Abstract
As revealed by Fukushima Daiichi nuclear disaster, countermeasures against severe accident in nuclear power plants are an urgent need. In particular, from the viewpoint of protecting a containment and suppressing the diffusion of radioactive materials, it is important to develop the device which allows a filtered venting of contaminated high pressure gas. In the filtered venting system that used in European reactors, so called Multi Venturi Scrubbers System is used to realize filtered venting without any power supply (Lindau, 1988) (Rust, et al., 1995). The system operates with any power supply and high pressure gas filled in the containment. This system is able to define to be composed of Venturi Scrubbers (VS) and a bubble column. In the VS, scrubbing of contaminated gas is promoted by both gas releases through a submerged VS and gas-liquid contact with splay flow formed by liquid suctioned through a hole provided by the pressure difference between inner and outer parts of a throat part of the VS. This type of the VS is called self-priming ones. However, the scrubbing mechanism of the self-priming VS including effects of gas mass flow rate and shape of the VS are understood insufficiently in the previous studies. In this study, to understand the VS operation characteristics for the filtered venting, we discussed the mechanisms of the self-priming phenomena and the hydraulic behavior in the VS. In this paper, we conducted a visualized observation of the hydraulic behavior in the VS and measured liquid flow rate of the self-priming. As a result, it is shown that there is the possibility that the VS decontamination performance falls low level with no self-priming.

1. Introduction
In the wake of Fukushima Daiichi nuclear disaster, reviews of the safety of nuclear facilities have been conducted in the world beginning with Japan. Countermeasures against a severe accident (SA) in nuclear power plants are an urgent need. In particular, from the viewpoint of protecting containment and suppressing diffusion of radioactive materials, it is important to install filtered venting devices to release high pressure pollutant gas to the atmosphere with elimination of radioactive materials from the gas.

One of the devices is a Multi Venturi Scrubbers System (MVSS), which is composed of “Venturi Scrubbers (VS)” part and a “bubble column” part and which is a decontamination system with gas-liquid contact. Figure 1 shows a simplified image of the system with single VS. A VS is a venturi tube with one or some holes for suction. The venturi tube has three parts; a convergent, a throat and a diffuser part. The throat part has the narrowest area between the convergent and diffuser parts. On a typical VS type, there are holes for suction in the throat part and these holes lead the inside and outside of the tube. In European reactors, the MVSS is used to realize filtered venting with any power supply. It is reported that the MVSS were installed to reactors in Europe in 1980s for the first time (Lindau, 1988) (Rust, et al., 1995). And a new type of the MVSS was developed (Nuclear Services, 2012).

The MVSS system is installed at outside of the reactor building and connected with the containment by pipings with
rupture disks. In the case of SA, the rupture disk is broken at high pressure and the system is operated to release high pressure gas safely. In this system, the relief gas is led into a number of the submerged VSs via a central line connected the containment, and discharged out into the pool. As one of the operation modes, dispersed and film flows are formed in the VS, and bubbly flow is appeared in the upper part of the VS. With these flow conditions, interfacial area is remarkably large, and radioactive materials which are contained in the gas phase are caught in the liquid phase. Finally, the filtered gas is released into the atmosphere. When the filtered venting system is used, the gas contains steam and the pool reaches a condition of thermal equilibrium finally. On this condition, the hydraulic behavior assumed to be like without effect of heat in the VS.

