PERFORMANCE MEASUREMENT AND VISUALIZATION ON THE REFRIGERANT DISTRIBUTION IN THE VERTICAL MANIFOLD OF THE MICROCHANNEL TUBE HEAT EXCHANGER

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THESIS
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Abstract

This project studies the liquid refrigerant distribution of an intermediate vertical manifold in a multi-pass evaporator.

A new test rig is designed and built to circulate R410A through the vertical microchannel manifold. Refrigerant is circulated into the manifold through the lower set of parallel microchannels and exits through the upper set. Three experimental circular manifolds were developed, each with the microchannels inserted to half depth. The first is an aluminum manifold used in industry with 5 inlet and 5 exit microchannels; the second is a transparent replica of the first; the third is a transparent manifold with 10 inlet and 10 exit microchannels used to study the effect of increasing manifold length and microchannel number.

The inlet mass flow rate ($m_{in}$) and quality ($x$) are two main parameters affecting the distribution. The inlet quality was varied from 0.2 to 0.8, and the inlet mass flow rate was varied from 0.8 to 4.5 g/h per microchannel. For all three manifolds, the best distribution is generally found at high $m_{in}$ and low $x$, and the worst at high $x$ and extreme values of $m_{in}$. At low qualities, 0.2 and 0.4, the distribution improves with increasing mass flow rate, and at high qualities, 0.6 and 0.8, the distribution is optimum at intermediate mass flow rates, and gets worse as $m_{in}$ increases or decreases. Likewise, for a fixed mass flow rate, the distribution generally improves as quality decreases. A comparison of the two transparent headers shows that increasing the number of microchannels in the header generally improves the distribution.

The two-phase flow regimes bubbly flow, churn flow and semi-annular flow are observed through visualization results. The flow regime is dependent on $m_{in}$ and $x$. At constant $m_{in}$, increasing the inlet quality would transition the flow regime from bubbly, to churn, and then to semi-annular flow. At a fixed intermediate inlet quality (e.g., 0.4), the flow regime would change from churn to semi-annular as $m_{in}$ increases. The variation of liquid distribution closely follows the transition of flow regime. Based on the visualization results and force balance analysis, the liquid distribution is mainly determined by the competition between the inertial and buoyancy forces. The force balance determines where liquid goes, and further determines the distribution. Froude number is an appropriate parameter to predict the flow regime. However, it is not good enough to predict the distribution because it does not include the important effects of top pressure.
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<table>
<thead>
<tr>
<th>variable</th>
<th>unit</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>[m]</td>
<td>diameter of the manifold</td>
</tr>
<tr>
<td>Fr</td>
<td>[-]</td>
<td>Froude number</td>
</tr>
<tr>
<td>G</td>
<td>[kg/m(^2)s]</td>
<td>effective mass flux in the manifold</td>
</tr>
<tr>
<td>h(_{\text{sub}})</td>
<td>[kJ/kg]</td>
<td>enthalpy at the subcooled point</td>
</tr>
<tr>
<td>h(_{\text{sup1}})</td>
<td>[kJ/kg]</td>
<td>enthalpy at the superheated outlet of the 1(^{st}) branch</td>
</tr>
<tr>
<td>h(_{\text{sup2}})</td>
<td>[kJ/kg]</td>
<td>enthalpy at the superheated outlet of the 2(^{nd}) branch</td>
</tr>
<tr>
<td>h(_{\text{sup3}})</td>
<td>[kJ/kg]</td>
<td>enthalpy at the superheated outlet of the 3(^{rd}) branch</td>
</tr>
<tr>
<td>h(_{\text{sup4}})</td>
<td>[kJ/kg]</td>
<td>enthalpy at the superheated outlet of the 4(^{th}) branch</td>
</tr>
<tr>
<td>h(_{\text{sup5}})</td>
<td>[kJ/kg]</td>
<td>enthalpy at the superheated outlet of the 5(^{th}) branch</td>
</tr>
<tr>
<td>h(_{\text{out1}})</td>
<td>[kJ/kg]</td>
<td>enthalpy entering the 1(^{st}) branch</td>
</tr>
<tr>
<td>h(_{\text{out2}})</td>
<td>[kJ/kg]</td>
<td>enthalpy entering the 2(^{nd}) branch</td>
</tr>
<tr>
<td>h(_{\text{out3}})</td>
<td>[kJ/kg]</td>
<td>enthalpy entering the 3(^{rd}) branch</td>
</tr>
<tr>
<td>h(_{\text{out4}})</td>
<td>[kJ/kg]</td>
<td>enthalpy entering the 4(^{th}) branch</td>
</tr>
<tr>
<td>h(_{\text{out5}})</td>
<td>[kJ/kg]</td>
<td>enthalpy entering the 5(^{th}) branch</td>
</tr>
<tr>
<td>L</td>
<td>[m]</td>
<td>length from the bottom microchannel to the top one</td>
</tr>
<tr>
<td>LF</td>
<td>[-]</td>
<td>liquid fraction</td>
</tr>
<tr>
<td>m</td>
<td></td>
<td>mass</td>
</tr>
<tr>
<td>m(_{\text{bar_L}})</td>
<td>[g/s]</td>
<td>average liquid mass flow rate of the five branches</td>
</tr>
<tr>
<td>m(_{\text{in}})</td>
<td>[g/s]</td>
<td>inlet mass flow rate</td>
</tr>
<tr>
<td>m(_{\text{dot_out1}})</td>
<td>[g/s]</td>
<td>two-phase mass flow rate in the 1(^{st}) branch</td>
</tr>
<tr>
<td>m(_{\text{dot_out2}})</td>
<td>[g/s]</td>
<td>two-phase mass flow rate in the 2(^{nd}) branch</td>
</tr>
<tr>
<td>m(_{\text{dot_out3}})</td>
<td>[g/s]</td>
<td>two-phase mass flow rate in the 3(^{rd}) branch</td>
</tr>
<tr>
<td>m(_{\text{dot_out4}})</td>
<td>[g/s]</td>
<td>two-phase mass flow rate in the 4(^{th}) branch</td>
</tr>
<tr>
<td>m(_{\text{dot_out5}})</td>
<td>[g/s]</td>
<td>two-phase mass flow rate in the 5(^{th}) branch</td>
</tr>
<tr>
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<td>[g/s]</td>
<td>liquid mass flow rate in the 1(^{st}) branch</td>
</tr>
<tr>
<td>m(_{\text{dot_Lout2}})</td>
<td>[g/s]</td>
<td>liquid mass flow rate in the 2(^{nd}) branch</td>
</tr>
<tr>
<td>m(_{\text{dot_Lout3}})</td>
<td>[g/s]</td>
<td>liquid mass flow rate in the 3(^{rd}) branch</td>
</tr>
<tr>
<td>m(_{\text{dot_Lout4}})</td>
<td>[g/s]</td>
<td>liquid mass flow rate in the 4(^{th}) branch</td>
</tr>
<tr>
<td>m(_{\text{dot_Lout5}})</td>
<td>[g/s]</td>
<td>liquid mass flow rate in the 5(^{th}) branch</td>
</tr>
<tr>
<td>n</td>
<td>[-]</td>
<td>number of branches</td>
</tr>
<tr>
<td>P(_{\text{in}})</td>
<td>[kPa]</td>
<td>pressure at the inlet of the test section</td>
</tr>
<tr>
<td>P(_{\text{out}})</td>
<td>[kPa]</td>
<td>pressure at the outlet of the test section</td>
</tr>
<tr>
<td>Q(_{\text{in}})</td>
<td>[W]</td>
<td>power needed to heat to certain quality</td>
</tr>
<tr>
<td>Q(_{\text{dot_out1}})</td>
<td>[W]</td>
<td>power needed to heat to the superheat point in the 1(^{st}) branch</td>
</tr>
<tr>
<td>Q(_{\text{dot_out2}})</td>
<td>[W]</td>
<td>power needed to heat to the superheat point in the 2(^{nd}) branch</td>
</tr>
<tr>
<td>Q(_{\text{dot_out3}})</td>
<td>[W]</td>
<td>power needed to heat to the superheat point in the 3(^{rd}) branch</td>
</tr>
<tr>
<td>Q(_{\text{dot_out4}})</td>
<td>[W]</td>
<td>power needed to heat to the superheat point in the 4(^{th}) branch</td>
</tr>
<tr>
<td>Q(_{\text{dot_out5}})</td>
<td>[W]</td>
<td>power needed to heat to the superheat point in the 5(^{th}) branch</td>
</tr>
<tr>
<td>T(_{\text{in}})</td>
<td>[°C]</td>
<td>temperature at the inlet of test section</td>
</tr>
<tr>
<td>T(_{\text{out1}})</td>
<td>[°C]</td>
<td>temperature at the outlet of the 1(^{st}) branch</td>
</tr>
<tr>
<td>variable</td>
<td>unit</td>
<td>description</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>T_out2</td>
<td>[°C]</td>
<td>temperature at the outlet of the 2\textsuperscript{nd} branch</td>
</tr>
<tr>
<td>T_out3</td>
<td>[°C]</td>
<td>temperature at the outlet of the 3\textsuperscript{rd} branch</td>
</tr>
<tr>
<td>T_out4</td>
<td>[°C]</td>
<td>temperature at the outlet of the 4\textsuperscript{th} branch</td>
</tr>
<tr>
<td>T_out5</td>
<td>[°C]</td>
<td>temperature at the outlet of the 5\textsuperscript{th} branch</td>
</tr>
<tr>
<td>T_sub</td>
<td>[°C]</td>
<td>temperature at the subcooled point</td>
</tr>
<tr>
<td>T_sup</td>
<td>[°C]</td>
<td>temperature at the superheat point</td>
</tr>
<tr>
<td>U_{X,j}</td>
<td>[-]</td>
<td>uncertainty of independent variable</td>
</tr>
<tr>
<td>U_Y</td>
<td>[-]</td>
<td>uncertainty of dependent variable</td>
</tr>
<tr>
<td>v</td>
<td>[m/s]</td>
<td>velocity</td>
</tr>
<tr>
<td>x_in</td>
<td>[-]</td>
<td>inlet quality</td>
</tr>
<tr>
<td>x_dot_out1</td>
<td>[-]</td>
<td>quality entering the 1\textsuperscript{st} branch</td>
</tr>
<tr>
<td>x_dot_out2</td>
<td>[-]</td>
<td>quality entering the 2\textsuperscript{nd} branch</td>
</tr>
<tr>
<td>x_dot_out3</td>
<td>[-]</td>
<td>quality entering the 3\textsuperscript{rd} branch</td>
</tr>
<tr>
<td>x_dot_out4</td>
<td>[-]</td>
<td>quality entering the 4\textsuperscript{th} branch</td>
</tr>
<tr>
<td>x_dot_out5</td>
<td>[-]</td>
<td>quality entering the 5\textsuperscript{th} branch</td>
</tr>
<tr>
<td>X_j</td>
<td>[-]</td>
<td>independent variable</td>
</tr>
<tr>
<td>Y</td>
<td>[-]</td>
<td>dependent variable</td>
</tr>
<tr>
<td>ρ_l</td>
<td>[kg/m\textsuperscript{3}]</td>
<td>liquid density</td>
</tr>
<tr>
<td>ρ_v</td>
<td>[kg/m\textsuperscript{3}]</td>
<td>vapor density</td>
</tr>
<tr>
<td>σ</td>
<td>[-]</td>
<td>maldistribution ratio</td>
</tr>
<tr>
<td>τ</td>
<td>[kg m\textsuperscript{2}/s]</td>
<td>angular momentum</td>
</tr>
</tbody>
</table>
1 Introduction

It is widely acknowledged that maldistribution multi-pass microchannel evaporator reduces hydraulic and thermal performance. This is because it causes higher pressure drop and decreases the heat transfer coefficient. Both of these reduce the efficiency of the HVAC system.

