Two-phase pressure drops of Staggered Mini Channel Printed Circuit Heat Exchanger

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1. Introduction

Heat exchangers have been widely used for various purposes such as heat recovery, freezing, and industrial systems. These days, high efficiency and small heat exchangers are demanding. A PCHE(Printed Circuit Heat Exchanger) is an integrated plate heat exchanger developed by applying chemical etching, which is manufactured by stacking etching-flow-channel plates using diffusion bonding. One advantage of PCHE is that this technology can increase the coefficient of heat transfer while increasing the coefficient of friction. This is due to a smaller flow channel diameter, resulting in a greater pressure drop in the heat exchanger.

Researchers have tried to analyze the characteristics of hydraulic performance by predicting pressure drops in various types of PCHE. Ngo et al. [1] evaluated PCHE with S-shaped fin configurations. The performance of the modeled PCHE was compared to that of the zig-zag channel configuration PCHE. Nikitin et al. [2] investigated the performance of PCHE in supercritical CO2 loops. The research proposed empirical correlations for predicting local heat transfer coefficients and pressure drops as a function of Reynolds numbers. Kim et al. [3] investigated a hydraulic performance of microchannel PCHE. Chen et al. [4] applied PCHE to the High Temperature Helium test Facility (HTHF) and conducted an experiment under pressure of 3Mpa.

A variety of correlations exist to get the two-phase friction multipliers. In the past, correlations inferred under individual experimental conditions can be identified, and in recent years, general correlations are induced based on the large databases created before.

2. Design and Experimental apparatus

Figure 1. shows a two-phase pressure drop experimental system. Following the single-phase pressure drop experiment in Hwang et al.(2020), the pressure drop experiment at the two-phase flow was conducted [5]. In order to obtain the two-phase friction multiplier, the single-phase friction correlation was referred. Two-phase pressure drop can calculate through multiplying with single-phase pressure drop and a two-phase friction factor. Therefore, to obtain the two-phase friction multiplier, the pressure of the two-phase pressure drop obtained through the experiment was divided by the single-phase pressure drop.

\[
\frac{dp}{dz}_F = \phi_L \left( \frac{dp}{dz}_L \right) = \phi_G \left( \frac{dp}{dz}_G \right)
\]

Water and air are mixed in the mixer and injected into the test section. The total length of the test section is 1700mm. The height of the ports measuring the pressure drop are 400mm and 1405mm from the entrance of the test section, considering the fully developed region of the velocity field. To get the hydraulic diameter, take the value by CAD to get a volume and wetted area of staggered geometry [6].

\[
D_h = \frac{4A}{P} = \frac{4AL}{PL} = \frac{4V}{A_{wet}}
\]

\[
- A : \text{area [m}^2]\n- P : \text{perimeter [m]}\n- V : \text{volume [m}^3]\n\]
- $L$: length [m]
- $A_{wet}$: wetted area [m$^2$]

It was tested using room temperature water, with a water flow range of 0.50 to 3.50LPM and an air flow range of 0.1 to 4.0LPM. Range of Reynolds numbers by flow rate is $422 < Re_L < 2955$, $14 < Re_G < 570$. The experimental results in Hwang et al.(2020) show that the range of Reynolds numbers separating laminar from turbulence in the features of this geometry is approximately 900 [5]. Therefore, the range of water flow rates used in the experiment shows both laminar and turbulence, and only the laminar region can be observed in the range of air flow rates. Correlations compared to experimental results are listed in Table 1.

The differential pressure transmitter used in this experiment is a Sensys with a measurable range 0 to 300kPa. The pump used in this experiment is pedro company’s PV55-50Hz and the flowmeter used is KI flowmeter’s KIF 500 series.

3. Results and Discussion

Figure 3 compares the two-phase friction factor based on the Martinelli parameter and experimental two-phase friction factor. In the lower range of Martinelli parameters, the two-phase friction factor has a higher value than the correlation, and as it increases to the higher range, and converges to the correlation equation following the Martinelli parameter increases. As noted on equation (1), when two-phase friction factor getting closer to 1, two-phase pressure drop value converges to that of single-phase pressure drop.

\[
\frac{dP}{dz}_P = \phi_1 \left( \frac{dP}{dz}_L \right)_{L}, \quad \phi_2 = 1 + \frac{C}{X} + \frac{1}{X^2}, \quad X^2 = \frac{(dP/dz)_L}{(dP/dz)_G}
\]

Table 1. Two-phase friction multiplier correlation

<table>
<thead>
<tr>
<th>Authors</th>
<th>Equation</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| Lockhart and Martinelli [5] | \[
\frac{dP}{dz}_P = \phi_1 \left( \frac{dP}{dz}_L \right)_{L}, \quad \phi_2 = 1 + \frac{C}{X} + \frac{1}{X^2}, \quad X^2 = \frac{(dP/dz)_L}{(dP/dz)_G}
\] | Hydraulic diameter 1.49~25.83 [mm], water, oils, hydrocarbons |
| Kim and Mudawar [6] | \[
\begin{align*}
S_{uG0} &= \frac{\rho_s \phi D_b}{\mu G}, \\
Re_L &= \frac{G \phi D_b}{\mu L}, \\
Re_G &= \frac{G \phi D_b}{\mu G}, \\
Re_{Lo} &= \frac{G \phi D_b}{\mu L}
\end{align*}
\] | Hydraulic diameter 0.0695~6.22 [mm], Mass flux 4.0~9528 [kg/m$^2$s] |

The gap between the difference of the friction factors and those obtained in the experiment is shown in Table 2, and error is calculated using equation (3). Table 2 shows the results obtained from comparing with Lockhart and Martinelli correlation.

\[
Error = \frac{\text{Theo} - \text{Exp}}{\text{Exp}} \times 100(\%)
\]
Table 2. Comparison of Lockhart and Martinelli correlation

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Gas</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>Laminar</td>
<td>126.90</td>
</tr>
<tr>
<td>Turbulent</td>
<td>Laminar</td>
<td>21.42</td>
</tr>
<tr>
<td>Laminar + Turbulent</td>
<td>Laminar</td>
<td>56.58</td>
</tr>
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</table>

Table 3 shows the results from Kim and Mudawar correlation. The result of Kim and Mudawar correlation have much less error percentages than Lockhart and Martinelli correlation. The less error value of the Kim and Mudawar correlation is an expression formed based on a wider database than the Lockhart and Martinelli correlation, since it is improved from Lockhart and Martinelli correlation. A lower Martinelli parameter indicates a smaller pressure drop on the water side and a lower flow rate. Thus, in areas with high Martinelli parameters as show in Table 2, mass flux on the water side is high, and it is estimated that the channel in the staggered type does not flow into the space on the fins and on the bottom, but flows like a single flow path.

Table 3. Comparison of Kim and Mudawar correlation

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Gas</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>Laminar</td>
<td>23.83</td>
</tr>
<tr>
<td>Turbulent</td>
<td>Laminar</td>
<td>18.27</td>
</tr>
<tr>
<td>Laminar + Turbulent</td>
<td>Laminar</td>
<td>20.12</td>
</tr>
</tbody>
</table>

4. Conclusions

The two-phase pressure drop experiment were conducted on the staggered mini channel. The Reynolds numbers for liquid used in the experiment is 422~2955, and gas Reynolds number range is 14~570. Liquid is the range of both laminar and turbulent, but for gas, the range corresponding to laminar. Based on above range, the difference was checked by comparing two different correlations. Kim and Mudawar correlations have much less difference compare to Lockhart and Martinelli correlation. The two-phase friction factor results requires modification to lower Martinelli parameter range.

Acknowledgement

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