There are two types of the VS, one is a self-priming VS, and the other is a forced feed mode VS. In 1998, M. Lehner performed research by use of both self-priming and forced feed mode VS (Lehner, 1998). The VS is characterized by a low pressure and a high velocity gas in the throat part (Lindau, 1988). There are holes for suction in the throat part of the self-priming VS. By a pressure difference between this low pressure and outer side pressure of the VS or pumping power for the forced feed mode VS, liquid in the pool is suctioned to the inside of the VS through the holes. In the results, a dispersed liquid and a film flow are formed in the VS. In the self-priming VS, the suction of pool water through the holes in the throat part is called a self-priming or a self-priming phenomena. Because the self-priming VS require no external power supply, a few filtered venting systems that use the self-priming VS as decontamination device were developed and adopted in some nuclear power plants. M. Ali discussed about the applicability of Filtered Containment Venting System (FCVS) that use multi venturi scrubbers for filtered venting at a throat gas velocity range from 120 to 200 m/s (Ali, 2013). The gas velocity is one of important parameters of the VS to evaluate the performance of the filtered venting system. In the SA, a gas velocity strongly depends on a progress of the SA, and the gas velocity might reach a sonic velocity in the throat part of the VS. To evaluate the performance and to consider operating characteristics of the VS for the filtered venting, the effects of the gas velocity must be examined under as wide range as possible. However, it is concluded that the effects of the gas velocity were studied insufficiently in existing research.

In this study, we focused on the effects of the gas velocity on the self-priming phenomena and the hydraulic behavior in the VS. Because, for decontamination, large gas-liquid interfacial area in the VS is necessary. In other words, to form the gas-liquid interface area, self-priming is required. In this study, if the self-priming occurred, we defined that the VS is under operating condition. However, if the self-priming was not observed, we judged that the VS is under the non-operating condition. To understand the VS operation characteristics for filtered venting, firstly, pressure distributions in

![Fig. 1](image1.png)

Fig. 1 The venturi scrubber system has venturi part and bubble column part. In the system, pollutant gas is scrubbed by gas-liquid contact and released to atmosphere as cleaned gas.

![Fig. 2](image2.png)

Fig. 2 In theoretical analysis, only gas flows in the VS. In the 1st step, pth was calculated. In the 2nd step, suctioned liquid flow rate is calculated if there was pth at the throat. Dot line shows a vertical shock wave. If Mth equals 1, it is assumed that it occurs

the VS were calculated by theoretical analysis. In the analysis, we consider only a gas single phase flow in the VS. Based on this theoretical analysis, a pressure difference between throat part and outside of the VS was calculated. Finally, liquid flow rate by the self-priming phenomena was evaluated by using the pressure difference and the pressure loss in the hole for suction. In the second step, experimental observation of the self-priming phenomena and the hydraulic behavior in the VS is conducted. Moreover, the hydraulic behavior is considered with an image processing and obtained results were compared with theoretical analysis results. In the third step, liquid flow rate is measured experimentally, and compared with theoretical results. Finally, from these results, the mechanism of self-priming as operating characteristics of the VS and the relationship between it and hydraulic behavior is discussed.

2. Theoretical analysis

In this section, theoretical analysis is performed to evaluate pressure in the throat part in the VS: \( p_{th} \) and a liquid flow rate by the self-priming: \( G_L \). In the throat part, by neglecting the effects of compressibility of gas, it is considered that the static pressure decreases with increasing gas flow velocity and the pressure difference between inside and outside occurs. Liquid around the VS is suctioned through the hole by the pressure difference as a driving force. In this section, to understand the effect of gas flow for the self-priming phenomena, we develop a theoretical analysis model to evaluate the pressure distribution in the VS and the suctioned liquid flow rate.

In this model, as shown in Fig.2, the VS is divided into three parts, a convergent, a throat and a diffuser part, and there is a hole for suction in the throat part. The compressible gas flows into the VS from the outside isentropically. The VS is surrounded by liquid, and surrounding liquid can be suctioned by the pressure difference in the throat part. In the VS, it is considered that an annular dispersed flow is be formed (Lehner, 1998). Because the annular dispersed flow has relatively small effects on the pressure distribution in the VS, in this analysis, the flow in the VS assumed one dimensional compressible gas single phase flow to simplify the model.