This project extends the maldistribution study into the intermediate manifold of an evaporator with parallel microchannels. The experimental tests will be done in three types of vertical manifolds. The aluminum manifold is designed as a part of the evaporator in the residential AC unit. The first transparent manifold is to simulate the liquid distribution of the aluminum manifold. And the second transparent manifold is to study the effects of increasing the manifold length and microchannel number. R410a is chosen as the working fluid. The inlet mass flow rate and quality are the two main parameters in this study. The project was devised to understand what the distribution would be if the inlet mass flow rate, quality or both change.

This report comprises six other chapters. Chapter 2 reviews the previous ACRC projects and papers from other institutes. Chapter 3 covers the description of experiment facilities. Chapter 4 discusses the results of the 5+5 aluminum manifold and the distribution profiles. Chapter 5 analyzes the results and distribution profiles of the 5+5 transparent manifold. Chapter 6 presents the results and distribution profiles of 5+10 transparent manifold. Finally, the visualization images are illustrated in Chapter 7. The flow regimes are defined and they are compared with the distribution profiles.
2 Literature Review

Since the refrigerant distribution in the evaporator plays such an important role to the performance of HVAC&R systems, it has been greatly studied. The single phase fluid (water or air) was first used, Keller (1949). The guideline to design a manifold with uniform distribution in single phase condition was available, Samson et al. (1987). Then, the two-phase effects attracted more attention. The air-water mixture became the working fluid, Rong (1995), Osakabe et al. (1999), Webb and Chung (1999). It was found that the presence of two-phase refrigerant significantly changed the distribution features. In recent years, the two-phase refrigerant was more commonly used to consider the effects of fluid properties. The results from the combined tests show that maldistribution is a very complicated problem that is affected by many parameters. These include manifold geometry and orientation, fluid properties, inlet mass flux and quality, etc.

2.1 ACRC Projects

Beaver et al. (1999) investigated the maldistribution of R744 in a tilted microchannel heat exchanger by measuring the outlet air temperature at different locations. Two types of maldistribution are found: one in the horizontal manifold and the other in the ports of a single microchannel tube. It was shown that more liquid appeared at the end of the header and the back ports of a single microchannel tube. Three heat exchangers with different inlet types were tested. One heat exchanger with flash gas bypass had a better distribution profile, and consequently better system performance.

Song and Bullard (2002) first conducted experiments in a MAC2 indoor evaporator with a conical distributor. They modeled and validated the maldistribution problem with heat transfer by measuring the superheat at the outlets. A capacity drop due to maldistribution was presented. In a microchannel type evaporator, the maldistribution was investigated by inspecting the frost on the evaporator. Results showed that in a vertical manifold, the distribution of R744 was more uniform at low quality. At high qualities, the tubes near the bottom or top received less liquid due to the balance between inertial, gravitational and shear forces.

Tompkins et al. (2002) modeled and experimentally studied the maldistribution in a microchannel evaporator’s manifold. The adiabatic manifold was placed horizontally with downward flow in microchannels. Single phase air and water as well as two-phase air-water mixture were used as the working fluid. The tests were conducted at different inlet mass flux
and qualities. The distribution was good when the manifold area ratio was low. When the manifold cross sectional area was large, the model matched the experiment data.

Yoo et al. (2002) presented the distribution results of air-water in a microchannel evaporator. The flow regimes in both the horizontal and vertical manifolds were defined and used to explain the distribution profiles. For the horizontal manifold, when the inlet tube was longer, the distribution was better. However, no specific trend on the reduced data was found. The impacts from quality and mass flux were not obvious. For the vertical manifold, the distribution was less uniform at downward flow (short inlet) than upward (long inlet). The impacts from quality and mass flux on the normalized STD were also not obvious.

Zhang et al. (2003) continued Yoo et al. (2002)'s work by replacing air-water with R134a in a horizontal manifold. The variables that were looked into included inlet mass flux, inlet quality, flow developing region length and flow path cross-sectional area. The distribution was improved by increasing mass flux and quality, or when the entrance distance was short. A similar normalized analysis was also conducted in order to find the correlations between flow parameters and distribution results.

Fei and Hrnjak (2004) focused on the experimental study and CFD simulation of R134a flow in manifolds. Reasonable simulation results from FLUENT 6 were presented. They were compared with the experiment data and visualization images. The idea to relate the inlet flow development with the distribution result was presented. Changing the inlet mass flux and inlet quality would vary the flow pattern either in the inlet tube or in the manifold. This further changed the distribution profile. The flow regime map concerning the maldistribution was constructed. Dimensional analysis also showed that the non-dimensional Fr, Re and We were the most important parameters. Among the primary parameters, inlet quality seemed to have more impact.

Bowers et al. (2006) looked into the maldistribution in a horizontal rectangular and a horizontal circular manifold. They considered the effects of microchannel protrusion, mass flux, quality and inlet distance. The protrusion depth and inlet distance were the two most important parameters. Increasing either the quality or mass flux would barely improve the distribution. However, increasing the depth of microchannel protrusion would do the job. When the entrance distance was short, better distribution was found. They also analyzed the distribution profiles with the visualization results. They found that the distribution in the manifold had to do with the flow regime both in front of and in the manifold.
Elbel and Hrnjak (2004) expanded Beaver et al. (1999)’s work on flash gas bypass. They further confirmed that flash gas bypass would improve the distribution because ideally single phase liquid would be provided to the evaporator.

2.2 Other Papers

Watanbe et al. (1995) studied the maldistribution of R11 in both horizontal and vertical manifolds in an adiabatic condition. Although the maldistribution features were different in the horizontal and vertical manifold, the data trend was observed to be similar, and it also corresponded to the inlet flow condition, i.e. mass flow rate and quality. A predicting equation was developed and validated. Vapor Reynolds number and/or liquid Weber number were the variables in the equation. The flow pattern in the inlet main pipe was also noticed.

Vist and Peterson (2004) elucidated the effect of factors on the distribution, including inlet vapor fraction, heating load, manifold diameter and inlet tube length. Both the horizontal and vertical manifolds were investigated. Refrigerant R134a was used. Results showed the vapor fraction had more effect on the distribution than mass flow rate and heating load. An analysis about the inlet flow pattern was tried to explain the maldistribution.

Cho and Cho (2006) found the effect of manifold orientation on the distribution. Their experiments were conducted in a microchannel heat exchanger with R22. The heat exchanger was heated sometimes, and other times not heated. They also found the inlet quality (range from 0.1 to 0.3) has negligible effect on the distribution.

In Hwang et al.’s experiments (2007), the maldistribution of R410a in a horizontal manifold of a minichannel evaporator was examined. The minichannel tubes were heated. The effect of flow pattern was illustrated by showing the visualization results. It was also shown that the inlet location and mass flow rate strongly affected the distribution.

Lee (2008) conducted experiments in an adiabatic vertical manifold with air and water. The visualization results showed three regions were formed in the manifold in all test conditions. Both the flow separation location and recirculation in the manifold affect the distribution shape.

Brix et al. (2009) modeled and validated the microchannel evaporator’s performance considering maldistribution effect. The maldistribution of both refrigerant and air side reduced the cooling capacity significantly.

It is noteworthy that most of the above experiments are done in low qualities, i.e. <0.5, because the inlet manifold is the one modeled. It is the first manifold in a multipass evaporator,
so the feeding fluid is mostly provided by a single circular tube from the expansion valve at low qualities. In this project, the intermediate manifold in a multipass evaporator is studied. The refrigerant is provided by multi-parallel microchannel tubes from the inlet manifold at different levels of qualities.
3 Experimental Facilities

3.1 Test System Design

The test loop has been constructed to model the distribution in the microchannel evaporator with R410a. Figure 3-1 is the schematic of the experimental system. The liquid refrigerant is pumped into the inlet manifold while the inlet mass flow rate is measured. The design of the inlet manifold section is shown in Figure 3-2. The liquid refrigerant is assumed to distribute evenly into the 5 microchannel tubes, where the refrigerant is heated to the desired quality.
The connection between the inlet manifold section and test manifold section is accomplished by using the fitting in Figure 3-3. The microchannel tube is inserted through the side block, o-ring and into the center block from each side. An o-ring is placed in the chamfered groove of the center block to seal the microchannel tubes. The three blocks are tightened with the nuts and bolts. This solution will allow easy replacement of the test section with a transparent manifold or new geometry manifold.

![3D Drawing](image1.png)  ![Actual Photograph](image2.png)

**Figure 3-3: Connections of Two Microchannel Tubes**

![Test Manifold Section Design Schematic](image3.png)

**Figure 3-4: Test Manifold Section Design Schematic**
The design of the test manifold section is shown in Figure 3-4. Three models are developed and tested. The first is aluminum manifold with five parallel microchannels as inlet tubes, and the other five as the outlet tubes, Figure 3-4. The other two models are 5+5 transparent manifold and the 5+10 transparent manifold. The transparent ones will be discussed later. In the test manifold, due to the effect of maldistribution, different amounts of liquid refrigerant enter the five outlet microchannel tubes. In these tubes, the refrigerant will be heated again to reach a certain superheat. The same method is applied when connecting the test manifold section with the outlet tubes. The outlet tube is a microchannel-to-round tube. The design of it is shown in Figure 3-5. It facilitates the connection of the test section to the rest of the system. The actual photo of the whole test section is shown in Figure 3-6.

![Microchannel to Round Tube Connection Design](image)

**Figure 3-5: Microchannel to Round Tube Connection Design**

![Heat Exchanger Structure](image)

**Figure 3-6: Heat Exchanger Structure**

After measuring the mass flow rate in each outlet microchannel tubes, the superheated vapor is cooled in the condenser. There are two cooling systems to serve individually. When the test capacity is small, Cooling System A is applied. Vapor is cooled in a plate heat exchanger (PHX) by the ethylene glycol from the outdoor chiller. The flow rate of the ethylene glycol is adjusted by throttling and bypassing to match the capacity of the test section. When the test capacity is large, Cooling System B is applied. It is a typical refrigeration cycle including
evaporator, compressor, condenser and thermal expansion valve. Its capacity is controlled by a variable frequency drive (VFD) to match that of the test section.

After the vapor refrigerant is cooled, with the help of the subcooler and receiver, the subcool condition is ensured. The liquid goes back to the pump and completes the circulation.

3.2 Test Parameter

The target of this project is to search for the condition in which the maldistribution ratio \( \sigma \) is around 0.1, although when \( \sigma =0 \), the distribution is strictly uniform. \( \sigma \) is defined as

\[
\sigma = \frac{1}{\bar{m}_L} \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\dot{m}_{\text{Lout,}i} - \bar{m}_L)^2}
\]  

\( \dot{m}_{\text{Lout,}i} \): mass flow rate of the liquid refrigerant in the \( i \)th passage.

It is easy to show the maldistribution result with one number using this method. However, in order to illustrate the distribution profile, it is necessary to apply the liquid fraction method. This method was discussed by Fei and Hrnjak (2004). The liquid fraction is defined as

\[
LF = \frac{\dot{m}_{\text{Lout,}i}}{\sum_{i} \dot{m}_{\text{Lout,}i}}
\]  

3.3 Thermodynamic Processes

![P-h Diagram of the Thermodynamic Process](image)
The thermodynamic processes are shown in the P-h diagram of R410a, Figure 3-7. Before entering into the inlet manifold, the temperature $T_{in}$ and pressure $P_{in}$ are measured to ensure the subcooling. Likewise, the outlet temperature $T_{out,i}$ for each microchannel is measured to ensure the superheating. The outlet pressure $P_{out}$ of only one tube is measured and the others are assumed to be the same.

