ABSTRACT The transient static pressure of the air located along the centerline of the spray from a DISI pressure swirl injector was measured for different injection pressures, fuel temperatures and injection durations. The drop in the pressure at the centerline was found to be mainly attributed to the swirling liquid and enhanced with the swirling velocity manifested by the injection pressure. With increasing the injection duration, the pressure was found to be continuously dropped, although the measured swirling momentum of the liquid reaches an asymptotic value and remains constant until the needle starts to close. This implies that the pressure at the centerline of a transient spray does not reach its asymptotic value which corresponds to the case of a continuously injected spray. At higher fuel temperature, the air pressure at the centerline increases and can reach a value more than atmospheric pressure due to the sudden evaporation of the fuel after being released underneath the needle. This high air pressure pushes the main stream of the spray to the radial direction resulting in a larger hollow cone shape along the spray streamlines was formed. This shape assists in equalizing the pressure between the center line to have a robust spray that has limited variation with the operating condition and can be used in spray guided gasoline direct injection system. By cutting the nozzle to have a tapered nozzle with an angle less than the flow angle the swirling motion. The link between the pressure drop across the spray and liquid film profile for different operating conditions was presented using a simple analytical model. The injector was then modified to eliminate the pressure drop at the center line to have a robust spray that has limited variation with the operating condition and can be used in spray guided gasoline direct injection system. By cutting the nozzle to have a tapered nozzle with an angle less than the flow angle the opened hollow cone shape along the spray streamlines was formed. This shape assists in equalizing the pressure between the centerline and outer part of spray envelop. The results showed that there is a potential from tapered nozzle spray to be independent of the operating conditions without much sacrifice of the atomization quality.

Keywords: swirl spray, DISI (direct-injection spark-ignition) engine, static pressure, tapered nozzle, opened hollow cone

1. INTRODUCTION

Direct-injection spark-ignition (DISI) engine has become an alternative of the conventional gasoline engine due to its potential for improving fuel consumption and reducing engine-out emissions. Achieving desirable mixture distribution near the spark plug and extending operation regime of stratified charge combustion are the key factors to keep the potentials of the DISI engine. The spray characteristics from DISI injectors are more critical than from conventional injectors due to the insufficient time for the mixture formation and the need for precise fuel distribution for every injection regime [1]. Therefore, identifying the factors affecting the DISI spray characteristics such as injection pressure, fuel temperature and surrounding air condition is very important for the optimized combustion of DISI engine.

Previous researches showed that the application of swirl spray for the DISI engine fulfills the requirements for wall-guided combustion systems as the result of enhanced atomization through the break-up of conical liquid film which is initially formed inside the nozzle by the strong rotational momentum [2]. However, the combustion concept of DISI engine is transferring from wall-guided system to spray-guided system to achieve lower emissions and improved fuel economy. Spray-guided combustion system strongly requires robust and well-atomized spray. Unfortunately, the spray shape of swirl injector experiences severe changes with various surrounding and operating conditions, and the main reasons of these variations are the alterations of spray momentum and the static pressure inside the spray [2, 3]. Most of previous studies focused on the analysis of spray structure at different operating conditions and alterations of the spray momentum caused by the variation of injection velocity, atomization process and ratio between axial and radial velocity of spray [4–7]. Generally the pressure drop at the centerline of swirling jet and the associated possible central recirculation zone (CRZ) and enhanced turbulence intensities were studied by many authors especially for gas turbine swirler application [8, 9]. However, there have not been many researches about the transient swirling spray and the associated pressure inside the swirl spray during the spray development and after being developed. The static pressure distribution inside the DISI swirl spray was shown using the volume of fluid method (VOF), however, there was no experimental validation for the predicted pressure [10]. There was still no profound investigation on the static pressure distribution inside the spray and its influence on spray development at different operating conditions.

