FLOW OF R134a THROUGH MICRO-ORIFICES

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ABSTRACT

This paper presents the experimental results for R134a flowing through micro-orifices with diameters of 31 and 52 \( \mu \text{m} \), and length-to-diameter ratio of 2.5 and 4.2, respectively. For liquid flow without flashing, the experimental data were in rough agreement with macroscale results. The conventional orifice equation is still applicable. For liquid flow with flashing, the experimental results indicate significant departure of flow characteristics from macroscale orifices. The flow was not choked even when downstream pressure was reduced to more than 400 kPa below saturation pressure corresponding to inlet temperature, whereas in normal size orifices with length-to-diameter ratio larger than 2, the flow is typically choked as downstream pressure is reduced below saturation pressure. Semi-empirical model was developed based on correction of the orifice equation.

NOMENCLATURE

\( A \): Area

\( v \): Fluid velocity

\( C_d \): Discharge coefficient

\( x_{\text{out}} \): downstream quality

\( C_x \): Emperical constant

\( \rho \): Density

\( D \): Orifice diamter

\( \beta \): Ratio of orifice to conduit diameter

\( m \): Mass flow rate

\( r \): Orifice radius

\( \sigma \): Surface tension

\( \mu \): Viscosity

\( \Delta p \): Pressure drop

INTRODUCTION

During the past decades, there has been a growing interest in various branches of industry to develop miniature thermal and mechanical systems. Shannon et al. (1999) are developing a small cooling system which uses an orifice with diameter of 30 ~ 52 \( \mu \text{m} \) as expansion device. The whole system is about 100mm square, 2.5mm thick with cooling capacity of 3 ~ 30W while operating between 20 °C (evaporation temperature) and 50 °C (condensation temperature). The design of such a system needs to characterize refrigerant flow through micro-orifices with/without flashing. Studies on flow through macro and micro scale orifices are summarized in Table 1. Most of the earlier studies focused on orifices with diameter close to or larger than 1mm. In addition, all of the micro-orifice studies in open literature are dealing with single-phase flow only.

Normally the thickness of the orifice plate used in a flow meter should not exceed 1/8 of the orifice bore (Cusick, 1961), and the flow is typically single phase. Single-phase flow through this type of orifice can be calculated with the orifice equation:

\[
m = C_d A \sqrt{2 \rho \Delta p (1 - \beta^4)}
\]  
(1)

The discharge coefficient, \( C_d \), is a function of \( \beta \) and the orifice flow Reynolds number, \( \text{Re} \).

\[
\text{Re} = \frac{\rho v D}{\mu}
\]  
(2)

Equation (1) can also be used for orifices (orifice tubes) with \( L/D > 1/8 \), but \( C_d \) may also be a function of \( L/D \) ratio and orifice diameter, in addition to \( \text{Re} \) and \( \beta \).
Table 1 Summary of orifice studies in macro and micro scale

<table>
<thead>
<tr>
<th>Reference</th>
<th>L/D</th>
<th>Diameter (µm)</th>
<th>Testing condition</th>
<th>Testing Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benjamin &amp; Miller, 1941</td>
<td>&lt; 1</td>
<td>6000 ~ 23000</td>
<td>LT&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Water</td>
</tr>
<tr>
<td>Davies &amp; Daniels, 1973</td>
<td>&lt; 1</td>
<td>762 ~ 1422</td>
<td>LL&lt;sup&gt;b&lt;/sup&gt;, LT, TT&lt;sup&gt;c&lt;/sup&gt;</td>
<td>R12</td>
</tr>
<tr>
<td>Mei, 1982</td>
<td>7 ~ 12</td>
<td>1000 ~ 1700</td>
<td>LT</td>
<td>R22</td>
</tr>
<tr>
<td>Krakow &amp; Lin, 1988</td>
<td>2 ~ 7</td>
<td>889</td>
<td>LT</td>
<td>R12</td>
</tr>
<tr>
<td>Aaron &amp; Domanski, 1992</td>
<td>5 ~ 20</td>
<td>1100 ~ 1720</td>
<td>LT</td>
<td>R22</td>
</tr>
<tr>
<td>Kim &amp; O’Neal, 1994a, 1994b</td>
<td>5 ~ 20</td>
<td>1000 ~ 1720</td>
<td>LT, TT</td>
<td>R134a, R22</td>
</tr>
<tr>
<td>Singh &lt;i&gt;et al.&lt;/i&gt;, 2001</td>
<td>22 ~ 31</td>
<td>1220 ~ 1700</td>
<td>LT, TT</td>
<td>R134a</td>
</tr>
<tr>
<td>Ramamurthi &amp; Nandakumar, 1999</td>
<td>1 ~ 50</td>
<td>300 ~ 2000</td>
<td>LL</td>
<td>Water</td>
</tr>
<tr>
<td>Wang &lt;i&gt;et al.&lt;/i&gt;, 1999</td>
<td>NA</td>
<td>150 ~ 370</td>
<td>LL, GG&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Water, nitrogen</td>
</tr>
<tr>
<td>Hasegawa, 1997</td>
<td>0.05 ~ 1.14</td>
<td>10 ~ 1000</td>
<td>LL</td>
<td>Water, silicon oils, glycerin water</td>
</tr>
<tr>
<td>This paper</td>
<td>2.5 ~ 4.5</td>
<td>31 ~ 52</td>
<td>LL, LT</td>
<td>R134a</td>
</tr>
</tbody>
</table>