Knowing the subcooling point, the amount of heat can be determined in order to reach certain quality $x_{in}$, e.g. 0.2, by calculating $h_{sub}$. This method determines the test condition of inlet quality. For each of the outlet microchannels, as the superheat point is known, which means $h_{sup,i}$ is known, the outlet enthalpy $h_{out,i}$ can be calculated by measuring the power of the heaters $\dot{Q}_{out,i}$ and the 2-phase mass flow rate $\dot{m}_{out,i}$,

$$h_{out,i} = h_{sup,i} - \frac{\dot{Q}_{out,i}}{\dot{m}_{out,i}}$$  \hspace{1cm} (3-3)

Now, the outlet quality $x_{out,i}$ can be found from the P-h diagram combining $h_{out,i}$ with $P_{out}$. Since $x_{out,i}$ is also the ratio of vapor mass flow rate to 2-phase mass flow rate, $m_{out,i}$ can be calculated. Finally, $\sigma$ can be evaluated based on its definition.

3.4 Equipment
3.4.1 Microchannel Tube Description

The microchannel tube used in this project has 17 ports. The cross section width is 13.6mm, while the thickness is 1mm. Each port’s width is on the order of 0.5mm. The hydraulic diameter of the microchannel tube is 0.52mm. The total length in the test manifold section is about 330 mm.

![Figure 3-8: Microchannel Cross Section](image)
3.4.2 Transparent Manifold Description

Several methods of making the transparent manifold are studied. The final solution is shown in Figure 3-9. The manifold is made of the PVC tube with ID 1/4” and schedule 40. The gap between microchannel tube and PVC tube is sealed by applying JB-WELD on both inside and outside of the PVC tube. It also serves to hold the microchannel tubes to a certain depth, e.g. half of the ID. In addition, an epoxy block is made to increase the pressure tolerance and ensure the transparency outside the PVC tube. The manufacturing process is shown in Figure 3-10. A polypropylene mold is made at first, and then the manifold with microchannel tubes is held with the clamp. It allows the epoxy to be poured into the mould until it solidifies.

Figure 3-9: Final model of the Transparent Manifold
3.4.3 Visualization Equipment

Based on the previous study, Bowers and Hrnjak (2008), a high speed camera is used for visualizing the flow structures in the transparent manifold. The high speed camera, Model Phantom v4.2, is manufactured by Vision Research. The setup of the high speed camera and back lighting are shown in Figure 3-11. The details of this technology are discussed thoroughly in Bowers and Hrnjak (2008)’s paper. In this project, the exposure time of the camera is set from 80msec to 100msec. The framing rate is at 2200 frames per seconds. The resolution is set as 512x512 or 256x512. The visualization results are recorded using the manufacturer’s software. A screen shot of it is shown in Figure 3-12.

Figure 3-11: High Speed Camera Setup
3.4.4 Measuring Equipments Description and Accuracy Analysis

In the experiment, parameters are measured, including the temperature, pressure and mass flow rate, etc. The equipments to fulfill the measurement are discussed in this section. The accuracies of the equipments are also presented for later uncertainty calculation.

Temperature

The Quick Disconnect Thermocouples, manufactured by Omega Engineer Inc, are used to measure the temperatures. The manufacturer’s accuracy is ±0.5 °C.
Pressure

The inlet and outlet pressures are measured with Sensotec’s TJE model pressure transducers with the range up to 500 psig (≈3.35 MPa). The manufacturer’s accuracy is ±1%. They were calibrated by measuring the pressure and output voltage at several pressures, and applying the linear curve-fit.

Mass flow rate

The mass flow rate is measured using Micro Motion (coriolls type) mass flow meters. The model of the sensor for the inlet one is D 40, the model for the outlet ones are D 06, while the model of the transmitters are RFT 9712.
The inlet mass flow rate is controlled by adjusting the metering valve in the bypass of the gear pump and the variable frequency device (VFD), Figure 3-16. The VFD is manufactured by GE Fuji (Model: AF-300 E11, 3kW). The bypass valve is first set to a certain opening. Then the VFD automatically adjusts the mass flow rate during the experiments based on the measured value. The frequency can either be set from the panel or from a foreign signal. In this project, it is set by the signal from data logger, which is controlled by the VEE program in the computer. As the frequency changes, the speed of the pump varies. In this way, the inlet mass flow rate is adjusted.

![Figure 3-16: Equipments to Control Inlet Mass Flow Rate](image)

In determination of the adequacy of the mass flow meter, three factors should be considered. They include the pressure drop in Micro Motion, the manufacturer’s accuracy and the difference between Micromotions in series connection.

By checking the calibration chart from the manufacturer (Figure 3-17), the pressure drop is negligible (less than 0.1 bar) for D06, when vapor R410a passes through it. It is also negligible for liquid R410a going through D40. The manufacturer’s accuracy is ±0.15% for D06 and ±0.75% for D40.
To check equal readings of five outlet mass flow meters, they were connected in series and the flow rate was measured with water running, Figure 3-18. Results show (in Table 3-1 and Figure 3-19) that the deviation from the average value is ±15% for Test Condition #1, ±4% for Test Condition #2, and ±2% for the rest. They are satisfactory. Nevertheless, care should be taken when the flow rate is smaller as the deviation would be larger.
Table 3-1: Outlet Flow Meters Accuracy Check Results

<table>
<thead>
<tr>
<th>Micro Motion</th>
<th>Mass Flow Rate [g/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Condition #</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>MM #1</td>
<td>0.4916</td>
</tr>
<tr>
<td>MM #2</td>
<td>0.5439</td>
</tr>
<tr>
<td>MM #3</td>
<td>0.56098</td>
</tr>
<tr>
<td>MM #4</td>
<td>0.56625</td>
</tr>
<tr>
<td>MM #5</td>
<td>0.62375</td>
</tr>
<tr>
<td>Average (Ave)</td>
<td>0.557296</td>
</tr>
</tbody>
</table>

Figure 3-19: Difference between Flow Meters in Series Connection

Heater Power

Cartridge heaters are used in this system to either generate the inlet quality or ensure the superheat value. They are 1/4” diameter, 2” long with capacity of 200W at 240V. In order to deliver the heat evenly to the microchannel, the heater is put in an aluminum U-channel, and then covered with thermal conductive paste, Figure 3-20.
Thus, to provide sufficient heating capacity, each microchannel is equipped with six heaters. Each one is put onto surface of the microchannel and wrapped with aluminum tape. The heaters are insulated with fiberglass, so the heat loss to the atmosphere is neglected. The layout of the heaters is illustrated in the following picture (Figure 3-21).

The heaters of the inlet 5 microchannels are controlled all together with one VFD (GE Fuji AF-300 E11, 5kW). The heaters on the outlet microchannels are controlled individually for each microchannel with the VFD. Again, the frequency for VFD is set by the signal from the data logger. Since the output voltage is varied along with the frequency, the heaters’ power can be adjusted.
The power of the heaters is measured by the watt transducer from Ohio Semitronics, Inc. The model is GW5-024CX5, with the range from 0 to 16kW. The accuracy is ±0.2% of the reading.

3.4.5 Data Acquisition and System Control

Data Acquisition

All measured and control signals are acquired by data logger and recorded in the computer. The data is recorded using HP 75000B data logger (Figure 3-24). There are four different cards that can receive either the thermocouple signal directly or the 0-5V voltage.
signal which is then converted to the desired value using VEE program (Figure 3-25). There are another two D/A cards that are connected to the frequency drivers and used to control the VFD.

![Data Logger](image1.png)

**Figure 3-24: Data Logger**

**System Control**

![Screenshot of VEE Program](image2.png)

**Figure 3-25: Screen Shot of VEE Program**

The software VEE is used for recording the data as well as controlling the VFDs (for inlet mass flow rate and heater powers). A screen shot of the VEE interface is shown in Figure 3-25.

The inlet heaters are controlled in an open loop. The amount of heat is determined by the enthalpy difference between the subcooling point and the desired quality.

Control of the outlet heaters is in a closed loop. The power of the heaters varies based on the set superheat value. To meet the control requirements, certain parameters should be calculated first by linear fitting of the R410a P-h curve, which includes saturated liquid and vapor temperature based on saturated pressure as well as saturated liquid and vapor enthalpy based
on saturated temperature and/or pressure. The subcooling and superheating can be determined based on the calculated saturated liquid and vapor temperature. From the R410a P-h diagram, it is found that the isothermal curve beyond the saturated liquid line is nearly perpendicular to the x axis (enthalpy), so the enthalpy at the subcooling point is assumed to equal to that of the saturated liquid point at the temperature equal to the subcooling point. The curve-fit results are shown in Appendix A. With these values at hand, the power to reach certain quality and/or certain superheat can be determined.

By programming the above strategy into the VEE program, it is feasible to obtain the desired value and the measured value at the same time. Next, one must apply the proportional controller in VEE to let the data logger send certain signals to VFDs. Then, the adjustment can be made and the control of the test facility can be achieved.

3.5 Test Matrix

Three models of the manifold are tested: 5+5 aluminum, 5+5 transparent and 5+10 transparent manifolds. Other variables include quality (0.2, 0.4, 0.6, and 0.8) and mass flow rate (from 0.8 to 4.5 kg/h for each microchannel).
4  5+5 Aluminum Manifold

The distribution in the 5+5 aluminum manifold is investigated in this chapter. This type manifold serves as the shakedown tests and the baseline.

4.1  Test Conditions

According to the test matrix, the mass flow rate of R410a in each microchannel should cover the range from 0.8 to 4.5kg/h. In this type manifold, the details of the test conditions are shown in Table 4-1. Although the inlet mass flow rate should be tested from 1.11g/s to 6.25g/s, the system is not stable at 1.11g/s. Hence, the tests at this condition are not conducted, but it is possible to predict the distribution based on the results at other conditions. On the other hand, another two tests at 7.27g/s are taken, in order to find better distribution at low qualities.

<table>
<thead>
<tr>
<th>$m_{in}$ [g/s]</th>
<th>quality [-]</th>
<th>$m_{in}$ [g/s]</th>
<th>quality [-]</th>
<th>$m_{in}$ [g/s]</th>
<th>quality [-]</th>
</tr>
</thead>
<tbody>
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<td>1.11</td>
<td>0.2</td>
<td>4.19</td>
<td>0.2</td>
<td>7.27</td>
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</tr>
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<td></td>
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<td></td>
<td>0.4</td>
<td></td>
<td>0.4</td>
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<td></td>
<td>0.6</td>
</tr>
<tr>
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<td>0.8</td>
<td></td>
<td>0.8</td>
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<td>0.8</td>
</tr>
<tr>
<td>2.14</td>
<td>0.2</td>
<td>5.22</td>
<td>0.2</td>
<td></td>
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</tr>
<tr>
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<td></td>
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<td>0.4</td>
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<tr>
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<td>0.8</td>
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<td>0.8</td>
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<td>0.8</td>
</tr>
<tr>
<td>3.17</td>
<td>0.2</td>
<td>6.25</td>
<td>0.2</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td></td>
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<td>0.4</td>
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<td>0.6</td>
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<td>0.6</td>
<td></td>
<td>0.6</td>
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<tr>
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<td>0.8</td>
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<td>0.8</td>
<td></td>
<td>0.8</td>
</tr>
</tbody>
</table>

4.2  Test Results

The following is a notation schematic figure. It applies to the results of 5+5 manifolds.