The aim of this research is to experimentally identify the factors affecting the static pressure drop inside the swirl spray and its effect spray development, and then modifying the injector nozzle to minimize the static pressure drop. By modifying the injector nozzle to have a tapered nozzle exit, it redistributes the axial and radial velocity; but importantly, it alleviates the static pressure drop inside the spray by reducing swirling motion of the spray without sacrificing much of the atomization quality. The study about the tapered nozzle has been carried out from some researchers to create the robust spray at the various surrounding conditions [11, 12]. However, their research was limited to
large taper angle more than 45° which is not enough to change the swirling motion of the spray at the exit. Moreover, the spray from large taper angle showed unstable shape at the various surrounding conditions. In this study, a small taper angle less than 45° is chosen for the minimization of swirling motion.

The static pressure inside the spray at different operating conditions is measured using a pressure transducer. To find out the transient development of swirling motion, the dynamic pressure and flow angle of spray, ratio between axial velocity and radial velocity, at the nozzle exit is measured using another pressure transducer having larger diameter and microscopic imaging system. Finally, to find out the relation between the static pressure drop and the spray shape, the macroscopic and microscopic spray images are obtained and a mathematical film divergence model is applied.

The current research provides a motive to further development in swirl injector by investigating the effect of swirling motion on the static pressure drop inside the swirl spray.

2. EXPERIMENTAL SETUP AND CONDITIONS

Schematic diagram of experimental apparatus is shown in Fig. 1. Fuel is pressurized using a high pressure nitrogen tank and the injection pressure is controlled by a pressure regulator. Injection duration and capture timing of spray image is controlled using a delay generator. To measure the static pressure of the air located inside the spray, a pressure transducer equipped with an extended small diameter probe, having diameter of 0.6mm, is inserted along the centerline of the spray close to the nozzle axis as shown in Fig. 1(a). The pressure transducer has a response time of 0.1ms and a maximum test range of 5kPa. The probe was aligned to be at the center of the nozzle hole and spray images were obtained simultaneously during the pressure measurements to make sure that the spray is not disturbed. The spray image analysis confirmed that the extended probe can access up to 0.5mm distance from the nozzle without disturbing the spray shape. If the probe approaches closer than 0.5mm, uncertainty in the measured pressure values increases due to the relatively large volume of the probe compare to the air volume. The transducer probe orifice was vertically facing nozzle axis. Because the air velocity at the centerline is very small and its direction is upward due to the center recirculation zone [10, 13], the pressure measured by the probe becomes mainly a static pressure with a small dynamic part that could be neglected.

Another pressure transducer, having a diameter of 5mm, is installed at 2mm distance from the nozzle along the nozzle axis to obtain the total axial pressure of the liquid spray at the nozzle exit. At this location, the probe cross section is large enough to contain all the spray droplets without being affected by the rebounded droplets which can give a noisy signal. The measured pressure signals are processed using a data acquisition system with acquisition rate of 100kHz.

In order to capture the macroscopic structure of spray development, Mie scattering method is employed using laser sheet beam. A 6W water-cooled Ar-ion laser was used as the light source. Laser sheet beam is formed using a convex lens and a cylindrical lens. A charge coupled device (CCD) camera was used to capture the Mie scattering images with exposure time of 10μs and a CCD array of 1280x1024 pixels. To measure the flow angle at the nozzle exit, a microscopic lens (CFV-3) was mounted in front of CCD camera. A spark light was used as a light source to focus on the very minute surface area of spray at the nozzle exit.

The injection pressure was set as 30, 50 and 70bar and the injection duration was varied from 1.5ms to 4ms. The injector and the fuel temperature is varied from 25°C, 55°C, 85°C representing the cold start condition to 85°C representing the warming-up condition. All the tests were conducted at atmospheric conditions. The taper angle and flow angle are defined as shown in Fig. 2. Three nozzles were tested with different taper angles 50°, 60° and 70°. Experimental conditions are listed in Table 1.