<sup>a</sup>LT: Liquid upstream Two-phase downstream
<sup>b</sup>LL: Liquid upstream Liquid downstream
<sup>c</sup>TT: Two-phase upstream Two-phase downstream
<sup>d</sup>GG: Gas upstream Gas downstream

Ramamurthi and Nandakumar (1999) evaluated the discharge coefficients for demineralized water flow through sharp-edged orifices of D = 0.3 ~ 2 mm, and L/D = 1 ~ 50. In the separated flow regime, $C_d$ is not a function of Reynolds number, and the pressure drop across the orifice is due mainly to the pressure loss at the orifice entry, which is proportional to the dynamic head $\rho v^2/2$. For reattached flow, e.g., the flow reattached on the wall after vena contracta, and the pressure drop should include friction loss. Since friction loss is related to Re, $C_d$ for reattached flow is a function of Re. The test results for 300 µm orifice with L/D = 5 demonstrated that $C_d$ initially increased with increase of Reynolds number when Re < 7000 (reattached region), then abruptly dropped to values corresponding to separated flows and did not change with Re any more. For 2000 µm orifice with L/D = 5, the transition to separated flow occurs at Re of 35,000. In separated flow region, the authors demonstrated that the discharge coefficient was larger for smaller orifices, and they attributed this phenomenon to the effect of surface tension. The contribution of pressure by surface tension pumping is $2\sigma/r$ where r is the radius of the orifice and $\sigma$ is surface tension.

Wang <i>et al.</i> (1999) used 150 ~ 370µm orifices as flow restriction device in micro check valves. They tested water and nitrogen flow through these orifices, and found that the macro-scale model correctly predicted the qualitative characteristics of the valve, but gives about 20-30% lower flow rate.

Hasegawa, <i>et al.</i> (1997) tested Stokes flow (low Reynolds number) of water and nitrogen through orifices ranges from 10 µm to 1mm. The test results were compared with numerical analysis of a Newtonian fluid by the finite element method. The results showed that the predicted pressure drop underestimated the measured value when the size of the orifice is smaller than 35 µm. They concluded that flow through very small orifices is different from that through ordinary size ones which can be solved with a Navier-Stokes equation.

When orifices are used as expansion devices in refrigeration industry, they typically work under liquid upstream two-phase downstream (LT) condition. When liquid flashes while passing through the expansion device, the flow may be choked. Choked flow is defined as the phenomenon that occurs when the mass flow rate remains constant even when there is a further reduction in downstream...
pressure. A constant-flow area expansion device that is sensitive to the downstream pressure (not choked) would be detrimental to system performance and reliability (Aaron and Domanski, 1990).

Normally an orifice with L/D < 1 does not choke the flow (Benjamin and Miller 1941, Davies & Daniels 1973). Krakow & Lin (1988) tested orifice tubes with L/D of two and seven with R12. They found that the flow was primarily dependent on the upstream conditions and not on the downstream pressures, thus a choking phenomenon was indicated. Aaron & Domanski (1990) and Kim & O’Neal (1994a, 1994b) investigated flow through orifice tubes with L/D between 5 and 20. Their results showed that critical (choked) flow was established when the downstream pressure was below the saturation pressure corresponding to the upstream temperature. Singh et al. (2001) tested R-134a flow through orifice tubes with L/D = 20 ~ 30. They found that for the choked flow condition, the mass flow rate was a strong function of inlet pressure, inlet subcooling, and diameter, but relatively weak function of length.