Figure 4-1: Notation Schematic for 5+5 Manifold
4.2.1 Quality Effect at Same Mass Flow Rate

The distribution profiles are shown at certain inlet mass flow rate, from Figure 4-2 to Figure 4-7. The abscissa represents the liquid fraction while the ordinate represents the inlet quality. The extent of the color represents different branches, and the branches are grouped together at the same quality. In this way, it is convenient to observe how distribution results change when the quality varies at a fixed inlet mass flow rate. Generally, increasing the quality causes worse distribution. The results can be categorized into three groups.

Group 1 includes the results at $m_{in}=7.27$, 6.25 and 5.22g/s. Take $m_{in}=6.25$g/s for an example, Figure 4-3. The distribution is best at $x=0.2$. When $x$ increases, the distribution gets worse. Then, most of the liquid leaves the second branch, and there is less and less liquid at the bottom tubes. Group 3 includes the results at $m_{in}=3.17$ and 2.14g/s. Results of $m_{in}=3.17$ are taken as the example, Figure 4-6. The best distribution is also at $x=0.2$, and get worse when $x$ is larger. However, at high quality, most liquid leaves at the bottom tube instead of the second one. It looks like a reversed triangle shape at high quality of $m_{in}=3.17$, compared to the profile at $m_{in}=6.25$g/s at $x=0.8$. Group 2 only includes results at $m_{in}=4.19$g/s, Figure 4-5. It is similar to the transition from Group 1 to Group 3.
Figure 4-2: Distribution Profile @ $m_{in}=7.27\text{g/s}$ for 5+5 Aluminum Manifold

Figure 4-3: Distribution Profile @ $m_{in}=6.25\text{g/s}$ for 5+5 Aluminum Manifold
Figure 4-4: Distribution Profile @ $m_{in}=5.22g/s$ for 5+5 Aluminum Manifold

Figure 4-5: Distribution Profile @ $m_{in}=4.19g/s$ for 5+5 Aluminum Manifold
Figure 4-6: Distribution Profile @ $m_{in}=3.17\text{g/s}$ for 5+5 Aluminum Manifold

Figure 4-7: Distribution Profile @ $m_{in}=2.14\text{g/s}$ for 5+5 Aluminum Manifold
The following question may be raised: when the liquid fraction is small, is it because that there is little fluid (either vapor or liquid) in the tube or mainly vapor flowing in the tube? The following analysis clarifies this issue. The tests at $m_{in}=2.14g/s$ are chosen as an example. Figure 4-8 illustrates outlet qualities’ distribution as the inlet quality changes. Since the quality is the ratio of vapor mass flow rate to the two-phase mass flow rate, it indirectly shows the percentage of the liquid among the two-phase flow in each branch. In other words, it shows how much liquid is flowing in each branch.

![Figure 4-8: Comparison of quality $m_{in}=2.14g/s$ for 5+5 Aluminum Manifold](image)

Figure 4-8: Comparison of quality $m_{in}=2.14g/s$ for 5+5 Aluminum Manifold
Figure 4-9 shows the distribution of two-phase mass flow rate distribution at various inlet qualities. Figure 4-9 is interesting because it shows that, when the inlet flow rate is low, i.e. $m_{in}=2.14 \text{g/s}$, there is relatively small amount of fluid leaving from the highest branch, either vapor or liquid. Comparing these two figures with the distribution profiles in Figure 4-6, the outlet qualities' variation between the tubes seems to be a more important factor. Meanwhile, the difference between two-phase mass flow rates also has some impact. More figures like Figure 4-8 and Figure 4-9 at other test conditions are shown in Appendix C.
At the same inlet mass flow rate, take an average of the two-phase mass flow rate in each branch at various inlet qualities. The results are shown in Figure 4-10. The mark denotes the average value, while the bar shows the deviation from it. It illustrates that among all the test conditions, there is not enough fluid leaving from the highest tube. This is the main reason that uniform distribution is not reached. From this point of view, the inadequacy of the two-phase mass flow rates in the highest branch becomes the main factor.

Figure 4-10: 2ф Flow Rate Comparison for 5+5 Aluminum Manifold
4.2.2 Mass Flow Rate Effect at Same Quality

The same results are shown from Figure 4-11 to Figure 4-13, but in a different way. The abscissa still represents the liquid fraction, but the ordinate represents the inlet mass flow rate. In each figure, the quality is held constant. In this way, it is easy to look into how the inlet mass flow rate affects the distribution at certain quality. This is also related to the case when the speed of the compressor is changing.

At x=0.2, Figure 4-11, when the inlet mass flow rate decreases from 7.27g/s, the liquid amount in the highest branch reduces. However, the liquid fractions in other branches are almost not affected. The similar profiles for the bottom four branches are kept.

It is a different story when x=0.4, Figure 4-12. Similarly, there is less liquid in the highest branch when reducing the inlet mass flow rate. Comparing with the case when x=0.2, there is less liquid in the system, so the second branch follows the same trend as the first one: when the inlet mass flow rate is reducing, the liquid fraction keeps reducing. Meanwhile, the liquid fractions at the bottom tubes are increased. This changes the distribution profile significantly.

The variation of distribution profile looks similar for x=0.6 and 0.8, Figure 4-13 and Figure 4-14. At high $m_{in}$, most of the liquid leaves from the second highest branch. At low $m_{in}$, most of it leaves from the lowest branch. The distribution profile looks reversed, comparing it for $m_{in}=2.14g/s$ with that for $m_{in}=6.25g/s$. 
Figure 4-11: Distribution Profile @ x=0.2 for 5+5 Aluminum Manifold

Figure 4-12: Distribution Profile @ x=0.4 for 5+5 Aluminum Manifold
Figure 4-13: Distribution Profile @ x=0.6 for 5+5 Aluminum Manifold

Figure 4-14: Distribution Profile @ x=0.8 for 5+5 Aluminum Manifold

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4.2.3 Analysis of Maldistribution Ratio

Figure 4-15 shows the maldistribution ratio at all test conditions. None of the test conditions meets the desired value, i.e. $\sigma=0.1$. Among all the tests, when $m_{in}=7.27\text{g}/\text{s}$ and $x=0.2$, the distribution is the best. The worst case is at $m_{in}=2.14\text{g}/\text{s}$ and $x=0.8$. At low qualities of 0.2 and 0.4, the variation of $\sigma$ is singular. It keeps decreasing as $m_{in}$ is higher. For $x=0.8$ and 0.6, there is a minimum value of the maldistribution ratio. For $x=0.8$, it is at $m_{in}=4.19\text{g}/\text{s}$, and for $x=0.6$, it is at $m_{in}=5.25\text{g}/\text{s}$. Then, it is conceivable that there might be some minimum value for $x=0.4$ and 0.2, if the inlet mass flow rate were increased to a higher value. However, it is not reached yet in this project. The maldistribution ratio is presented in another way in Figure 4-16, versus the reduced mass flow rate. A similar parameter as this reduced mass flow rate can be found in Bowers et al (2004) (liquid scaled effective mass flux). An almost linear reduction is found in Figure 4-16, especially at low qualities.

![Figure 4-15: Maldistribution ratio for 5+5 Aluminum Manifold](image-url)
4.3 Uncertainty Analysis

The uncertainty analysis is conducted in EES. It is based on the known accuracy of the facilities, shown in Section 3.4.4. The basic calculation function is

$$U_Y = \sqrt{\sum_j \left( \frac{\partial Y}{\partial X_j} \right)^2 U_{X_j}^2}$$  \hspace{1cm} (4-1)

The results are shown in Figure 4-17 and Figure 4-18. In Figure 4-17, the uncertainties of σ are lower than 1% for all test conditions. The absolute value of this uncertainty is from 0.00006 to 0.0111, so σ is relatively accurate. Figure 4-18 shows that the accuracy of the liquid fraction is generally good. The absolute value of this uncertainty is from 0.0005 to 0.0031. In some cases, the liquid fractions seem to be not very accurate. It corresponds to the branch when there is only a little amount of liquid. For example, when \( m_{in}=2.14/\text{s} \) and \( x=0.8 \), the liquid fraction at the highest branch is 0.0093. And the uncertainty is as high as 180%. The absolute uncertainty doesn’t vary too much, and it is of the same magnitude as the liquid fraction. Thus, when value of the liquid fraction is small, the relative uncertainty will be very high.
Figure 4-17: Uncertainty of Maldistribution ratio for 5+5 Aluminum Manifold
4.4 Conclusions

In this chapter, the results in a 5+5 aluminum manifold are presented. The effects of inlet mass flow rate and quality are studied.

Generally, the most uniform distribution appears at high inlet mass flow rate and low quality. The worst case is at low inlet mass flow rate and high quality. At fixed inlet mass flow rate, the ways that the distribution profile will vary with changing the quality can be divided into three groups. In Group 1, more liquid is found in the second branch after increasing the quality, while in Group 3, more liquid is found in the bottom branch. Group 2 looks like a transition from Group 1 to Group 3. Consider the effect of inlet mass flow rate at fixed quality. Among the test conditions, the distribution is more and more uniform when increasing the inlet mass flow rate at low qualities. On the other hand, at high quality cases, there is a best distribution case. And either increasing or decreasing the inlet mass flow rate, the distribution will get worse. As the inlet mass flow rate decreases, the largest liquid fraction branch “shifts” from the second to the bottom one.
The uncertainty analysis proves that the results are relatively accurate of both the maldistribution ratio and liquid fraction. Only when the liquid fraction at the certain particular branch is small, the relative uncertainty will be very high.
5  5+5 Transparent Manifold

After testing the aluminum one, a similar transparent manifold was tested. The experiment data and analysis are shown in this chapter. A brief investigation between the aluminum and this transparent manifold is also made, so as to explain the discrepancy of the results.

5.1 Test Conditions

Similar test conditions as in Table 4-1 are shown in Table 5-1. Again, tests at $m_{in}=1.11\text{g/s}$ cannot be conducted due to system instability. More tests are conducted at quality of 0 and 0.95. The 0 quality tests are for providing the single phase condition as the basis. However, it is not exactly the 0 quality tests because the subcooling at the inlet is not high enough and there is flashing. Even though, the tests still provide some insights, especially with the visualization results. Intuitively, when the quality is close to 1, it will be nearly single phase vapor flow. The distribution will be relatively uniform. Hence, tests at quality of 0.95 are conducted, in order to prove this intuition.

Table 5-1: Test Conditions for 5+5 Transparent Manifold

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</table>
5.2 Test Results

5.2.1 Quality Effect at Same Mass Flow Rate

The distribution profiles of this transparent manifold are presented from Figure 5-1 to Figure 5-5. In this section, they are shown in a similar way as in Section 4.2.1. In each figure, the inlet mass flow rate is fixed. The abscissa represents the liquid fraction, while the ordinate represents the quality. Although it is not quite obvious, the results can also be categorized into three groups.

Group 1 includes the results at $m_{in}=6.25\text{g/s}$ and $m_{in}=5.22\text{g/s}$. At $m_{in}=6.25\text{g/s}$, in Figure 5-1, the distribution is relatively uniform when the quality is low. As the quality increases, more and more liquid appears in the second and third branches. This is similar for $m_{in}=5.22\text{g/s}$, in Figure 5-2. The only difference is that at the highest quality, 0.95, more liquid leaves from the third branch instead of the second one, when $m_{in}=5.22\text{g/s}$.

The results at $m_{in}=4.19\text{g/s}$ and $m_{in}=3.17\text{g/s}$ are in Group 2. For $m_{in}=4.19\text{g/s}$, in Figure 5-3, the liquid fraction of the third branch increases as the quality is larger while that of the other branches are reduced. When the quality is increased from 0.8 to 0.95, the distribution profile looks more uniform. The vapor distribution helps to improve the liquid distribution. At $m_{in}=3.17\text{g/s}$, Figure 5-4, a similar trend on the distribution variation is found. And when the quality is 0.95, the distribution is not worse than that at $x=0.8$, although the distribution profile looks quite different: the liquid fraction of the fifth branch is the largest one.