Table 1. Test conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection pressure</td>
<td>30bar, 50bar, 70bar</td>
</tr>
<tr>
<td>Injector temperature</td>
<td>25°C, 55°C, 85°C</td>
</tr>
<tr>
<td>Injection duration</td>
<td>1.5ms, 3ms, 4ms</td>
</tr>
<tr>
<td>Taper angle</td>
<td>50°, 60°, 70°</td>
</tr>
<tr>
<td>Injector</td>
<td>Pressure swirl injector</td>
</tr>
<tr>
<td>Fuel</td>
<td>Commercial gasoline</td>
</tr>
</tbody>
</table>

Fig. 1 Schematic diagram of experimental apparatus

(a) Setup for pressure measurement
(b) Setup for spray imaging
3. RESULTS AND DISCUSSIONS

3.1 Temporal static pressure development

The temporal static pressure inside the spray is plotted in Fig. 3. The static pressure starts to be negative value at approximately 0.6ms after start of injection and it has a peak value at 3.7ms after start of injection. Considering the normal delay time for the formation of swirl motion measured from imaging work is approximately 0.5ms and the sensor delay time is 0.1ms, it can be concluded that the start of static pressure drop reasonably matches with the start of swirling motion development. The delay time is considered as the time needed for the needle to be opened from the initial signal given to the solenoid in addition to the time for the liquid film to be formed and the flow angle to be reached a fixed value. The flow angle was measured from the liquid streamlines of the spray at the nozzle exit.

As the liquid film inside the nozzle rotates its angular momentum transferred to the air through the shear layer and accordingly it is expected to have a radial pressure gradient with minimum value at the centerline [8]. The pressure drop at the centerline is proportional to the square of swirling velocity for the case of simple radial equilibrium flow (solid vortex with no radial velocity). The flow pattern inside the swirling flow depends mainly on the swirl number \( S_n \) which is defined as the ratio of the axial flux of swirl momentum to the axial flux of axial momentum times the equivalent exit radius [8, 13].

The \( S_n \) for the different conditions can be calculated by assuming:

\[
S_n = \frac{\int UWr^2 dr}{\int U^2 r dr'}
\]

where, the \( \theta \) is the flow angle and \( U_t \) is the total velocity.

The value of \( S_n \) in all tested cases was more than 0.6 which is the critical value to form a center recirculation vortex [8]. Although the recirculation of air flow inside the DISI injector has not been confirmed experimentally, some models, in spite of the difficulties of measurements close to the injector, showed that the small droplets measured at the center line of the spray was moving upward [10]. More work will be continued to estimate the velocity field inside the injector based on the measured pressure in this work.

3.2 Temporal static pressure at different operating conditions

Static pressure at different location

The temporal static pressure at different vertical distances from nozzle is presented in Fig. 4. To check whether the spray structure is affected by the inserted probe, the spray image was simultaneously captured with the pressure measurements and then compared with original spray image. The spray image did not show any difference until the probe approaches to the 0.5mm distance from nozzle. Figure 4 shows that the static pressure drop is recovered as the distance from nozzle increases. This is attributed to the associated reduction in swirling motion due to the aerodynamic drag and also to the radial divergence of the spray at the downstream of spray. In fact, after the liquid film is broken-up, the atomized droplets moves in a linear motion depending on its initial axial and radial momentum after being imparted form the liquid film. However, because the droplets are released from the peripheral of a cylindrical liquid film, the conical spray is formed. The resultant moving direction of all the droplets can still lead the swirling motion of the air inside the spray envelop with less effect as the distance from the nozzle exit increases.
Static pressure at different injection pressures

Figure 5 shows the temporal static pressure and flow angle of spray at various injection pressures. The minimum value of static pressure becomes smaller indicating much more drop in the pressure as the injection pressure increases as shown in Fig. 5(a). This is attributed to the enhanced swirling flow at high injection pressure. The measured flow angle, the ratio between axial velocity and radial velocity at the nozzle exit, shown in Fig. 5(b) remains constant even the swirling motion and momentum increased. This indicates that there is also equal increase in the axial velocity. The motion of the flow at the nozzle exit was visualized by focusing the camera on the very minute surface area of the spray at nozzle exit with relatively longer camera exposure time [14] and then the image is analyzed and the flow angle was determined using Otsu’s method implemented in the Matlab imaging toolbox.

