Discharge Coefficient of Swirling Nozzle with Swirling Chamber Volume Variation for Liquefied Petroleum Gas

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Abstract: The phenomenon of vapor blockage (vapor lock) on LPG hose is one of major causes of fires and explosions on the gas stove system. Vapor blockage is very easy to occur during the liquid phase of the LPG flow along the hose. One way to prevent the liquid phase flow of LPG to the hose of the gas stove is by adding a swirling nozzle on the regulator. Different from other type of nozzles, a swirling nozzle has a swirling chamber in it which can generate a vortex effect, so that the atomization process is better. This study is focused to experimentally investigate the swirling chamber volume relationship with the LPG mass flow rate, discharge coefficient (CD), flow coefficient (KD), Reynolds Number and the swirling flow number. Results of experiments showed that the volume of the swirling chamber in swirling nozzle gives effects on the LPG mass flow rate through the swirling nozzle. It can be confirmed that the larger of swirling chamber volume, the greater the mass flow rate through the swirling nozzle. The increase of mass flow rate causes the discharge coefficient (CD), flow coefficient (KD), the Reynolds number and flow number also increase.

Key words: Vapor lock · Swirling nozzle · Discharge coefficient · Flow coefficient · Reynolds number · Flow number

INTRODUCTION

In Indonesia, fire accidents due to the explosions of commercial tanks of LPG (Liquefied Gas Petroleum) used for gas stove happens quite a lot. Since the government launched a program of conversion from kerosene to LPG, the public has received information and dissemination of the program regarding the correct procedures to prevent an explosion due to incorrect handling of the LPG tanks and its connection to the gas stoves. One of the procedure is that the installation of LPG gas cylinders should be completely straight, not be tilted and rolled over to avoid any leaks [1, 2]. However, this is often disregarded by the people who are just converting from using kerosene based cooking stove to the gas stove. Placement position of LPG cylinders that are too skewed or throwing the tanks causes the liquid LPG flow to the fuel line. This will lead to evaporation of the liquid fuel along the fuel line. The evaporation process will be followed by the volume expansion, which will cause a vapor blockage (vapor lock) in the fuel line. Consequently, the vapor blockage will later inhibit the flow rate of LPG. This phenomenon will cause a delay in the pressure release in the fuel tank. Hence, an increase in temperature would potentially lead to an explosion of the tank.

A method to prevent the vapor lock can be done by installing a device that can change the LPG liquid into vapor. Thus, the LPG that flows along the fuel line is in dry vapor phase, so that the specific volume changes are very small and expansion along the channel volume is also small. One type of the devices often used to convert liquid fuel into vapor is a swirling nozzle. A swirling nozzle will enhance the evaporation process of the liquid fuel by breaking the liquid into droplets. One important parameter that indicates the performance of the swirling Nozzle is discharge coefficient (CD). Theoretically a discharge coefficient is the ratio of the actual mass flow
Swirling nozzles often referred as a pressure swirl atomizer which serves to break the liquid into droplet. Fig. 1 shows the basic scheme of a swirling nozzle. Liquid is fed into the swirling chamber through a tangential line to give liquids with a high angular velocity and form a liquid coating to the internal surface of free-floating in the swirling chamber, giving rise to the vortex core. The liquid is then removed from the nozzle in the shape of a hollow conical sheet which breaks up into droplets [3, 4].

The dimensions of swirling nozzles which was used in this study can be seen in Fig. 2.

Swirling chamber volume of swirling nozzle which used in this study can be varied by adjusting the length of swirling chamber. The parameters to be considered in a swirling design of the nozzle and spray to predict the outcome include the flow number (FN) which can be calculated by (1).

$$FN = \frac{Q}{\pi D^2 / 4}$$

where $Q$ is the LPG mass flow rate, $D$ is the pipe diameter, and $L$ is the length of the pipe.
where $\dot{m}_L$ is the liquid flow rate, $\rho_L$ is the fluid density and $\Delta P_L$ is the liquid pressure differences.