In Group 3, $m_{in}=2.14\text{g/s}$, Figure 5-5, the distribution is relatively good when the quality is 0. Once the quality reaches 0.2, there is not liquid in the highest branch, and this deteriorates the liquid distribution. As the quality is larger, more and more liquid leaves the manifold from the bottom two branches, and the liquid at the fourth branch is the dominant one between these two.
Figure 5-1: Distribution Profile @ $m_{in}=6.25\text{g/s}$ for 5+5 Transparent Manifold

Figure 5-2: Distribution Profile @ $m_{in}=5.22\text{g/s}$ for 5+5 Transparent Manifold
Figure 5-3: Distribution Profile @ $m_{in}=4.19\text{g/s}$ for 5+5 Transparent Manifold

Figure 5-4: Distribution Profile @ $m_{in}=3.17\text{g/s}$ for 5+5 Transparent Manifold
Figure 5-5: Distribution Profile @ $m_{in}=2.14\text{g/s}$ for 5+5 Transparent Manifold
Again, the causes of the above distribution profiles are the variation of the two-phase mass flow rate and the quality in each branch. This is illustrated in Figure 5-6 and Figure 5-7. The tests at $m_{in}=2.14g/s$ are taken as the example. In the highest branch, not only is the two-phase flow rate low, but it is almost the only vapor present. Comparing these two figures with Figure 5-5, the variation of the quality looks to be a more important factor. The similar figures showing the results at other test conditions are presented in Appendix D.

Figure 5-6: Comparison of quality @ $m_{in}=2.14g/s$ for 5+5 Transparent Manifold
Figure 5-7: Comparison of $2\phi$ Mass Flow Rate @ $m_\text{in}=2.14\text{g/s}$ for 5+5 Transparent Manifold
Also, the average of the two-phase mass flow rates is taken in each branch at various inlet qualities while the inlet mass flow rate is fixed. The mark is the average value while the bar is the deviation. The two-phase mass flow rate relates to the liquid distribution. This is particularly obvious for the first branch. Even though the highest inlet mass flow rate is reached, the two-phase mass flow rate is still low. Therefore, the liquid fraction of the first branch is always smaller. The exact uniform distribution cannot be reached due to this effect.

Figure 5-8: 2φ Flow Rate Comparison for 5+5 Transparent Manifold
5.2.2 Mass Flow Rate Effect at Same Quality

Similarly, the same results are shown in a different way to illustrate the effect of inlet mass flow rate.

Figure 5-9 shows that when the quality is as low as 0, the distribution is generally uniform at every inlet mass flow rate. The liquid distribution becomes a little worse as the inlet mass flow rate decreases. The liquid fraction in the highest branch is a little smaller. This also affects the liquid fraction of other branches being a little bit different.

For the case as x=0.2, the liquid fraction of the highest branch is also reducing as $m_{in}$ is smaller. At $m_{in}=6.25g/s$, the liquid fraction of the other branches are decreased gradually from the second to the fifth branch. When the inlet mass flow rate decreases, more and more liquid “appears” at the bottom branches. This changes the distribution profiles. It is similar the trend for x=0.4, x=0.6 and x=0.8, and it is more obvious. When the inlet mass flow rate is reduced to 2.14g/s, the liquid inertia is smaller. The liquid fraction in the second branch is reduced significantly. And in the case of x=0.8, there is no liquid that leaves from the second branch.

During the transition, the distribution becomes worse and worse as the $m_{in}$ is smaller, except for x=0.8. The best distribution appears at $m_{in}=3.17g/s$. Either increasing or decreasing $m_{in}$ deteriorates the distribution.

In Figure 5-14, the distribution profiles look quite different. There is no liquid in the highest branch no matter what inlet mass flow rate it is. Among the other four branches, when the inlet mass flow rate is high (6.25 and 5.22g/s), the liquid mainly leaves from the top two branches. However, when $m_{in}$ is low (3.17 and 2.14g/s), most liquid is found at the bottom two branches. And at the intermediate $m_{in}$ (4.19g/s), the liquid distribution is more uniform.
Figure 5-9: Distribution Profile @ x=0 for 5+5 Transparent Manifold

Figure 5-10: Distribution Profile @ x=0.2 for 5+5 Transparent Manifold
Figure 5-11: Distribution Profile @ x=0.4 for 5+5 Transparent Manifold

Figure 5-12: Distribution Profile @ x=0.6 for 5+5 Transparent Manifold
Figure 5-13: Distribution Profile @ $x=0.8$ for 5+5 Transparent Manifold

Figure 5-14: Distribution Profile @ $x=0.95$ for 5+5 Transparent Manifold
5.2.3 Analysis of Maldistribution Ratio

Figure 5-15 presents the maldistribution ratio of all the test conditions. Among them, the best distribution is at low quality and high inlet mass flow rate, while the worst appears at two extreme conditions of the high quality, either lowest or highest inlet mass flow rate. Generally, the maldistribution ratio becomes larger with the quality increased. The only two exceptions are at $m_{in}=3.17$ and $4.19\text{g/s}$, when the quality is changed from 0.8 to 0.95. When the quality is as low as 0, 0.2 and/or 0.4, the maldistribution ratio keeps reducing (almost linearly) with the increasing $m_{in}$. When $x$ is 0.6, this reducing trend is flat at $m_{in}=3.17$ and $4.19\text{g/s}$. When $x$ is as high as 0.8 and/or 0.95, there is a minimum value of the maldistribution ratio. Beyond this minimum value, the maldistribution ratio gets larger, i.e., the distribution is worse. In Figure 5-16, the maldistribution ratio is also presented versus reduced mass flow rate. An almost linear reduce of the maldistribution ratio is found at low qualities, whereas for $x=0.8$ and 0.95, it is not obvious.

![Figure 5-15: Maldistribution ratio for 5+5 Transparent Manifold](image-url)
5.2.4 Comparison with 5+5 Aluminum Manifold’s Results

It is noticeable that the results of the 5+5 transparent manifold are not exactly the same as the results of the 5+5 aluminum manifold, despite the fact that the transparent manifold is similar to the aluminum manifold.

The discrepancy of the results may be mainly due to the variation of the manifold’s internal diameter. The chosen PVC tube to manufacture the transparent manifold is the closest one available from the industry. Its internal diameter is 15.44mm, while that of the aluminum one is 14.94mm. Besides, when making the aluminum manifold, the JB-WELD epoxy has to be put inside the PVC tube. Then, its internal area is not as circular as the aluminum manifold’s internal area. Also, the transparent manifold is a little longer. Its material is PVC instead of aluminum, so the wall shear force is different. All of these may affect the final distribution results.
5.3 Uncertainty Analysis

The uncertainties of this transparent manifold at all test conditions are calculated in EES based on Eqn. (4.1). Figure 5-17 presents the uncertainties of the maldistribution ratio at all test conditions. It illustrates the decent accuracy of the maldistribution ratio. The uncertainties are within 2.20%. Its absolute value is from 0.000025 to 0.028.

Figure 5-17: Uncertainty of Maldistribution Ratio for 5+5 Transparent Manifold
Figure 5-18 shows the uncertainties of liquid fraction. The absolute value of this uncertainty is from 0.00018 to 0.00479. Figure 5-18 illustrates that the accuracies of most tests are satisfactory. The only exceptions are when the liquid fraction in certain branch is very small. For example, as in Figure 5-1, the liquid fraction of the fifth branch at $m_{in}=6.25\text{g/s}$ and $x=0.95$ is as small as 0.0129, and its uncertainty is as high as 140%. This is due to that the absolute uncertainty is almost on the same order of the liquid fraction. Hence, the liquid fraction is small. The relative uncertainty is very high.

![Graph showing uncertainty of liquid fraction for every branch for 5+5 transparent manifold](image)

**Figure 5-18: Uncertainty of Liquid Fraction for Every Branch for 5+5 Transparent Manifold**

### 5.4 Conclusions

In this section, the distribution results of 5+5 transparent manifold are presented. The results are similar to those of 5+5 aluminum manifold. The little discrepancy may be due to the variation in the manifold’s internal diameter as well as other effects.

When the inlet mass flow rate is fixed, the distribution is generally uniform at low qualities. Distribution becomes worse at high qualities. When increasing the quality, the ways that distribution profile changes can be categorized into three groups. In Group 1, most liquid leaves the manifold from the top branches at high quality; in Group 2, most liquid leaves from
the center branches; and in Group 3, most liquid leaves from the bottom branches. The
distribution profiles are determined by both the distribution of outlet quality and two-phase
flow rate in each branch. The results are presented in another way – fixing the quality and
letting the y-axis represents the inlet mass flow rate. It is found that when the inlet mass flow
rate is reduced from 6.25 to 2.14g/s, more and more liquid appears at the bottom branches.
This is the case for quality as 0.2, 0.4, 0.6 and 0.8. But as for quality of 0.95, it is different. The
distribution is relatively uniform at $m_\text{in}=4.19g/s$, and getting worse either increasing or
decreasing the inlet mass flow rate.

The uncertainty analysis proves the results of the maldistribution ratio and liquid
fraction are trustworthy.
6 5+10 Transparent Manifold

This type of manifold is supposed to model the 10+10 microchannel tubes. However, in order to facilitate the connection of the test manifold section to the existing system, only five inlet microchannel tubes are connected and allow the refrigerant to pass through. The other five inlet microchannel tubes are blocked and just serve as an obstruction in the manifold. In this way, it resembles the 10+10 manifold most. The configuration is shown in Figure 6-1. Because there are more microchannels, the manifold is twice the length while the diameter is the same.

![Figure 6-1: Photo of 5+10 Transparent Manifold](image)

As shown, two of the outlet microchannel tubes are grouped with a “Y” connection, Figure 6-2. The refrigerant in these two tubes is heated together to certain superheat. Hence, among the results of the distribution profiles, only five liquid fractions are shown, whereas actually each liquid fraction represents the liquid amount in the two branches connected with the “Y”.

![Figure 6-2: Photo of the "Y" Connection](image)
6.1 Test Conditions

Based on the test matrix in Section 3.5, the test conditions for this manifold are determined and presented in Table 6-1. It is noticed that since the number of the tubes are doubled, the inlet mass flows are also twice as those for 5+5 tubes manifolds. And due to the safety reasons, the tests at $m_{in}=12.50\text{g/s}$ and $x=0.8$ and $0.95$ are not conducted.

Again, due to subcooling at the inlet is not high enough, the 0 quality tests at $m_{in}=2.22, 4.28$ and $6.33\text{g/s}$ is not exactly 0 quality. The flashing is present along the microchannels. However, for $m_{in}=8.39, 10.44$ and $12.50\text{g/s}$, high subcooling is available, so the tests at $x=0$ is single phase liquid flow.

Table 6-1: Test Conditions for 5+10 Transparent Manifold

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<tr>
<th>$m_{in}$ [g/s]</th>
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<th>$m_{in}$ [g/s]</th>
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</table>
6.2 Test Results

Figure 6-3 shows the schematic of 5+10 manifold, as well as the notations that will be shown in the distribution profile results.

![Schematic of 5+10 Manifold](image)

Figure 6-3: Notation Schematic of 5+10 Manifold

6.2.1 Quality Effect at Same Mass Flow Rate

The distribution profiles of the 5+10 transparent manifold are presented from Figure 6-4 to Figure 6-9. In each figure, the inlet mass flow rate is fixed. The abscissa represents the liquid fraction, and the ordinate represents the inlet quality. Generally, the distribution is less uniform with increasing quality. The results can also be categorized into three groups.

