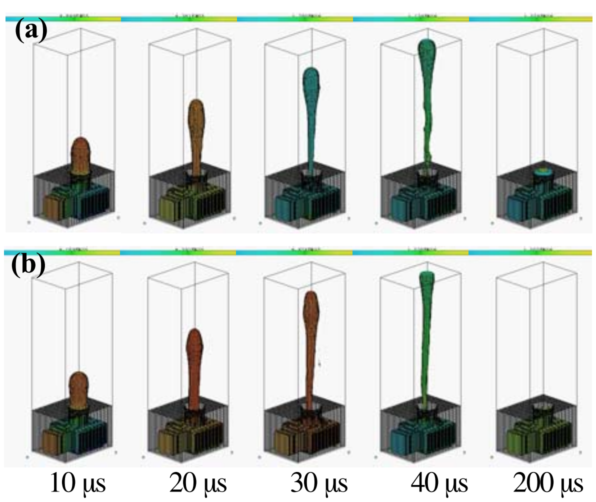

Figure 4. Computational results of (a) water and (b) fuel droplet ejection at 10, 20, 30, 40, and 200 µs

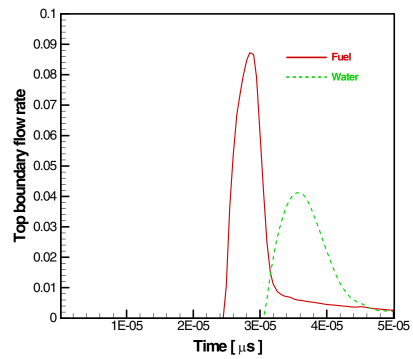

Figure 5. Volume flow rate of water and fuel through the top section of computational domain

Thermal Bubble Micro-Fuel Injector Testing

During the ejection testing, the ejected flow rate of the fuel injector is measured by the flow meter. In this study, the flow meter was located between the fuel tank and fuel injector. Figure 6 shows the ejection instant state of the fuel injector unit and microcosmic view on one-single nozzle ejection status. When applying the inkjet printing technology to fuel injection system, the ejection is actuated by a digital control system and four or eight of micro fuel injector units were arranged surrounded the throttle body and the fuel droplet distributions could be controllable. Figure 7 shows the ejection testing state on the injection system and reveals the good performance of atomization into small fuel droplets.

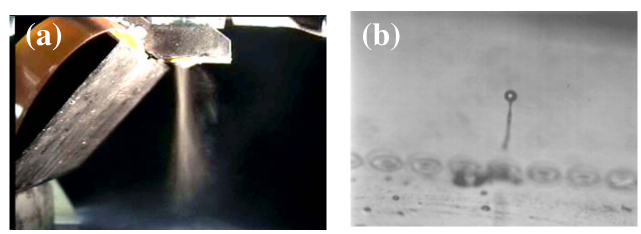

Figure 6. (a) Ejection state of the unit, and (b) One-single nozzle ejection state

Figure 7. Ejection test on the throttle body

In Fig. 8, the experimental result shows that ejected fuel droplet volume is increased with increasing the applied electrical power on the fuel injector. The atomized fuel droplet volumes are controlled within 100 pl. ~ 500 pl. as the applied electrical power increased. Comparing with the commercial inkjet print head model type of HP51629, the fuel ejection flow rate of this study is four times and the volume of fuel droplet is five times of HP51629. Figure 9 shows that the ejection rate, defined as the ratio of ejected droplet volume by the firing chamber size, is increasing with the pulse width increasing with the same voltage and firing frequency. It is important to monitor temperature on nozzle plate surface during firing operation for thermal heat generated by thermal bubble fuel injector pumping out the working fluid through the nozzles. As shown in Fig. 10, temperature on the surface of nozzle plate is about 70°C with the heating pulse width of 4 μSec. While temperatures on nozzle plate surface are going down to around 55°C for the heating pulse width increase to 7 μSec. Therefore, with increasing the ejected flow rate of fuel droplet taking away heat generated by the heater of thermal bubble generator, temperature on the nozzle plate surface will decrease.

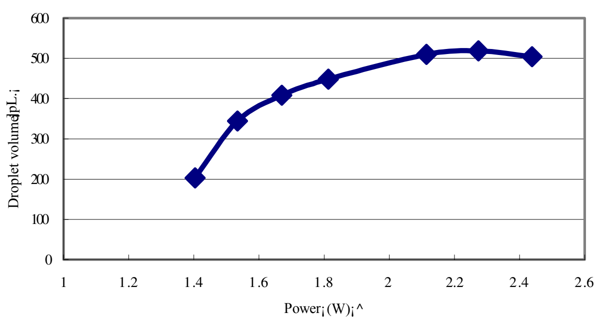

Figure 8. Relation between ejected droplet volume and power

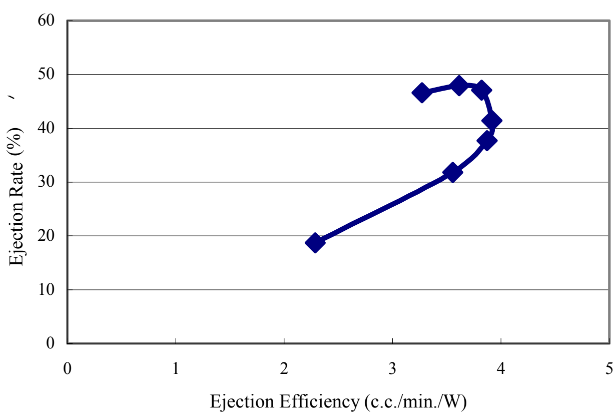

Figure 9. Ejection rate vs. Ejection efficiency

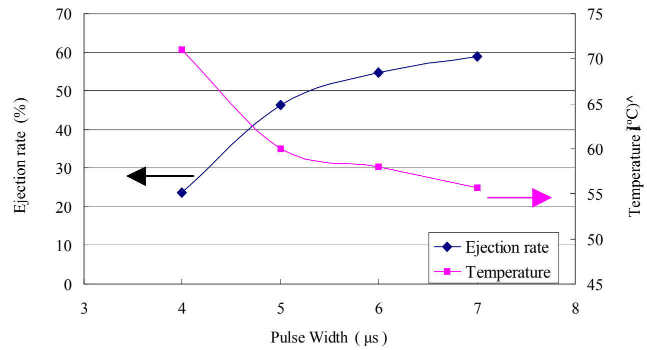

Figure 10. Ejection rate and temperature vs. heating pulse width

Conclusion

Fuel injection system, in tendency of increasing efficiency and decreasing fuel consumption, is the core technology of the automobile engine. The thermal bubble micro-fuel injector developed in this study is able to reduce the air pollutions and the costs of product with a large impact and market potential in this field. This study redesigns the sizes and locations of heaters within the thermal bubble micro-fuel injector. The atomized fuel droplet volumes are controlled within 100 pl. ~ 500 pl. and the ejection efficiency is almost about 60 % to reduce heat-accumulated effect. In this study, it reveals that the micro-pulsation fuel injection engine system runs smoothly. It could be applied to the 125 c.c. engine of motorcycle operating on different loading and speed ranges. Simulation on the ejection performance with working fluid of gasoline also is shown in this study. It shows that the ejection speed of gasoline is larger than that of water and volume flow rate of gasoline is about the same with the water.

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Biographies

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