The main objective of this work is to investigate liquid flow with flashing (LT) through micro-orifices. Before proceeding to LT flow, it is necessary to understand liquid only flow (LL) in micro-orifices. Hasegawa et al. (1997) has studied liquid flow through micro-orifice as small as 10 µm, but it is under very low Reynolds numbers (Re < 100) and small L/D values (L/D < 1.2). In addition, the study of Hasegawa et al. indicates that single-phase flow through micro-orifices smaller than 35 µm in diameter may be different from the classic theories. Therefore, LL flow was investigated before LT experiment.

**EXPERIMENTAL FACILITY**

The micro-orifice experimental facility is shown schematically in Figure 1. Because the flow rate is very small, the apparatus was designed as a once-through system for simplicity and flow stability. The system consists of a refrigerant supply tank, control valve, test section, and receiver tank for adjusting the experimental conditions. The refrigerant tank contains saturated R134a, which was maintained at a desired pressure using a variable transformer (variac) and an electric resistance heater. Liquid refrigerant was driven into the test loop by placing the supply pipe at the bottom of the reservoir. The receiver tank was exposed to room temperature or placed in ice bath, which provided a stable lower pressure. The orifice downstream pressure (P_{oo}) was adjusted by a control valve. The orifice upstream subcooling was controlled by adjusting the heating power of a rope heater, which was wrapped around the tube upstream of test section.

![Figure 1: Experimental apparatus](image)

The receiver tank was placed on a digital balance (Sartorius model BP6100A), and the small flow rate was measured by weighing the liquid accumulation during a long period of stable state. A Rheotherm® mass flow rate meter was installed before the test section, as a redundant way of flow rate measurement. In fact, the mass flow rate meter could only guarantee accuracy in a very limited region and most of the flow rates were out of this range. In addition, the balance was more accurate than the
mass flow rate meter when the flow was stable. Therefore, the balance weighting results were used for data analysis. On the other hand, since the reading of flow rate meter is continuous, it could help to make sure a steady state has reached. A filter with mesh size of 0.5\(\mu\)m was installed just before the flow meter to protect it from dust particles. Because the mass flow rate meter is based on liquid flow energy balance, a subcooler and a sight-glass was used to make sure subcooled liquid entering the flow meter. The mass flow rate measurement error was estimated to be within \(\pm 1\%\).

The test section was shown in Figure 2. It consists of the orifice, orifice holder, filter, thermocouples, and pressure transducers. The orifice holder was manufactured from delrin®️, which had two parts (A and B in Figure 2). The orifice was sandwiched between the two parts, and sealed with a very thin layer of epoxy. A filter with mesh size of 0.5\(\mu\)m was inserted into the inlet of the orifice holder to avoid clogging of the orifice. The orifice upstream and downstream fluid temperatures were measured using two type-T thermocouples (\(T_{oi}\) and \(T_{oo}\) in Figure 2), both of which were inserted into the center of the flow stream with distances of 5 mm from the orifice. A pressure transducer (Setra model 206, 0 ~ 1724 kPa), \(P_{oi}\) in Figure 2, was used to measure the orifice upstream pressure. The pressure tap was drilled after the filter, since the pressure drop across the filter may not be negligible. A T-compression-fitting, which was connected directly to the test section, was used for downstream pressure measurement (not shown in Figure 2). The temperatures and pressures were monitored using a computer data acquisition system. The estimated accuracy of the temperature measurements was \(\pm 0.2^\circ\)C. The pressure transducer was calibrated to \(\pm 0.13\%\) full-scale accuracy.

![Figure 2: test section](image)

Figure 2: test section

![Figure 3: Schematic drawing of the micro-orifices tested (a) 52\(\mu\)m (b) 31 \(\mu\)m](image)
The orifice is a pinhole drilled by laser on a 130µm thick, 9.5mm diameter stainless steel foil. The dimensions of the orifices are shown in scale in Figure 3. An Olympus microscope with magnification of 1000 was used to measure the orifice size and observe the entrance condition. When front-lighted mode was used, the orifice surface conditions could be observed, as shown in Figure 4 (a) and (c). Burrs were observed at the periphery of the hole. The bur is about 20% of the orifice diameter in size and about 5 µm in height. Back lighted mode was used to measure the orifice size, as shown in Figure 4 (b) and (d). The two orifices were measured to be 52.0 and 31.0 µm in diameter, with errors within ±0.5 µm.