Group 1 includes the distribution profiles at $m_i=12.50, 10.44$ and $8.39 \text{ g/s}$. In this group, the tests at $x=0$ are exactly single-phase liquid flow. Even in the single-phase flow condition, the distribution is not absolutely uniform. More liquid leaves from the bottom branch than the top one. This is probably due to the variation of hydrostatic pressure. Once the vapor is present, it is two-phase flow and most of the liquid leaves from the second branch. The liquid fraction decreases gradually from the second branch to the fifth. The liquid fraction of the first branch is related to the inlet mass flow rate. It is larger at higher inlet mass flow rate, but it is still always smaller than that of the second branch. This type of profile appears in most of the two-phase flow distribution profiles in this group. This becomes more obvious if the quality is increased. At some conditions, the fifth branch doesn’t even have any liquid flowing.

The distribution profiles at $m_i=6.33 \text{ g/s}$ is categorized as Group 2. At low qualities, the distribution profile resembles that in Group 1 at low qualities. The liquid fraction of the second
branch is largest, and reduces gradually to the fifth one. Less liquid leaves from the first branch than the second one. However, at high qualities, due to the inlet mass flow rate not being high enough, compared to that in Group 1, most liquid leaves from the center branch. The liquid fraction reduces gradually either to the top or bottom branch.

The distribution profiles at $m_{in}=4.28$ and $2.22\,\text{g/s}$ are in Group 3. Because the inlet mass flow rate is even less, at low qualities the liquid cannot reach the second branch in the manifold. Therefore, in most cases, most liquid leaves from the fourth branch, and decreases gradually either to the top or bottom branch.

Figure 6-4: Distribution Profiles @ $m_{in}=12.50\,\text{g/s}$ for 5+10 Transparent Manifold
Figure 6-5: Distribution Profiles @ $m_{in}=10.44\text{g/s}$ for 5+10 Transparent Manifold

Figure 6-6: Distribution Profiles @ $m_{in}=8.39\text{g/s}$ for 5+10 Transparent Manifold
Figure 6-7: Distribution Profiles @ $m_{in}=6.33\text{g/s}$ for 5+10 Transparent Manifold

Figure 6-8: Distribution Profiles @ $m_{in}=4.28\text{g/s}$ for 5+10 Transparent Manifold
Figure 6-9: Distribution Profiles @ $m_{in}=2.22\text{g/s}$ for 5+10 Transparent Manifold
It is already mentioned that the maldistribution of liquid fraction is because of the effects of both the two-phase mass flow rate and quality in the outlet microchannel tube in 5+5 manifold. It is also the case for 5+10 transparent manifold. The distribution profiles at $m_{in}=2.22g/s$ are taken as the example here. Figure 6-10 shows the variation of the quality in each outlet branch, while Figure 6-11 shows the variation of two-phase mass flow rate. Comparing these two figures with the above distribution profiles shows that the variation of the quality is a more important factor in determining the distribution profile. Similar figures as Figure 6-10 and Figure 6-11 at different test conditions are shown in Appendix E.

Figure 6-10: Comparison of quality @ $m_{in}=2.22g/s$ for 5+10 Transparent Manifold
Figure 6-11: Comparison of 2φ Mass Flow Rate @ $m_p=2.22\text{g/s}$ for 5+10 Transparent Manifold
Figure 6-12 shows the variation of two-phase flow rate in each branch at different inlet mass flow rate. The mark in the figure represents the average value, and the bar represents the deviation due to the changing of inlet quality. It is shown that the variation is present in every test condition. Even in the high inlet mass flow rate, the two-phase mass flow rate of the first branch is still less than the second one. This may explain the distribution profile of the top branch.

![Figure 6-12: 2φ Flow Rate Comparison for 5+10 Transparent Manifold](image)

6.2.2 Mass Flow Rate Effect at Same Quality

The same results of the 5+10 manifold are presented in a different way while holding the inlet quality constant. The abscissa still represents the liquid fraction, but the ordinate represents the inlet mass flow rate.

At x=0, the distribution is generally uniform. For exact single-phase flow condition of \(m_{in}=12.50, 10.44\) and \(8.39\,\text{g/s}\), the bottom branch receives most liquid and the top one receives the least. For other conditions, due to the flashing, the distribution profiles are different. Also, as the inlet mass flow decreases, the liquid fraction of the top branch is smaller and smaller.
For tests at x=0.2, 0.4, 0.6 and 0.8, the transition of distribution profile looks quite similar. At lowest inlet mass flow rate, the fourth branch has the largest liquid fraction, while it reduces gradually either to the top or bottom branch. At highest inlet mass flow rate, most liquid leaves from the second branch and the liquid fraction decreases gradually either to the top or bottom branch. At intermediate inlet mass flow rate, the distribution profile is just the transition of the above two types.

At the highest quality of 0.95, the only difference is at lowest inlet mass flow rate. Because the liquid amount in the manifold is relatively small, the inertia of the liquid is smaller. Then, most liquid leaves from the fifth branch instead of the fourth one.

Figure 6-13: Distribution Profiles @ x=0 for 5+10 Transparent Manifold
Figure 6-14: Distribution Profiles @ $x=0.2$ for 5+10 Transparent Manifold

Figure 6-15: Distribution Profiles @ $x=0.4$ for 5+10 Transparent Manifold
Figure 6-16: Distribution Profiles @ x=0.6 for 5+10 Transparent Manifold

Figure 6-17: Distribution Profiles @ x=0.8 for 5+10 Transparent Manifold
Figure 6-18: Distribution Profiles @ x=0.95 for 5+10 Transparent Manifold
6.2.3 Analysis of Maldistribution ratio

Figure 6-19 shows the maldistribution ratio at all test conditions. The best distribution is at $m_{in}=10.44$, $x=0.2$. The worst is $m_{in}=4.28$, $x=0.95$. At $x=0.2$, the maldistribution ratio decreases continuously from the lowest inlet mass flow rate until the smallest number is reached $m_{in}=10.44$. Then, the maldistribution ratio increases. At $x=0.4$, the maldistribution ratio keeps reducing as the inlet mass flow rate increases. It is not strictly the same for $x=0.6$, but it is generally following the same trend. It is a little complicated for $x=0.8$ and 0.95. There is both a maximum and a minimum maldistribution ratio as the inlet mass flow rate increases from 2.22g/s to 10.44g/s. The maldistribution ratio versus the reduced mass flow rate is shown in Figure 6-20. A generally good linear relation between the maldistribution ratio and reduced mass flow rate can be found.
Figure 6-20: Maldistribution Ratio vs. Reduced Mass Flow Rate for 5+10 Transparent Manifold

6.2.4 Comparison with 5+5 Transparent Manifold

In the 5+10 transparent manifold, the number of the microchannels is twice as much as that in the 5+5 transparent manifold. Therefore, PVC tube that is twice as long is chosen as the manifold, while keeping the distance between the microchannels the same. These two changes have both the positive and negative effects on the distribution. The mass flow rate in each microchannel is already decided and set based on the heat transfer calculation. When the tube number is doubled, the inlet mass flow rate is also twice larger. Based on the results of the 5+5 transparent manifold, one main cause of maldistribution is that the inlet mass flow rate is not high enough, so the top branch cannot receive much flow. Thus, increasing the tube number is a positive factor. On the other hand, the manifold is longer. It consequently requires higher inlet mass flow rate so as to let the liquid reach the top branch. This is the negative factor. Both of them affect the distribution profiles. However, it is found that the positive factor is dominant. The distribution results are better for the 5+10 transparent manifold at most test conditions.
6.3 Uncertainty Analysis

The uncertainties of the 5+10 transparent manifold are calculated using the same method as in Section 4.3. The uncertainties of the maldistribution ratio at all test conditions are illustrated in Figure 6-21. It is proved that the results are trustworthy with the uncertainty no higher than 4.5%. Its absolute value is from 0.0000025 to 0.0429.

Figure 6-21: Uncertainty of Maldistribution ratio for 5+10 Transparent Manifold
The uncertainties of liquid fraction are presented in Figure 6-22. The absolute uncertainty is from 0.00017 to 0.015. The accuracy of most tests is satisfactory. However, since the absolute uncertainty is relatively steady, when the liquid fraction is very small, the relative uncertainty would be very large, e.g., the fifth branch at $m_{in}=8.39$g/s and $x=0.8$.

![Figure 6-22: Uncertainty of Liquid Fraction for Every Branch for 5+10 Transparent Manifold](image)

6.4 Conclusions

The distribution results of 5+10 transparent manifold are presented in this section. Generally, as the tube number is doubled, the mass flux in the manifold is larger. And then, most of the distribution results are better than those for 5+5 transparent manifold.

While holding the inlet mass flow rate fixed, three groups of results can be categorized. In Group 1, increasing quality will shift the relatively uniform distribution profile to the one that the second branch has most liquid. In Group 2, most liquid leaves from the center branch at high quality; while in Group 3, it is the fourth branch. The other branches receive less liquid. The effects of two-phase mass flow rate and outlet quality in each branch are once again proved to be related to the distribution profile. When the inlet quality is fixed, the variation of distribution...
profile according to inlet mass flow rate is found. Generally, the profile is transited from fourth branch dominant to second branch dominant as the inlet mass flow rate increases. Only in x=0, the distribution is relatively uniform. And decreasing the inlet mass flow rate just causes less liquid fraction of the top branch.

Although the uncertainties of this manifold are a little large, they are still satisfactory for both the maldistribution ratio and liquid fraction in each branch.
7 Visualization Results Analysis
While taking the data of the experiments, videos about the flow patterns in the manifold are also taken by the high speed camera. The details of the high speed camera are already mentioned in Section 3.4.3. In this section, the visualization results will be shown and analyzed. All of the visualization results for both 5+5 and 5+10 transparent manifolds are presented in Appendix F. The analysis in this section applies both to the 5+5 and 5+10 transparent manifolds.

7.1 Flow regimes
Among all the tests, four kinds of flow regimes are found. They are single-phase, bubbly, churn and semi-annular flow. The examples of the four flow regimes are shown in Figure 7-1. The detail of each flow regime will be analyzed later. Figure 7-1 also shows that at fixed inlet mass flow rate, increasing the quality will transit the flow regime from bubbly, to churn, and then to semi-annular flow. The images in Appendix F also illustrate this point. The reason of this transition is probably that the dominant factor is changed from buoyancy to inertia. The flow regimes for 5+5 transparent manifold are listed in Table 7-1, and those for 5+10 transparent manifold are listed in Table 7-2. (Note: SP: single-phase, B: bubbly, C: churn, SA: semi-annular)
Table 7-1: Flow Regimes for 5+5 Transparent Manifold

<table>
<thead>
<tr>
<th>$m_{in}$ [g/s]</th>
<th>quality [-]</th>
<th>Flow Regime</th>
<th>$m_{in}$ [g/s]</th>
<th>quality [-]</th>
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<td>C</td>
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<td></td>
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<tr>
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<td>0.95</td>
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Table 7-2: Flow Regimes for 5+10 Transparent Manifold

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<th>Flow Regime</th>
<th>$m_{in}$ (g/s)</th>
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<td></td>
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<td>C</td>
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<td>0.4</td>
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<td>SA</td>
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<td>0.95</td>
<td>SA</td>
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<tr>
<td>6.33</td>
<td>0</td>
<td>B</td>
<td>12.50</td>
<td>0</td>
<td>SP</td>
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<tr>
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<td>C</td>
<td></td>
<td>0.2</td>
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<tr>
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<td>0.8</td>
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<td></td>
<td>0.95</td>
<td>SA</td>
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On the other hand, the flow regime would also change if the quality is fixed and let inlet mass flow rate varies. It is illustrated in Figure 7-2. When $x=0.4$, at low inlet mass flow rate, the inertia is relatively low. Therefore, buoyancy is the dominant one. The churn flow regime is observed. Increasing the inlet mass flow rate would causes higher inertia. Then, the inertia is the dominant one. The flow regime becomes the semi-annular flow.