Orifice diameter ($D_o$) must be selected, while the determination of other geometrical parameters need to consider the following dimensionless groups $\Lambda_p/(D_oD_a)$, $D_o/D_a$, $L_o/D_o$ and $L_p/D_p$. The ratio $L/D_o$ should be reduced in order to minimize friction losses to the wall. However, the restriction is necessary to achieve stability of fluid flow and the formation of a uniform vortex sheet. This ratio should be higher than 0.5 and the recommended value is 1, as proposed by El Kobt et al. [5]. $L_o/D_o$ should be reduced to minimize the friction losses in the orifice. Furthermore, the ratio $L_p/D_p$ should not be less than 1.3 for the channel short tangential spray will cause instability (Tippler and Wilson) [6]. Two other dimensionless groups $\Lambda_p / (D_oD_o)$ and $D_o/D_p$, affect the discharge coefficient (CD). Furthermore, the ratio $L_p/D_p$ not be less than 1.3 for the channel [4].

For a single-phase fluid, discharge coefficient can be calculated using the formula given in (2).

$$CD_i = \frac{\dot{m}_i}{\dot{m}_{theory}} = \frac{\dot{m}_i}{A_i \sqrt{2 \rho_i \Delta P_i}}$$

where $CD_i$ is discharge coefficient of the liquid or gas, $\dot{m}_i$ is a liquid or gas flow rate of actual, $A_i$ is swirling nozzle cross-sectional area, $\rho_i$ is the density of the liquid or gas and $\Delta P_i$ is difference in pressure injection of fluids or gases.

Meanwhile for a two-phase flow, the discharge coefficient can be obtained from (3) as proposed by Zhang et al. [7].

$$m_{TP} = \frac{CD_{TP} A_{TP} Y_{TP}}{\sqrt{1 - \beta^4}} K_L \sqrt{2 \rho_i \Delta P_{TP}}$$

Thus, the discharge coefficient for a two-phase flow is given by (4):

$$CD_{TP} = \frac{m_{TP} \sqrt{1 - \beta^4}}{A_{TP} Y_{TP} K_L \sqrt{2 \rho_i \Delta P_{TP}}}$$

$$\beta = \frac{d}{D}$$

where $m_{TP}$ is two phase actual mass flow rate, $CD_{TP}$ is two phase discharge coefficient, $A$ is sectional area of nozzle orifice, $Y_{TP}$ is compressibility coefficient, $K_L$ is liquid phase coefficient, $\rho_L$ is liquid density, $\rho_g$ is gas/vapor density, $\Delta P_{TP}$ is two-phase pressure difference, $\beta$ is nozzle diameter ratio, $d$ is nozzle diameter and $D$ is pipe diameter.

$K_L$ is coefficient of liquid phase, which can be calculated using (5) as proposed by Jorge et al. [8].

$$K_L = \frac{1}{\sqrt{x \left( \frac{\rho_L}{\rho_g} - 1 \right) + 1}}$$

Compressibility Coefficient ($Y_{TP}$) is calculated with (6) as proposed by Zhang, et al. [9]:

$$Y_{TP} = Y_i (1 - \alpha) + Y_g \alpha$$

where $Y_{TP}$ is two phase LPG compressibility coefficient, $Y_i$ is liquid phase LPG compressibility coefficient, $Y_g$ is gas/vapor phase LPG compressibility coefficient and $\alpha$ is vapor fraction. In (6), the vapor fraction, $\alpha$ can be determined from (7) and relates to vapor quality as shown in (8).

$$\alpha = \frac{A_{vapor}}{A_{liquid} + A_{vapor}}$$

$$x = \frac{1}{1 + \rho_L (1 - \alpha) / \rho_g \alpha}$$

In addition to the discharge coefficient (CD), the ratio between actual mass flow rate to ideal mass flow rate is often expressed as flow coefficient (KD). Flow coefficient (KD) is a function of the CD and the ratio between the diameter of the orifice and the inlet nozzle [10] as shown in (9).

$$KD = \frac{CD}{\sqrt{1 - \beta^4}}$$

Other parameters which are calculated to illustrate the performance of swirling nozzle is flow number (FN) [3]. Flow Number (FN) is calculated by (9):

$$FN = \frac{m_{TP}}{\sqrt{x \Delta P_{TP}}}$$

where $\rho$ is two phase LPG density.