In the first step of the model development, the pressure distribution, especially pressure in throat part: \( p_{th} \), is calculated with the following assumptions. This pressure value is considered as the effects of cross-section change for flow direction and compressibility of the fluid.

- The flow in the VS is a one dimensional compressible gas single phase flow. Therefore, the effects of the suctioned liquid are ignored.
- The flow is isentropic with no heat transfer between inside and outside of the VS.
- Gas flows parallel to the gravity.
- No pressure loss by friction on inner wall, the convergent and the diffuser part in the VS but only the hole for suction.
- In case of that Mach number in the throat part \( M_{th} \) equals 1, a vertical shock wave occurs in the diffuser part.
- Only the area of the shock wave is adiabatic flow.

In this second step, the suctioned liquid flow rate: \( G_L \) was calculated with the following assumptions.

- The static pressure in the throat of the VS is equivalent to the one calculated in the first step.
- The hydraulic head pressure occurs around the hole of the VS.
- Liquid is suctioned by the pressure difference, which is the difference between the static pressure and the hydraulic head pressure.
- The pressure loss caused by the friction on the inner wall, expansion and reduction of the flow area, acceleration of the flow and gravity head is considered.

Basic equations used in the first step were following equations; state equation and conservation equations for compressible fluids.

State equation:

\[
p = \rho RT
\]
Mass:
\[ \frac{\partial}{\partial x}(\rho u A) = 0 \]  
\[ (2) \]

Momentum:
\[ u \frac{\partial u}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x} \]  
\[ (3) \]

Energy:
\[ \frac{\partial}{\partial x} \left( h + \frac{1}{2} u^2 \right) = 0 \]  
\[ (4) \]

From Eq. (4), isentropic flow equations, \( p/\rho^\gamma=\text{const.} \) and \( p/\rho^\gamma_{\text{out}}=\text{const.} \), are obtained. In addition, by substituting Eq. (1) into these equations, Eq.(5) is obtained.

\[ \rho = \rho_0 \left( \frac{p}{p_0} \right)^{\frac{1}{\gamma}} = \frac{p_0}{RT_0} \left( \frac{p}{p_0} \right)^{\frac{1}{\gamma}} \]  
\[ (5) \]

From Eq. (3) and the isentropic flow equation, Bernoulli equation in steady isentropic flow is obtained. And by rearranged and substituting Eq.(1) into this one, Eq. (6) is obtained.

\[ u = \sqrt{\frac{2}{\gamma-1} \frac{p_0}{p_0^\gamma} \left( \frac{p}{p_0} \right)^{\frac{1}{\gamma}} - \frac{2\gamma RT_0}{\gamma-1} \left( \frac{p}{p_0} \right)^{\frac{\gamma+1}{\gamma}}} \]  
\[ (6) \]

By substituting Eq. (5) and Eq. (6) into mass flow equation: \( G = \rho u A \) obtained from Eq. (2), the following equation is obtained. Mass flow rate is expressed as a following equation of temperature, pressure.

\[ G = \rho u A = \frac{p_0 A}{\sqrt{RT_0}} \sqrt{\frac{2}{\gamma-1} \left( \frac{p}{p_0} \right)^{\frac{2}{\gamma}} - \left( \frac{p}{p_0} \right)^{\frac{\gamma+1}{\gamma}}} \]  
\[ (7) \]

From Eq. (7), cross-section area ratio-pressure ratio relation equation between a certain point and a certain criterion point in a flow of the VS is obtained. By using Eq. (7), following relation between a cross sectional area at arbitrary location: \( A \) and that at the outlet of the VS: \( A_{\text{out}} \) is obtained (Matsuo, 1994).

\[ \frac{A_{\text{out}}}{A} = \sqrt{\left( \frac{p}{p_0} \right)^{\frac{2}{\gamma}} - \left( \frac{p}{p_0} \right)^{\frac{\gamma+1}{\gamma}}} \]  
\[ \left( \frac{p_{\text{out}}}{p_0} \right)^{\frac{2}{\gamma}} - \left( \frac{p_{\text{out}}}{p_0} \right)^{\frac{\gamma+1}{\gamma}} \]  
\[ (8) \]