All experimental data were recorded in steady condition for at least ten minute. It was assumed that steady state was reached when the change in upstream temperature (\( T_{oi} \)) was within ±0.2 °C, upstream pressure change was within ±3 kPa, and downstream pressure change was within ±5kPa for a minimum of 5 minutes preceding data collection.

RESULTS AND ANALYSIS

Liquid upstream, Liquid downstream (LL)

The discharge coefficient for liquid upstream liquid downstream flow was calculated using equation (1), based on the measured pressure drop, mass flow rate, and orifice cross-section area. The results along with the error bars are shown in Figure 5. The error bars were determined using the uncertainty propagation function based on Taylor and Kuyatt (1994).

For 31µm orifice, \( C_d \) is about the same for the whole range of 1500 < Re < 4500, which indicates separated flow. Ramamurthi & Nandakumar (1999) observed that the transition from reattached region to separated region occurred at Reynolds number of 7000 and 3,5000, for 300 µm and 2000 µm orifices (L/D = 5), respectively. Hence, separated flow occurs at lower Reynolds number in micro-orifices than that in larger ones with the same L/D ratio.

The surface tension of R134a at the current test condition is about 0.0083N/m, which gives driving pressure for 31 µm orifice about 1kPa. This value is about the same as water flowing through 300µm orifice. However, the lowest pressure drop in the experiment of Ramamurthi & Nandakumar (1999) is about 20kPa, which makes the surface tension effect significant. On the other hand, the lowest pressure drop in the current work is 136kPa, thus the surface tension effect can be neglected. This could explain why \( C_d \) for 31 µm orifice in the present work (~ 0.67) is smaller than that of 300µm orifice (~0.8) in separated flow region, but it is almost the same as 2000 µm (~ 0.67) for which surface tension effect is also negligible.

The discharge coefficients for 52µm orifice are a little larger than that for 31µm orifice, but they still can be approximated as a constant value of 0.70. Constant discharge coefficients of 0.70 for 52 µm, and 0.68 for 31 µm orifices were shown to be capable of predicting all the experimental data within ±3%.
Liquid upstream, Two-phase downstream (LT)

The experimental range of liquid flow with phase change (LT) was chosen to be similar to that of Kim and O’Neal (1994a). The upstream subcooling changed from 4 °C to 26 °C, upstream pressure ranged from 900 to 1491 kPa, and downstream quality varied between 4% and 32%.

Figure 6 shows the relationship between mass flow rate and pressure drop for all the experimental data. The mass flow rate is a strong function of pressure drop, no matter what the values of upstream subcooling, upstream pressure and downstream pressure are. When compared with pure liquid flow data under the same pressure drop, the mass flow rate values are lower, but the differences are very small. Further analysis shows that the liquid flow model underpredicts almost all of the data, but most of the errors are within −15%.

Figure 6 indicates that liquid flow with flashing in micro-orifices can be approximated as pure liquid flow. In macroscale orifice tubes (Krakow & Lin 1988, Aaron & Domanski 1990, Kim & O’Neal 1994a, 1994b, Singh et al. 2001), the flow was normally choked when flashing occurs, and the flow characteristics for LT flow are quite different from that of LL flow. Typically, the mass flow rate is not directly related to pressure drop, but proportional to upstream pressure and upstream subcooling and not a function (or a very weak function) of downstream pressure. The differences between the current work and macroscale results suggest that the flow may not be choked in the current study.

Figure 7 (a) presents the effect of downstream pressure on mass flow rate for 52μm orifice. The upstream pressure was kept constant at 1310 ± 1 kPa. Three different upstream subcooling values, 4.4 ± 0.7 °C, 9.6 ± 0.5°C and 13.7 ± 0.4 °C were presented. The saturation pressure (P_{sat}) corresponding to the upstream temperature was also listed. The downstream pressure was reduced from at least 200 kPa.
below the corresponding saturation pressure. The mass flow rate increased monotonically as downstream pressure decreased. Obviously, the flow was not choked. In addition, the flow rate is only a very weak function of upstream subcooling, with the lower the subcooling the lower the mass flow rate.

![Graph](image1)

(a) 52 μm orifice, upstream pressure constant at 1310 ± 1 kPa

Figure 7: Flow dependency on downstream pressure as a function of upstream subcooling. Psat is the saturation pressure corresponding to inlet temperature

The downstream pressure effect on mass flow rate for 31μm orifice under upstream pressure of 1310kPa and three upstream subcooling levels (4.8 ± 0.5 °C, 13.9 ± 0.2 °C and 21.5 ± 0.2 °C) is shown in Figure 7 (b). For upstream subcooling of 21.5 °C, the flow rate increases monotonically with the decrease of downstream pressure, and the flow is not choked. For upstream subcooling of 4.8 & 13.9 °C, the flow rate increases proportionally for most of the region when the downstream pressure is reduced. However, when the downstream pressure is reduced below 450kPa, the mass flow rate remains almost constant. This might be because of experimental error or an indication of choked flow.