Static pressure at different injection duration

The static pressure and flow angle alterations at different injection durations are plotted in Fig. 6. The static pressure drop is enhanced as the injection duration increases with a shifted time of the peak. The flow angle remains constant after the 0.6ms. Regarding the constant flow angle at different injection duration and the fact that the pressure drop is mainly governed by the swirling velocity, the static pressure drop mainly depends on the temporal axial velocity directly related to the transient variation of injection rate or dynamic pressure at the nozzle exit.

Static pressure at different fuel temperature

The temporal static pressure and flow angle at different fuel temperature is shown in Fig. 7. The results show different tendency with different operating conditions. In case of high fuel temperature, the effect of flash boiling and evaporation should be considered. At 0.5mm distance from nozzle exit, the static pressure at 85°C fuel temperature shows the sudden rise and it could be due to the sudden evaporation of the fuel inside the nozzle [4, 6]. Some part of fuel near the air core is suddenly evaporated as a result of flash boiling and spontaneously increases the vapor pressure of the air core inside the nozzle. However, the static pressure shows a sudden drop at 3mm distance from the nozzle exit and interestingly it shows even lower value than 15°C fuel temperature condition. Two reasons could explain that pressure drop. The first reason is related to the increase in the spray angle at the nozzle exit which is associated to the increase in the pressure drop across the spray envelop and that is shown in Fig. 7(b). Increasing the spray angle at the nozzle exit causes sudden expansion to the air trapped inside the nozzle. If the rate of pressure increase due to fuel evaporation is less than the pressure decrease due to the air expansion, the static pressure drop is mainly attributed to the spray divergence. The second reason is related to the enhancement in the flow angle shown in Fig. 7(c). The increase of flow angle is directly related to the increase in swirl velocity relative to the axial velocity.

3.3 Temporal dynamic pressure variation at the nozzle exit

The temporal dynamic pressure variation of the liquid spray at the nozzle exit is measured and presented in Fig. 8. The specific value of the dynamic pressure is not matching.
with the true value of dynamic pressure because the liquid flow of spray is not impinging to the whole test area of pressure sensor, diameter of 5mm. Therefore, the data presented here is qualitative data to show the tendency for different operating conditions. The transducer was aligned to have its surface perpendicular to the spray axis and for further care the spray was visualized with high magnification during the pressure measurements to make sure that the spray geometry is not altered. As presented in Figs. 5 and 6, the flow angle at different injection pressure and duration conditions is constant. Therefore, the temporal dynamic pressure is directly related to the square of the tangential velocity or swirling motion of spray. The trend shown in Fig. 8 clearly shows that the end of the peak in the dynamic pressure for different injection pressures and durations is matching well with the ends of the peak of the static pressure shown previously in Figs. 5 and 6. However, the continuous decrease in static pressure with increasing the injection duration was not directly related to the dynamic pressure which almost maintained its maximum value as that for 1.5ms. When the injection time is 1.5 ms, the end of injection reaches before the pressure at the centerline reaches its minimum value that could be appeared if the spray is continuously injected. This also can raise a point that at what injection duration the formation of a central recirculation zone could be expected.