\( p_0 \) is stagnation point pressure and obtained by isentropic equation. \( p_{\text{out}} \) is assumed as atmospheric pressure in this study. To execute a convergence calculation, the static pressure for each cross-section area is obtained. However, if the Mach number in the throat part \( M_{\text{th}} \) equals 1, it is assumed that a vertical shock wave occurs and flow of this area is also assumed an adiabatic flow. In this case, \( p_0 \) is different in upstream side and downstream side of the shock wave. In Fig.2, these
different pressures are expressed as $p_{01}$ and $p_{02}$. For this reason, stagnation point change is required in the upstream and downstream area. In the upstream area, the stagnation point is set in the throat part of the VS. And in the downstream area, the point is done in the out of the VS. Eq. (8) is represented for the upstream area as the following equation.

$$
\frac{A}{A_{th}} = \left[ \frac{P_{th}}{P_{0}^{\gamma/\gamma-1}} - \frac{(P_{th})^{\gamma+1}}{\gamma} \right]^{\gamma/\gamma-1} - \left[ \frac{P}{P_{0}^{\gamma/\gamma-1}} - \frac{(P)^{\gamma+1}}{\gamma} \right]^{\gamma/\gamma-1}
$$

(9)

To obtain $p_{th}$, the following procedure is performed. Internal energy $h$ and sonic velocity $a$ for isentropic flow for perfect gas are expressed as $h = \gamma p / (\gamma - 1) \rho$ and $a = \sqrt{\gamma p / \rho} = \sqrt{\gamma RT_0}$ each other (K. Matsuo (1994)). From Eq. (4), the energy equation is represented and substituted by the sonic velocity equation, the following relation equation between a certain point and a stagnation point in a flow of the VS is obtained.

$$
\frac{a^2}{\gamma-1} + \frac{u^2}{2} = \frac{a_{th}^2}{\gamma-1}
$$

(10)

This equation is divided through by $a^2$ and Mach number, $M = u/a$. Mach number in throat $M_{th}$ equals 1 is considered and the following relation equation between temperature and Mach number, finally pressure one, is obtained in the throat part.

$$
\frac{P_0}{P_{th}} = \frac{T_0}{T_{th}}^{\gamma/\gamma-1} = \left(1 + \frac{\gamma-1}{2}\right)^{\gamma/\gamma-1}
$$

(11)

If the Mach number in the throat part $M_{th}$ equals 1, a vertical shock wave point is calculated by the following equation (Matsuo, 1994).

$$
\frac{P_{02}}{P_{01}} = \left[ \frac{\gamma}{(\gamma-1)M_1^2 + 2} \right]^{\gamma/\gamma-1} \left[ \frac{\gamma+1}{2\gamma M_1^2 - (\gamma-1)} \right]^{1/\gamma-1}
$$

(12)

In the second step, liquid flow rate was calculated with a following equation for pressure balance.

$$
p_{in} - p_{th} = \frac{1}{2} \rho_L u_L^2 + \rho_L gH + p_{loss}
$$

(13)

The first and second terms of right hand side of Eq.(13) are acceleration loss and gravity head respectively. And $p_{loss}$ indicates pressure loss caused by friction on the inner wall and expansion or reduction of flow area.