LPG two-phase density was calculated using (10).

$$\rho = \phi \rho_L + (1 - \phi) \rho_g$$

where $\phi$ is liquid volume fraction of LPG [3].
MATERIALS AND METHODS

The experimental setup is described in Fig. 3. Prior to the experiment a leak test was performed on the installation by using 8 bar pressurized air from the compressor. The experiment was carried out in a fuel flow line comprised of a LPG tank, fuel tube made of transparent acrylic for visual assessment and a Bunsen burner to flare the fuel. The fuel flow line is equipped with a swirling nozzle in the fuel tube section. In the experiment, three swirling nozzles were used with various volumes of chamber i.e. 13,465; 13,882 and 14,324 mm³. The fuel tank was placed in a tank holder specially designed to enable an inclination of fuel tank position. When the experiment test was conducted, the tube was inclined 90 degree to the vertical position. The flow rate of the gas was measured using a wet gas meter; meanwhile the measurements of flow temperature and pressure were electronically recorded by thermocouples and pressure transducers placed at two positions i.e. prior and after the swirling nozzle. The phase of fuel flow in the fuel line was assessed by direct visualization of LPG fuel appearance within the acrylic fuel tube using a high-performance digital camera. The captured image was then analyzed to calculate the vapor and liquid fraction of the LPG with the assistance of image processing software. The detail is discussed in the following section.

The calculation of the fraction of liquid and vapor requires the data of acrylic fuel pipe radius and height of LPG liquid flowing in the pipeline. The height fluid in the pipe obtained from the captured images which are then processed using the ImageJ program. Fig. 4 shows a screenshot of an image processing of the liquid height to determine the liquid fraction of LPG in the fuel pipe. The vapor fraction (α) of LPG in the pipe is calculated by (11).

\[
\alpha = \frac{V_p - V_{lp}}{V_p}
\]

(11)

where \(V_p\) is the pipe volume and \(V_{lp}\) is the volume of liquid in the pipe.

Volume of liquid LPG in the acrylic pipe can be calculated from the measurements of the radius of the pipe cross-section and the height of liquid LPG in the acrylic pipe. Fig. 5 illustrates the cross section of fuel pipe partly filled with the liquid phase of LPG and the method to derive the volume of liquid LPG in the pipe. The shaded area is the liquid part with height \(t\) as determined by processing the captured image.

Volume of liquid LPG per unit length of the pipe can be calculated by (12):

\[
V_{lp} = \left(\frac{\theta}{360} \Pi r^2\right)
\]

(12)

\[
\theta = 2 \cos^{-1}\left(\frac{r-t}{r}\right)
\]

(13)
Fig. 4: Image processing of to determine the height of liquid fraction

Fig. 5: Cross Section in the Acrylic Pipe

Furthermore, to calculate the mass flow rate, discharge coefficient (CD), flow coefficient (KD), flow number (FN) and the Reynolds number some properties of the fuel fluid including the density, dynamic viscosity and compressibility were determined by using REFPROP Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixture.

RESULTS AND DISCUSSION

Data is collected with swirling chamber volume variation on the swirling nozzle. LPG vapor fraction that flows into swirling nozzle was regulated by controlling the opening angle of control valve at opening angle 36°C. The results and processed data are summarized in Table 1.

Mass Flow Rate: Fig. 6 shows the mass flow rate of the LPG taken within 60 second for three cases of swirling chamber volume. It can be seen that the mass flow rate through the swirling nozzle is proportional to size of the volume of swirling chamber. The larger the swirling chamber volume, the greater the mass flow rate through the swirling nozzle. Moreover, the relationship between swirling chamber volume with mass flow rate can be seen in Fig. 7.