The L/D ratio of 31μm orifice (L/D = 4.2) is very close to the lowest L/D range of Kim and O’Neal (1994a), where L/D = 5 ~ 20. In addition, both investigations used the same refrigerant (R134a) and similar experimental conditions. Kim and O’Neal (1994a) demonstrated that choked flow conditions were typically established when the downstream pressures were reduced below the saturation pressure corresponding to the upstream pressure, and the flow rate change with the decrease of the downstream pressure beyond P_{sat} to the minimum pressure tested was less than 5%. However, Figure 7 (b) shows that choking did not occur for downstream pressure as low as 400 kPa below P_{sat}. In addition, Krakow and Lin (1988) reported choked phenomenon for R12 flowing through orifice of L/D = 2 and D = 889 μm, but the flow through 52μm orifice (L/D = 2.5) was not choked for a wide range of experimental conditions. Therefore it suggests that choked flow is much more difficult to be established in micro-orifices than in conventional scale ones.

Semi-empirical model for LT flow through micro-orifices was developed based on correction of the orifice equation.

\[ m = (1 - C_x x_{out})C_d A_0 \sqrt{2 \rho \Delta P} \]  

(3)

Where \( x_{out} \) is downstream vapor quality and \( C_x \) is an empirically determined constant. The discharge coefficients \( C_d \) are empirically determined value from LL test, which are 0.7 for 52μm orifice and 0.68 for 31 μm orifice. A constant value of \( C_x = 0.416 \) was found to be able predict 90% of the experimental data within deviation of ± 5%.

CONCLUSIONS AND RECOMMENDATIONS

This study is one of the first to study micro-orifice used as flow restrictor and expansion device. Orifices with inner diameter of 31 and 52μm, L/D ratio of 2.5 and 4.2, respectively, were tested under
both Liquid upstream Liquid downstream (LL) and Liquid upstream Two-phase downstream (LT) conditions. The micro-orifices have been observed under 1000-times magnification microscope before experiment. Actual diameters were measured, and the entrance surface condition was characterized.

For liquid flow without flashing (LL), the macroscale orifice equation is still applicable. The discharge coefficient was determined to be constant for Reynolds number ranging from 1500 to 6700, which indicates separated flow. When compared with macroscale orifice results, the flow separation occurs at lower Reynolds number.

For liquid flow with flashing (LT), the flow rate was still a strong function of pressure drop as in LL flow, but weakly dependent on upstream subcooling. For 52µm orifice, mass flow rate increases with decrease of downstream pressure for all three inlet subcooling values of 4.8°C, 13.9°C, and 21.5°C, even when downstream pressure has been reduced to 600 kPa below the saturation pressure, which means the flow was not choked. For 31µm orifice, the flow was not choked even when downstream pressure was 400kPa below the saturation pressure, for upstream subcooling of 4.8, 13.9 and 21.5 °C. Krakow & Lin (1988), Aaron & Domanski (1990), Kim & O’Neal (1994a, 1994b) have demonstrated experimentally that, for orifice with inner diameter around 1mm and L/D > 2, the flow was choked when downstream pressure was reduced below the saturation pressure. Therefore, LT flow through micro-orifices is different from that in conventional size orifices. Semi-empirical model was developed based on correction of the orifice equation. The model predicts 90% of the experimental data within deviation of ± 5%.

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REFERENCES
Davies, A. and Daniels, T.C., Single and two-phase flow of R12 through sharp-edged orifices, ASHRAE Transactions Vol. 79, Part1, 1973
Kim, Y. and O’Neal, D.,“Two-phase flow of R-22 through short-tube orifices”, ASHRAE Transactions, V(100) No.1, 1994b
K Krakow, K.I. and Lin, S., “Refrigerant flow through orifices”, ASHRAE Transactions, V(94), P.1, 1988
Taylor B.N. and Kuyatt, C.E., Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, National Institute of Standards and Technology Technical Note 1297, 1994
Wang, Xuan-Qi Lin, Qiao Tai, Yu-Chong, “A Parylene Micro Check Valve”, 1999 IEEE, pp.177-181