3. Air-Water Experiment
3.1 Experimental Apparatus

Figure 3 shows the outline of the experimental apparatus. The experimental apparatus was consisted of a modeled VS, a compressor, an overhead tank with water and a sampling device, mainly. Figure 4 shows details of the modeled VS. The modeled VS used in this study had a rectangular shape in cross section. The hole for suction was attached to overhead tank with a tube and the self-priming was reproduced by a suctioned water. Inlet cross section equaled to outlet cross section and reduction ratio at the throat was 0.286. To visualize the hydraulic behavior and confirm the occurrence of the self-priming at the throat, the modeled VS was made of a clear acrylic glass.
3.2 Experimental conditions and procedure

Table 1 shows experimental conditions. In this experiment, working fluids were air and tap water. These conditions shone in Table 1 were selected based on the operating condition and assumption with no effect of heat. Working conditions were atmospheric pressure and room temperature. The gas mass flow rate $G_G$ and hydraulic head at throat $H$ were experimental parameters. Based on the analytical results, if the gas flow rate is near or greater than 9.7 [g/s], the self-priming phenomena is suspended. Therefore, we changed $G_G$ from 0 to 9.7 [g/s] to include the suspension of the self-priming phenomena. $H$ was set to investigate the hydraulic pressure effects for self-priming and set to 0 and 900 [mm]. Experimental procedure was as follows. By opening the valve manually, high pressure air in the compressor tank flowed into the VS. By observation around the hole at the throat, if the occurrence of self-priming was confirmed, flow behavior in the modeled VS was recorded by a high speed video camera (Photron FASTCAM-MAX 120K) with the back light method. Recorded shutter speed was 10,000 [fps]. Suctioned and blew up water was collected at the sampling device and mass of collected water was measured to evaluate the liquid flow rate by the self-priming.

3.3 Image Processing

By observed images, there was gas-liquid two-phase flow, dispersed flow and film flow by suctioned water. Figure 5 shows an example of the image by the high speed video camera. In side view, a line near its center is the line of acrylic connection. Over a certain gas flow rate, the flow was smooth, but from a certain point, it changed complicated like the image in Fig.5. The point is considered as a change point of flow behavior and might fit the static pressure change point.

![Diagram of experimental apparatus](image1)

**Table 1 Experimental conditions**

<table>
<thead>
<tr>
<th>Fluids</th>
<th>Air &amp; Tap water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure &amp; Temperature</td>
<td>Atmospheric pressure &amp; Room temperature</td>
</tr>
<tr>
<td>Gas mass flow rate : $G_G$</td>
<td>1.0, 1.9, 2.9, 3.9, 4.8, 5.8, 6.8, 7.8, 8.7, 9.7 [g/s]</td>
</tr>
<tr>
<td>Hydraulic head at throat : $H$</td>
<td>0, 900 [mm]</td>
</tr>
</tbody>
</table>
on the pressure distribution in VS by the shock wave calculated by the theoretical analysis.

To compare the flow change point with the pressure change point, the change point of flow behavior was obtained by image processing in Fig. 6. Images taken by high speed video camera were manipulated to capture points of hydraulic behavior change. The light was incident for near side with backlight method. The image processing was performed through the following steps; firstly, average value in a horizontal direction of brightness each pixel of the target picture was taken. Its target area is in the center of the observed image in Fig.6 (a). Width of observed image is 128 pixels and the manipulated area centered the observed image is 3 pixels. (b) is captured brightness, which is horizontal average value in the manipulated area. The minimum value point is defined as the evaluated change point.

Fig. 7 At lower gas flow rate, a part of suctioned water atomized near the hole for suction and other part formed film flow. With increasing gas flow rate, amount of the dispersed flow seemed to increase and wave on the film flow became more finely. The origin of z axial fits the hole for suction. Red solid line shows film flow direction and yellow dot line shows dispersed flow direction.
the target area centered the observed image is 3 pixels. Processed area was between 5 [mm] to the outlet from the hole for suction for the downstream. If hydraulic behavior changes, the brightness had a large peak of brightness in the area in Fig.6 (b). The peak top was defined as a change point of hydraulic behavior. The change point was used to compare with pressure distribution to consider the effect of gas flow for hydraulic behavior. Detailed discussion about the change point of the hydraulic behavior is described in the chapter 4.