Discharge Coefficient and Flow Coefficient: Fig. 8 shows the discharge coefficient (CD) calculated within 60 second for three cases of swirling chamber volume. From Fig. 8 can be seen that the volume of swirling chamber has an influence on the discharge coefficient (CD). The larger the swirling chamber volume, the greater the CD. The relationship between the volumes of swirling chamber with CD can be seen in Fig. 9.

Moreover, Fig. 10 shows the flow coefficient (KD) calculated within 60 second and Fig. 11 show the relation between the swirling chamber volume and KD. Since the ratio of diameter of swirling nozzle orifice to the diameter of pipe very small, i.e. 0.09, the value of KD is similar to CD. From Fig. 10 it can be seen that the volume of swirling chamber has an influence on the flow coefficient (KD). The larger the swirling chamber volume, the greater the KD.

Reynolds Number: The Reynolds number of the fuel flow and its relation to the swirling chamber volume are shown in Fig. 12 and Fig. 13 respectively. From Fig. 12 it can be seen that the Reynolds number is proportional to the volume of swirling chamber. The larger swirling chamber, greater the Reynolds number. In case of swirling chamber volume 13.465 and 13.882 mm³, the flow of LPG fuel in the pipe line is a transitional flow. It is indicated from the
Table 1: Data Processing Results

<table>
<thead>
<tr>
<th>Volume Swirling Chamber (mm³)</th>
<th>Vapor Fraction of LPG into Nozzle</th>
<th>Average of LPG Pressure (bar)</th>
<th>Average of Mass Flow Rate (kg/s)</th>
<th>Average of Discharge Coefficient (CD)</th>
<th>Average of Flow Coefficient (KD)</th>
<th>Average of Reynolds Number of LPG</th>
<th>Average of Fanning Number (FN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.465</td>
<td>0.600</td>
<td>3.194</td>
<td>0.0014</td>
<td>0.27551</td>
<td>0.27552</td>
<td>2695.310</td>
<td>1.675E-07</td>
</tr>
<tr>
<td>13.882</td>
<td>0.600</td>
<td>2.889</td>
<td>0.0017</td>
<td>0.33369</td>
<td>0.33371</td>
<td>3061.748</td>
<td>2.037E-07</td>
</tr>
<tr>
<td>14.324</td>
<td>0.600</td>
<td>3.364</td>
<td>0.0021</td>
<td>0.41584</td>
<td>0.41585</td>
<td>4248.397</td>
<td>2.515E-07</td>
</tr>
</tbody>
</table>

Fig. 6: Mass Flow Rate

Fig. 7: The relationship between swirling chamber volume with mass flow rate

Fig. 8: Discharge Coefficient (CD) of Swirling Nozzle

Fig. 9: The relationship between swirling chamber volume with CD

Fig. 10: Flow Coefficient (KD) of Swirling Nozzle

Fig. 11: Relationship between swirling chamber volume with KD

Fig. 12: Reynolds Number of LPG flow through a swirling nozzle

Fig. 13: Relationship Between Chamber swirling Volume with Reynold Number
value of the Reynolds number which is in the range of 2100 to 4000. Meanwhile, in case of swirling chamber volume 14.324 mm$^3$ the flow is turbulent, suggested by value of the Reynolds number above 4000.

**Flow Number:** Fig. 14 shows the calculated flow number (FN) for three cases of swirling chamber volume. From the Fig., it can be seen that the flow number is proportional to the swirling chamber volume. The larger swirling chamber volume, the greater the flow number. Meanwhile, the relationship between the swirling chamber volume with flow number can be seen in Fig. 15.

**CONCLUSION**

An experimental investigation on the characteristics of swirling nozzle for an LPG fuel line application has been successfully done, focusing on the influence of swirling chamber volume to some important flow parameter. The swirling chamber volume of the swirling nozzle gives significant effects on the LPG mass flow rate flowing through the swirling nozzle. The larger swirling chamber volume, greater the mass flow rate through the swirling nozzle. Furthermore, the larger mass flow rate causes also greater discharge coefficient (CD), flow coefficient (KD), Reynolds number and flow number (FN).

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