$m_{in}=2.14\, g/s$  
$m_{in}=3.17\, g/s$  
$m_{in}=4.19\, g/s$  
$m_{in}=5.22\, g/s$  
$m_{in}=6.25\, g/s$

Figure 7-2: Transition of Flow Regimes as $m_{in}$ Increases
7.1.1 Single-Phase Flow

Among all the tests, this flow regime only occurs at $x=0$ and the subcooling at the inlet of test section is high enough. They are at $m_{in}=8.39, 10.44, 12.50\text{g/s}$ of 5+10 transparent manifold. Figure 7-3 is an example of single-phase flow. The corresponding distribution profile is also shown.

The manifold is full of the liquid refrigerant. The amount of liquid that leaves from one outlet is determined mainly by the hydrostatic pressure. Obviously, the hydrostatic pressure at the fifth branch is larger than that at the first branch. Therefore, the liquid fraction of the fifth one is larger.

$m_{in}=8.39\text{g/s} \ x=0$

![Figure 7-3: Single-Phase Flow](image)
7.1.2 Bubbly Flow
In most tests of \( x=0 \), the subcooling is not high enough. Flashing occurs in the aluminum inlet microchannel tubes. Therefore, there are dispersed bubbles that appear in the transparent manifold. Figure 7-4 provides an example of the bubbly flow regime.

The manifold is also almost filled with the liquid refrigerant. It is probably also buoyancy force dominant. It is noticed that the presence of bubbles changes the distribution. Although the top branch still has the smallest liquid fraction, the bottom one no longer has the largest liquid fraction. It may be due to the fact that the bubbles tend to flow upward. Along their upward flowing path, the liquid is “lifted up” a little bit. In other words, the pressure distribution in the manifold may be varied. The driving force (pressure difference between the point in the manifold and the outlet of microchannel tubes) of the fifth is not high enough to pull more liquid.

\[ m_{in}=6.33 \text{g/s} \ x=0 \]

![Bubbly Flow and Buoyancy Dominant Diagram](image)

Figure 7-4: Bubbly flow
7.1.3 Churn Flow

At low qualities, i.e. 0.2 and 0.4, there will be more vapor in the manifold. The vapor tends to move up, and churn the liquid flow. One example is presented in Figure 7-5.

Most of the manifold is immersed with the liquid refrigerant. This causes the liquid immersed part is shorter than in the previous flow regimes. In Figure 7-5, it is observed that there is little liquid at the part of top two inserted tubes. Correspondingly, the liquid fraction of these two tubes is very small (the liquid fraction of Branch #1 in the distribution profile).

Besides, eddies are noticed in the manifold between every two microchannel tubes. This is not seen in the bubbly flow. Since the quality is higher, the inertia is higher if the mass flow rate is fixed. This inertia may induce the vortex along the fluid flowing. The flow is more homogeneous than the semi-annular flow. There is continuous vapor-liquid phase separation. This helps to forms the two-phase eddies.

\[ m_{li} = 6.33 \text{g/s} \] \[ x = 0.4 \]

![Figure 7-5: Churn Flow](image)

When the inlet quality is fixed, increasing the inlet mass flow rate causes larger inertia. Therefore, a large eddy is noticed at higher inlet mass flow rate. This is shown in the left two
images of Figure 7-6. In some cases, the eddy only appears at bottom part of the manifold, while the top part is more like the semi-annular flow regime. This is shown in the right image of Figure 7-6. In this case, the flow regime is the transition from churn flow to semi-annular flow. The inertia is related to the pressure difference between the two ends of the inlet microchannel tube. One end is inserted in the manifold, so its pressure is related to the hydrostatic pressure. Assume the pressure at the other end of the microchannel is constant, and the same for all the inlet tubes. Then, the hydrostatic pressure is higher at the bottom of the manifold, so is the pressure at this end of the bottom microchannel tubes. Thus, the pressure difference is smaller for bottom tubes, so as the inertia. Therefore, even though the inertia of the top tubes is high enough to form the semi-annular flow, the bottom ones may still be the churn flow because of the lower inertia.

![Figure 7-6: The variation of Churn Flow Regime](image)

\[
\begin{align*}
\text{Inlet Mass Flow Rate} & = 2.22 \text{ g/s} \\
& \text{at } x = 0.2 \\
\text{Inlet Mass Flow Rate} & = 8.39 \text{ g/s} \\
& \text{at } x = 0.2 \\
\text{Inlet Mass Flow Rate} & = 8.39 \text{ g/s} \\
& \text{at } x = 0.4
\end{align*}
\]
7.1.4 Semi-Annular Flow

At high qualities, i.e., 0.8 and 0.95, most of the manifold is filled with vapor. Liquid jet flow comes out of the inlet microchannel tube, and then stays on the surface of the wall. A liquid film is formed. This flow regime is called semi-annular flow instead of annular flow because one side of the manifold is inserted with microchannel tubes and the flow direction in the side downward instead of upward. There is a big circulation of liquid in the manifold. Hence, it is not the strict annular flow.

Figure 7-7 shows the semi-annular flow regime at $m_{in}=6.33$ and $x=0.8$. It is found that liquid film flows upward along the manifold. At the intermediate location, the liquid film is separated from the surface and leaves from the outlet microchannel tubes. The tubes either above or below this separation location receives a little bit of the liquid. This corresponds to distribution profile at this condition.
Compared with the churn flow, it is liquid jet comes out of the inlet microchannel tubes. When the jet hits the surface of the wall, the liquid stays on the surface without splashing, Figure 7-8. The liquid film is formed. This phenomenon may be accounted by the surface tension. As in the steady condition, the liquid form is already formed. When the jet hits the liquid film, the surface tension helps to spread over the liquid film. Also, the velocity profile of the jet may also have impact on this phenomenon. Uniform velocity profile reduces the splashing when the jet hits the wall.

\[ \text{mach}_{in}=4.288 \text{ g/s x}=0.2 \quad \text{mach}_{in}=4.288 \text{ g/s x}=0.8 \]

Figure 7-8: Jet Inlet Flow at Semi-Annular Flow regime

Figure 7-9 shows the free body force analysis of the liquid film when it is about to enter the outlet microchannels. In the manifold, vapor tends to accumulate at the top end of the header. This introduces the pressure from the top. Thus, as the liquid film flows upward, it has to overcome the viscous and gravity forces, as well as the pressure at the top end. The inertia of the liquid film will be decreasing. The liquid film flows vertically. To allow the liquid to exit through the horizontal outlet, angular momentum must be supplied to the liquid film. The angular momentum is defined as
\[ \tau = d \times \frac{d(m \vec{v})}{dt} \]  

where \( \tau \) is angular momentum; \( d \) is manifold diameter; \( \vec{v} \) is upward velocity.

It is determined by the pressure difference at the inlet and outlet of the outlet microchannel tubes. It is relatively constant. Since the inertia of the liquid film is high initially, the provided angular moment is not high enough to change the liquid film’s direction and suck it into the outlets. Hence, the liquid “escapes” from the first a few outlets. The “red box” shows this area. Later when the liquid film’s inertia is reduced due to the effects of top pressure, viscous and gravity forces, the provided angular momentum is high enough to pull the liquid out of the manifold. The “blue box” shows this part. And then for upper microchannels, the liquid does not have enough inertia to overcome the forces at the top of the manifold, and therefore very little liquid exits.

Figure 7-9: Free Body Analysis of Semi-Annular Flow
Figure 7-10 shows the variation of the flow regime as the quality increases. Since the quality is higher, there is relatively more vapor in the system, and then the built-up pressure at the top end will be higher. It is then harder for the liquid film to flow upward. That is where the blue bar shows. On the other hand, at higher quality, the inertia is higher initially, so the liquid film can overcome the pressure difference of the outlet tubes for a longer distance. The red box area in the figure illustrates this point.

Figure 7-10: Variation of Semi-Annular Flow Regime as the Inlet Quality Changes
As the inlet mass flow rate increases, the inertia of the liquid film is simply larger. The liquid film can reach higher in the manifold until the pressure difference of the outlet microchannels comes into play. The red box in Figure 7-11 illustrates changing of the separation location.

Figure 7-11: Variation of Semi-Annular Flow Regime as the Inlet Mass Flow Rate Changes
7.2 Froude Number vs. Flow regime

Among the three two-phase flow regimes, buoyancy force is dominant in bubbly and churn flow regime, while inertia is dominant in semi-annular flow regimes. In the bubbly and churn flow, most part of the manifold is immersed with the liquid. The vapor just churns the flow on its way flowing upward. The liquid is like a quiescent phase in the manifold. In the semi-annular flow, it is mainly vapor in the manifold. Liquid flows upward as the liquid film on the wall. The vapor seems to be the quiescent phase.

It is proved by calculating Froude number. The Froude number is defined as the ratio of inertial to gravitation energy, Equation

$$Fr = \frac{Gx}{\sqrt{\rho_v (\rho_l - \rho_v) Lg}}$$  \hspace{1cm} (7-2)

where \(Fr\) is the Froude number; \(G\) is the manifold’s effective mass flux, as defined in Bowers et al (2004); \(x\) is inlet quality; \(L\) is the vertical length of the manifold.
Figure 7-13 and Figure 7-14 present the Froude number and flow regime for both 5+5 and 5+10 transparent manifold. It is obvious that the Froude number can represent the flow regime very well. The semi-annular flow regime is found at high Froude number, while the churn flow is at intermediate Froude number, and finally the bubbly or single phase flow at low Froude number.

Figure 7-13: Froude number and Flow regime for 5+5 Transparent Manifold
Figure 7-14: Froude Number and Flow regimes for 5+10 Transparent Manifold
Although the Froude number is appropriate to predict the flow regime, it is not a good parameter to predict the maldistribution ratio. The defined flow regime does not account for the size of the top part, where there may be no liquid. This area, however, has significant impact on the liquid distribution. An example of this point is shown in Figure 7-15. The quality is 0.2 for both, and the inlet mass flow rate is 2.22g/s and 10.44g/s, respectively. It can be seen that both of the flow regimes are churn flow. It is also proved in Figure 7-14. However, at $m_\text{in}=2.22\text{g/s}$, the liquid immerses most part of the manifold except the area of top first three microchannels, while almost the whole manifold is filled with liquid at $m_\text{in}=10.44\text{g/s}$. And this makes distribution profiles in Figure 7-15 so different. Furthermore, the maldistribution ratio is very different for the two conditions, Figure 6-19. Therefore, Froude number is not an appropriate parameter to account for the maldistribution ratio. Further exploration is needed.

Figure 7-15: Impact of the top no liquid zone on the distribution
7.3 Conclusions

In this section, four flow regimes are defined and analyzed. They are single-phase, bubbly, churn and semi-annular flow. All the flow regimes can be used to explain the corresponding distribution profile.

As the quality increases, the flow regime will shift from single-phase or bubbly flow to churn flow then to semi-annular flow. If the inlet mass flow rates increase, the transition would be from churn flow to semi-annular flow at some fixed quality. For the churn flow, the size of the eddy is related to the inertia. For semi-annular flow, how high can the liquid film flow and where the liquid film separation occurs is also determined by the inertia.