4. Results and Discussions

Figures 7 - 9 show pictures taken on an area above the throat part of the VS at front and side view. In the side view, a line near its center is the line of acrylic connection. The origin of the z axial is the hole for suction. Red line shows the film flow direction and a yellow line shows dispersed flow direction. Figure 7 shows visualized observation results at lower gas flow rate. Figure 8 shows the results at higher gas flow rate. Figure 9 shows the results at highest gas flow rate in this report. The gas flow was upward from bottom to top. Water was suctioned from outside into inside of the VS through the hole for suction in the throat part. A part of suctioned water formed jet flow, and changed dispersed flow with

Fig. 8 At higher gas flow rate, with increasing gas flow rate, atomization occurred on the film flow in diffuser part not only near the hole for suction and the film flow direction changed. And the change point moved for downstream. The origin of z axial fits the hole for suction. Red solid line and yellow dot line is same to it in Fig.7. Red plot shows the change point. Black dot line is center line of the wall connected the hole.

Fig. 9 At highest flow rate in this report, air exhausted from inside to outside of the VS through the hole for suction. The origin of z axial fits the hole for suction. Purple solid line shows air flow direction.
liquid droplets in a moment. Other part of the liquid formed the film flow. Under the low gas flow rate condition from 0 to 3.9 [g/s] comparatively, dispersed flow was occurred near the hole for suction. The droplet size was too small to measure, however, it seemed under 10 [μm]. About the size, Hesketh produced a similar finding (Hesketh, 1973). The film flow was calm in these case, however, under high gas flow rate condition from 5.8 to 7.8 [g/s], with increasing gas flow rate, atomization occurred in diffuser part and part of liquid formed dispersed flow in side view (Fig.8). And film flow expanded laterally. Depending on the gas flow rate, its film flow reached to the opposite wall. In front view, another part of film flow expanded and, on center line of the wall with the hole for suction, changed direction abruptly. The flow direction looked like U-shape. Behind the top of the U-shape, water reverse flow was formed, and at the top of the U-shaped, it crashed into the upward flow. This crush point moved to downstream with increasing gas flow rate. Compared this point with the atomization point at the diffuser, these were fit closely. Therefore, it is presented that the atomization was largely-concerned with the liquid crush. Thus, the gas-liquid two-phase flow had complicated hydraulic behavior in the diffuser part.

Figure 9 shows the result at the gas mass flow rate 9.7 [g/s]. In the figure, there was stagnant water in the downstream of the hole. As a initial condition of experiment, the VS was filled with stagnant water. A part of this stagnant water was not excluded until end of the experiment. By the observation, water suction stopped and air was out from the hole for suction. For the decontamination, gas-liquid interface area and gas-liquid relative velocity are important. However, in this condition, it can no longer be expected.

Figure 10 shows the comparison change points of hydraulic behavior obtained by image processing with the vertical shock wave point obtained by the theoretical analysis (Eq. (12)). Red triangle plots show the change points and red solid line shows the shock wave point. The measured change points of hydraulic behavior fitted closely with the top of U-shape of the visualized results. As shown in Fig.10, with increasing gas mass flow rate, the change points moved for the downstream. The predicted shock wave points have the same tendencies. As a result, it is considered that gas flow was dominant in the VS, the pressure distribution changed with the gas flow and its effect appeared on the liquid film flow as the change points and complicated hydraulic behaviors.

Figure 11 shows experimental and theoretical analysis results of the liquid flow rate. In Fig.11, red plots show the experimental results with no hydraulic head condition and blue plots shows with hydraulic head 900 [mm] condition. The origin of the head is the hole for suction. Green dot line shows the pressure in throat part calculated by the first step of the theoretical analysis. Red line shows the liquid flow rate calculated by the second step with no hydraulic head condition and blue solid line shows with hydraulic head 900 [mm] condition. With increasing gas flow rate, liquid flow rate of the predicted results was up and down. In addition, there is a flexion point. The liquid flow rate was reached to 0 [g/s] with a certain gas flow rate. This result fits the visualized observation result with no self-priming. In case of hydraulic head 900[mm], the result reaching to 0 [g/s] was same. As a result, it is considered that there is operation limit
of the VS with any hydraulic head. Why does self-priming of the VS stop. We considered that the results show the operation limit of the VS with two reasons; effects by gas single phase flow and gas-liquid two-phase flow.