### 3.4 Effect of static pressure on spray development

#### Analytical liquid divergence model

To investigate the effect of pressure difference on the spray shape, a simple liquid film divergence model suggested from Ramamurthi [15, 16] is employed. The liquid film profile at the nozzle exit is governed by a total differential equation which is derived from the balance of the forces acting to liquid film. This equation assumes that there is no radial pressure distribution across the liquid film thickness and the shear stress and any liquid surface instability is ignorable. The equation has the following form [15, 16]:

\[
\frac{\partial}{\partial r} \left( \frac{r \frac{\partial}{\partial r}}{1 + \frac{\partial^2}{\partial r^2}} \right) \left( \frac{r}{\frac{\partial^2}{\partial r^2}} \right) \left( \frac{We \tan^2 \alpha}{r^2} - \frac{2}{\frac{\partial}{\partial r}} - \frac{1}{\frac{\partial^2}{\partial r^2}} \right) = 0
\]

(4)

where,

- \(x = \text{axial location, } r = \text{film radius, } We = \text{Weber number}\)
- \(r = \frac{\delta}{R_o}, \quad x = \frac{x}{R_o}, \quad \alpha = \frac{\delta}{R_o}, \quad \frac{\partial}{\partial r} = \frac{\Delta P}{(\sigma / R_o)} \) and \(We = \frac{\rho R_o U^2}{\sigma}\)
- \(R_o = \text{nozzle radius, } \delta = \text{initial film thickness inside nozzle,}\)
- \(\Delta P = \text{pressure difference between inner and outer part of spray,}\)
- \(U = \text{injection velocity, } \rho = \text{liquid density, } \sigma = \text{surface tension}\)

### Table 2 Input data to liquid divergence model

<table>
<thead>
<tr>
<th>Initial film thickness</th>
<th>175µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial velocity</td>
<td>30m/s, 50m/s</td>
</tr>
<tr>
<td>Flow angle</td>
<td>30°</td>
</tr>
<tr>
<td>Surface tension</td>
<td>0.02N/m</td>
</tr>
<tr>
<td>Nozzle radius (R_o)</td>
<td>0.5mm</td>
</tr>
<tr>
<td>Liquid density</td>
<td>750kg/m³</td>
</tr>
</tbody>
</table>
Equation (4) was solved using the values shown in Table 2. The variables are fixed to certain values except the axial velocity. The values were chosen to represent the actual conditions where the initial film thickness and the flow angle are measured using microscopic imaging system and the other variables are given as the values at the atmospheric condition. The liquid film trajectory at different pressure difference between inner and outer part of spray is plotted in Fig. 9. The selected pressure range from 0kPa to 2.5kPa is the real static pressure range measured at different operating conditions. The result shows that the liquid film trajectory starts to collapse about 2mm from nozzle at axial velocity of 30m/s condition and 3mm from the nozzle at 50m/s condition. The spray shows less collapse at the higher axial velocity as a result of enhanced spray momentum. Although the measured static pressure drop shows the maximum value at the nozzle exit and it is continuously attenuated as it goes to the downstream, the result represents that the liquid film trajectory could be affected by the static pressure drop at the very close location from the nozzle. The pressure measured in this study is the average pressure at the center line within 0.2 mm, representing the probe orifice. However, the pressure across the inner surface of the liquid film could be higher due to the pressure gradient across the radius. Nevertheless, Fig. 9 is still providing some useful trend for fast engineering application. More investigation is needed to explore how the flow field behaving inside the spray and possibility of having reverse vortex and its characteristics under transient swirl velocity.

Spray development at different operating conditions

Fig. 10 shows the macroscopic spray images at different injection pressure and fuel temperature conditions. The spray is collapsed more at high injection pressure condition although the spray momentum is enhanced, as shown in Fig. 10(a). In this case, it is not easy to judge what parameter whether the static pressure drop or the outer airflow vortex flow has more contribution in collapsing the spray at high injection pressure because the vortex flow is also enhanced at high injection pressure. In case of high fuel temperature, the spray image also shows the spray collapse starting at the very short distance from the nozzle as shown in Fig. 10(b). Considering the initial axial momentum of spray is not stronger at high fuel temperature, it is concluded that the enhanced static pressure drop, evaporation and atomization of spray at high fuel temperature is the main reasons of spray collapse. From the results of mathematical model and spray images, it can be concluded that the static pressure drop is one of the main reasons causing the spray collapse although the characteristics of vortex flow at different operating conditions are not identified in this study.