The balance of the forces as inertia, viscous, gravity and pressure determines the liquid fraction in each branch. The flow regime is mainly related to the competition between inertia and buoyancy forces. It is directly illustrated in the diagram of Froude number. Although Froude number is related to the flow regime, it is not good for the maldistribution ratio.
References


Elbel, S.W., Hrnjak, P.S., 2003, Experimental and Analytical Validation of New Approaches to Improve Transcritical CO₂ Environmental Control Units, Contract Project CR-52, Air Conditioning and Refrigeration Center, Univ. Illinois at Urbana-Champaign


Song, S., Bullard, C.W., 2002, Experimental and Simulation Analysis of Microchannel Evaporators, Contract Report CR-47, Air Conditioning and Refrigeration Center, Univ. Illinois at Urbana-Champaign


Appendix A – Curve Fit of R410a Properties

Figure A-1: Curve Fit of Saturated Liquid Temperature vs. Saturated Pressure

Figure A-2: Curve Fit of Saturated Vapor Temperature vs. Saturated Pressure
Figure A-3: Curve Fit of Saturated Liquid Enthalpy vs. Saturated Pressure

\[ y = 1.9667651E-01 x^4 + 3.0830419E+00 x^3 + 2.1469215E+01 x^2 + 1.0093531E+02 x + 1.8735122E+02 \]
\[ R^2 = 9.9999984E-01 \]

Figure A-4: Curve Fit of Saturated Vapor Enthalpy vs. Saturated Pressure

\[ y = -1.8456558E-01 x^4 - 2.9253317E+00 x^3 - 1.4448990E+01 x^2 - 1.8864497E+01 x + 2.7934503E+02 \]
\[ R^2 = 9.9994975E-01 \]
Figure A-5: Curve Fit of Saturated Enthalpy vs. Saturated Temperature

\[ y = 6.7240075E-08x^4 + 1.6322165E-05x^3 + 2.6380251E-03x^2 + 1.5452430E+00x + 5.8429065E+01 \]

\[ R^2 = 9.9999999E-01 \]
Appendix B – Sample EES Code of Calculation

“Based on the measure temperature and pressure of the outlet microchannels, the enthalpy at the superheat point can be obtained”

\[ h_{\text{sup}1} = \text{Enthalpy}(R410A, T_{\text{out}1}, P=P_{\text{out}}) \]
\[ h_{\text{sup}2} = \text{Enthalpy}(R410A, T_{\text{out}2}, P=P_{\text{out}}) \]
\[ h_{\text{sup}3} = \text{Enthalpy}(R410A, T_{\text{out}3}, P=P_{\text{out}}) \]
\[ h_{\text{sup}4} = \text{Enthalpy}(R410A, T_{\text{out}4}, P=P_{\text{out}}) \]
\[ h_{\text{sup}5} = \text{Enthalpy}(R410A, T_{\text{out}5}, P=P_{\text{out}}) \]

“After the header, the liquid in each microchannel is different. It results in different energy to heat it to the superheat point. With \( h_{\text{sup}}, Q_{\text{dot}_\text{out}}, m_{\text{dot}_\text{out}} \) at hand, the enthalpy immediately after the header can be calculated”

\[ h_{\text{out}1} = h_{\text{sup}1} - \frac{Q_{\text{dot}_1}}{m_{\text{dot}_1}} \]
\[ h_{\text{out}2} = h_{\text{sup}1} - \frac{Q_{\text{dot}_2}}{m_{\text{dot}_2}} \]
\[ h_{\text{out}3} = h_{\text{sup}1} - \frac{Q_{\text{dot}_3}}{m_{\text{dot}_3}} \]
\[ h_{\text{out}4} = h_{\text{sup}1} - \frac{Q_{\text{dot}_4}}{m_{\text{dot}_4}} \]
\[ h_{\text{out}5} = h_{\text{sup}1} - \frac{Q_{\text{dot}_5}}{m_{\text{dot}_5}} \]

“Knowing the temperature and enthalpy in each out microchannel, the quality for each out microchannel can be looked up”

\[ x_{\text{out}1} = \text{Quality}(R410A, T_{\text{in}}, h=h_{\text{out}1}) \]
\[ x_{\text{out}2} = \text{Quality}(R410A, T_{\text{in}}, h=h_{\text{out}2}) \]
\[ x_{\text{out}3} = \text{Quality}(R410A, T_{\text{in}}, h=h_{\text{out}3}) \]
\[ x_{\text{out}4} = \text{Quality}(R410A, T_{\text{in}}, h=h_{\text{out}4}) \]
\[ x_{\text{out}5} = \text{Quality}(R410A, T_{\text{in}}, h=h_{\text{out}5}) \]

“The liquid mass flow at each out microchannel can be calculated based on the quality and total mass flow rate of that microchannel”

\[ m_{\text{dot}_\text{out}1} = (1-x_{\text{out}1}) \times m_{\text{dot}_\text{out}} \]
\[ m_{\text{dot}_\text{out}2} = (1-x_{\text{out}2}) \times m_{\text{dot}_\text{out}} \]
\[ m_{\text{dot}_\text{out}3} = (1-x_{\text{out}3}) \times m_{\text{dot}_\text{out}} \]
\[ m_{\text{dot}_\text{out}4} = (1-x_{\text{out}4}) \times m_{\text{dot}_\text{out}} \]
\[ m_{\text{dot, Lout}}5 = (1 - x_{\text{out5}}) \cdot m_{\text{dot, out5}} \]

"Average liquid mass flow rate"

\[ m_{\text{bar, L}} = \frac{1}{5} \cdot (m_{\text{dot, Lout1}} + m_{\text{dot, Lout2}} + m_{\text{dot, Lout3}} + m_{\text{dot, Lout4}} + m_{\text{dot, Lout5}}) \]

"Unbalance ratio"

\[ \sigma = \frac{1}{m_{\text{bar, L}}} \cdot \sqrt{\left( (m_{\text{dot, Lout1}} - m_{\text{bar, L}})^2 + (m_{\text{dot, Lout2}} - m_{\text{bar, L}})^2 + (m_{\text{dot, Lout3}} - m_{\text{bar, L}})^2 + (m_{\text{dot, Lout4}} - m_{\text{bar, L}})^2 + (m_{\text{dot, Lout5}} - m_{\text{bar, L}})^2 \right) / 5} \]
Appendix C – Quality and 2φ Flow Rate for 5+5 Aluminum Manifold

Figure C-1: Comparison of quality @ $m_{in}=7.27\text{g/s}$ for 5+5 Aluminum Manifold

Figure C-2: Comparison of 2φ Mass Flow Rate @ $m_{in}=7.27\text{g/s}$ for 5+5 Aluminum Manifold
Figure C-3: Comparison of quality @ $m_{in}=6.25\text{g/s}$ for 5+5 Aluminum Manifold

Figure C-4: Comparison of 2φ Mass Flow Rate @ $m_{in}=6.25\text{g/s}$ for 5+5 Aluminum Manifold
Figure C-5: Comparison of quality @ $m_{in}=5.22\text{g/s}$ for 5+5 Aluminum Manifold

Figure C-6: Comparison of $2\phi$ Mass Flow Rate @ $m_{in}=5.22\text{g/s}$ for 5+5 Aluminum Manifold
Figure C-7: Comparison of quality @ $m_{in}=4.19g/s$ for 5+5 Aluminum Manifold

Figure C-8: Comparison of 2φ Mass Flow Rate @ $m_{in}=4.19g/s$ for 5+5 Aluminum Manifold
Figure C-9: Comparison of quality @ $m_{in}=3.17\text{g/s}$ for 5+5 Aluminum Manifold

Figure C-10: Comparison of 2φ Mass Flow Rate @ $m_{in}=3.17\text{g/s}$ for 5+5 Aluminum Manifold
Appendix D – Quality and 2ρ Flow Rate for 5+5 Transparent Manifold

Figure D-1: Comparison of quality @ $m_{in}=6.25\text{g/s}$ for 5+5 Transparent Manifold

Figure D-2: Comparison of $2\rho$ Mass Flow Rate @ $m_{in}=6.25\text{g/s}$ for 5+5 Transparent Manifold
Figure D-3: Comparison of quality @ $m_{in}=5.22\text{g/s}$ for 5+5 Transparent Manifold

Figure D-4: Comparison of 2φ Mass Flow Rate @ $m_{in}=5.22\text{g/s}$ for 5+5 Transparent Manifold
Figure D-5: Comparison of quality @ $m_{in}=4.19g/s$ for 5+5 Transparent Manifold

Figure D-6: Comparison of $2\phi$ Mass Flow Rate @ $m_{in}=4.19g/s$ for 5+5 Transparent Manifold
Figure D-7: Comparison of quality @ $m_{in}$=3.17g/s for 5+5 Transparent Manifold

Figure D-8: Comparison of 2φ Mass Flow Rate @ $m_{in}$=3.17g/s for 5+5 Transparent Manifold
Appendix E – Quality and $2\phi$ Flow Rate for 5+10 Transparent Manifold

Figure E-1: Comparison of quality @ $m_{in}=12.50\text{g/s}$ for 5+10 Transparent Manifold

Figure E-2: Comparison of $2\phi$ Mass Flow Rate @$m_{in}=12.50\text{g/s}$ for 5+10 Transparent Manifold
Figure E-3: Comparison of quality @ $m_{in}=10.44g/s$ for 5+10 Transparent Manifold

Figure E-4: Comparison of 2φ Mass Flow Rate @$m_{in}=10.44g/s$ for 5+10 Transparent Manifold
Figure E-5: Comparison of quality @ $m_{in}=8.39$g/s for 5+10 Transparent Manifold

Figure E-6: Comparison of 2φ Mass Flow Rate @ $m_{in}=8.39$g/s for 5+10 Transparent Manifold
Figure E-7: Comparison of quality @ $m_{in}=6.33\text{g/s}$ for 5+10 Transparent Manifold

Figure E-8: Comparison of $2\phi$ Mass Flow Rate @ $m_{in}=6.33\text{g/s}$ for 5+10 Transparent Manifold
Figure E-9: Comparison of quality @ $m_m=4.28\text{g/s}$ for 5+10 Transparent Manifold

Figure E-10: Comparison of $2\phi$ Mass Flow Rate @ $m_m=4.28\text{g/s}$ for 5+10 Transparent Manifold
Appendix F – Visualization Results

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Figure F-1: Visualization Images @ $m_n$=6.25g/s for 5+5 Transparent Manifold

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Figure F-2: Visualization Images @ $m_n$=5.22g/s for 5+5 Transparent Manifold
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Figure F-3: Visualization Images @ $m_{in}$=4.19g/s for 5+5 Transparent Manifold

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Figure F-4: Visualization Images @ $m_{in}$=3.17g/s for 5+5 Transparent Manifold
Figure F-5: Visualization Images @ $m_{in}=2.14\text{g/s}$ for 5+5 Transparent Manifold

Figure F-6: Visualization Images @ $m_{in}=12.50\text{g/s}$ for 5+10 Transparent Manifold
$m_{in}=10.44\text{g/s}$

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Figure F-7: Visualization Images @ $m_{in}=10.44\text{g/s}$ for 5+10 Transparent Manifold

$m_{in}=8.39\text{g/s}$

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Figure F-8: Visualization Images @ $m_{in}=8.39\text{g/s}$ for 5+10 Transparent Manifold
Figure F-9: Visualization Images @ $m_n=6.33\text{g/s}$ for 5+10 Transparent Manifold

Figure F-10: Visualization Images @ $m_n=4.28\text{g/s}$ for 5+10 Transparent Manifold
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Figure F-11: Visualization Images @ $m_i=2.22\text{g/s}$ for 5+10 Transparent Manifold