Compared the experimental results with the analysis results of the liquid flow rate, but of course, peak point was misaligned each other, there were tendency to have a peak regardless of hydraulic head. Furthermore, compared pressure at throat with liquid flow rate results, gas mass flow rates of each peak point were fit. On the right side area from the peak points, the pressure at throat was increasing, so liquid flow rate decreased with decreasing the pressure difference for self-priming. As a result, it is expected that the reason of the air exhaust from the hole for suction on experimental results with the gas mass flow rate 9.7 [g/s] was pressure balance reverses between inside and outside of the hole with increasing gas flow rate.

As a result of the theoretical analysis, the pressure increasing in throat part over a certain gas flow rate is likely for all structure has a venturi shape. To avoid the condition, it needs to control gas flow rate with valve, to diverge gas into a number of the VS and so on. Alternatively, it needs proper placement and design for the hole on the understanding pressure distribution in detail in the VS.

5. Conclusion

To understand the operation characteristics of the Venturi scrubber for the filtered venting, we have studied about the self-priming phenomena and the hydraulic behavior. The one dimensional theoretical analysis, experimental observation and measurement were conducted. From these results, by analysis of them and cross comparison, we discussed about the mechanism of the self-priming as the operating characteristics of the VS and relationship between the self-priming and the hydraulic behavior. As results, we obtained following knowledge.

- Occurrence of self-priming phenomena with gas inflow to the VS was confirmed.
- With the self-priming, the dispersed flow and film flow are formed and these hydraulic behavior has smooth and complicated flow area in a certain gas flow rate range.
- In a certain higher gas flow rate, the VS lapses into suspension mode of the self-priming by reach to the sonic velocity in the throat part and pressure increasing in the VS.

Fig. 11 Liquid flow rate experimental results and theoretical analysis results has the same tendency qualitatively. The tendency is liquid flow rate becomes up, down and reaches to 0 [g/s] with increasing gas flow rate. $p_{th}$ has opposite tendency against liquid flow rate results. Solid line shows the liquid flow rate calculated by theoretical analysis. Plot shows the experimental liquid flow rate. Red means with no hydraulic head and blue does with the head 900 [mm]. Green dot line shows $p_{th}$. 
• It is possible that gas flow changes with increasing gas flow rate effects on hydraulic behavior like as complicated flow formation.

Nomenclature

Symbols

- \( A \) : Cross-section area [m\(^2\)]
- \( G \) : Mass flow rate [kg/s]
- \( g \) : Acceleration of gravity [m/s\(^2\)]
- \( H \) : Head [m]
- \( h \) : Enthalpy [m\(^2\)/s\(^2\)]
- \( j \) : Superficial velocity [m/s\(^2\)]
- \( M \) : Mach number [-]
- \( p \) : Pressure [Pa]
- \( q \) : Internal heat value per unit volume [W/m\(^3\)]
- \( T \) : Temperature [°C]
- \( u \) : Velocity [m/s]
- \( x \) : Coordinate [m]
- \( \gamma \) : Specific heat ratio [-]
- \( \rho \) : Density [kg/m\(^3\)]

Subscripts

- \( 0 \) : Stagnation point
- \( 1 \) : Upstream side
- \( 2 \) : Downstream side
- \( G \) : Represents gas phase
- \( L \) : Represents liquid phase
- \( th \) : Throat part
- \( out \) : Outlet
- \( \infty \) : Atmosphere

References