3.5 Minimization of static pressure drop using a tapered nozzle

To minimize the effect of static pressure drop during the spray development, tapered nozzles of which taper angle is less than 45° are chosen as alternatives. The tapered nozzle alters the symmetrical distribution of fuel and velocity to another state. The larger portion of fuel is positioned in some area with higher injection velocity, and the smaller portion of fuel is located in another area with lower injection velocity. This asymmetrical distribution of fuel and droplet velocity obstructs the swirling motion of the spray and finally increases the pressure at the centerline. Previous researches showed that the tapered nozzles that have a taper angle more than 45° experience alterations in spray shape at different surrounding conditions [11].
relative static pressure at different taper angles less than 45° is plotted in Fig. 11. The static pressure drop showed only slight increase until the taper angle reaches 30°, flow angle. If the taper angle is smaller than the flow angle, some liquid emerges very early than the rest which keep rotating inside the nozzle without being injected. Therefore, the fuel is not injected along the whole circumferential shape of the nozzle. This uncompleted circular shape is similar with the spray resulted from the L-step nozzle. L-step nozzle can be defined as the taper angle 0° condition. From the previous research, L-step nozzle showed V-shape spray with containing very rich area of spray [11, 12]. This is because of very high axial velocity to certain direction and too much impingement to the cut nozzle even though the resultant static pressure drop inside the spray will also be significantly reduced. In this study, the uncompleted circular shape of spray is defined as opened hollow cone spray. The spray shape at different taper angles is presented in Fig. 12. Hollow cone spray shape is sustained when the taper angle is larger than 30°, while opened hollow cone spray shape is appeared when the taper angle is less than 30° without containing too rich area of spray. The uncompleted circular shape of spray causes the uncompleted swirling motion and it finally causes the reduced pressure drop. Because of the balance in air pressure located inside the spray is now balanced with the surrounding pressure or combustion chamber pressure for the case of engine, it is expected to be much less sensitive to operating conditions.

4. CONCLUSIONS

The static pressure drop inside the swirl spray is measured at different operating conditions and its effect on spray shape is analyzed using imaging system and a mathematical model. Furthermore, the minimization of static pressure drop is pursued using the tapered nozzle. The derived conclusions are as follows.

1. Static pressure drop inside the spray is observed when the swirl spray develops. The static pressure is getting close to the atmospheric pressure as the axial distance from the injector increases. The static pressure drop is enhanced as the injection pressure and injection duration increase. In case of high fuel temperature, the static pressure is suddenly increased at the nozzle exit as a result of fuel evaporation and then shows the even lower value compared to the atmospheric temperature at the downstream of spray.

2. The static pressure drop inside the spray is directly related to the swirling motion of spray and it is confirmed by comparing the flow angle and temporal dynamic pressure with the temporal static pressure drop.

3. The collapse of spray is experimentally and mathematically observed and it was found that the static pressure is one of the factors affecting the spray development.

4. The attenuation of static pressure drop is achieved by reducing the taper angle less than the flow angle. The opened hollow cone spray shape was formed that assisted in balancing the pressure inside the spray with the surrounding pressure without containing locally very rich area which is observed at L-step nozzle.

5. NOMENCLATURE

- $m$ mass flow rate [kg/s]
- $\Delta P$ pressure difference [Pa]
- $r$ film radius [mm]
- $R_n$ nozzle radius [mm]
- $U$ injection velocity [m/s]
- $We$ Weber number
- $\alpha$ taper angle [deg]
- $\delta_i$ initial film thickness [mm]
- $\theta$ flow angle [deg]
- $\rho_f$ fuel density [kg/m$^3$]
- $\sigma$ surface tension [N/m]
ACKNOWLEDGEMENT

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6. REFERENCES