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Effect of Orientation on Performance of The Refrigerant Distributor

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ABSTRACT

Maldistribution of refrigerant two-phase flow in a DX evaporator is almost inevitable in real application because of the different properties of liquid and vapor. One of the main reasons for this is phase separation due to the effect of gravity. For vertical orientation, the influence of gravity on the operation of distributors is small. However, horizontal installation is more likely to be affected by gravity when the flow is not homogeneous. This paper presents an evaluation of the performance of a refrigerant distributor at three different orientations: horizontal, vertical upwards, and downwards. For each direction, the expansion device, distributor, and evaporator are connected in the same way to reduce the effect of test facility on the flow distribution. A transparent distributor with identical geometry of an original version is built for the purpose of visualization. Both distributors are tested under the same working conditions to investigate the individual difference. Results show that two-phase distribution at the horizontal orientation is similar to the vertical results, indicating no effect of gravity for the tested working conditions. However, the difference in individual distributor circuit due to manufacture will result in maldistribution in some degree.

1. INTRODUCTION

It is well known that the proper distribution of refrigerant two-phase flow through a multi-circuit evaporator is of great importance. To achieve more uniform distribution, refrigerant distributors of various types have been proposed. Schematics of two typical designs (Hrnjak, 2004) are illustrated in Figure 1. The first one (Figure 1a) is based on the principle that first generating a homogeneous liquid-vapor mixture by the orifice and then distributing the mixture to each branch before a sharp cone. The second one (Figure 1b) takes an opposite but also effective concept: separating the two-phase flow and then distributing each phase independently to each branch. The primary limitation of the second design is the installation angle. It can only work properly at the vertical orientation, while the first one is less affected by direction.
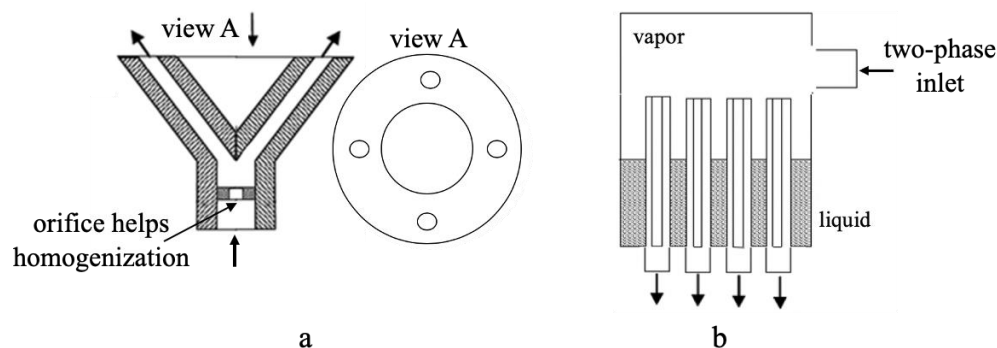

Figure 1: Two typical designs of distributor. (a) homogenize and distribute. (b) separate and distribute.

In addition to these two designs, some other types of distributors have been proposed and studied in the literature. Nakayama *et al*. (2000) compared the performance of a conventional distributor with a new design, which replaced the orifice with a capillary mixing space. They found that the new design outperforms the traditional distributor at various working conditions for vertical upwards orientation. When installed with a 15° inclination, the new design has a smaller decrease in performance than the conventional distributor. Aziz *et al*. (2012) investigated the performance of a simple one-inlet, two-outlet distributor with air and water. They claimed that the uniform distribution could be achieved at a high superficial velocity of air and water or by changing the installation angle from horizontal to vertical. Zhang *et al*. (2014) studied a reservoir type distributor under different operating conditions and orientations. When the inclination angle is within 15°, the standard deviation of the mass flow rate is less than 9%. As the inclination angle increases to 90° (horizontal), the standard deviation is more than 40%. Fay and Hrnjak (2011) compared the performance of a conical type distributor at three orientations: vertical downward, 22.5°, and 45° inclinations. The distribution of superheat showed similar patterns, indicating no effect of gravity. Heikal (2015) simulated flow distribution in various geometries of the distributor using FLUENT. The results indicated that distributor orientation had almost no impact on the two-phase flow distribution due to the high inlet velocity.

In general, vertical orientation is preferable than horizontal for most of the distributors. However, only a specified direction is allowed in some cases due to the space limitation. Therefore, the effect of orientation on the distributor performance is quite important. The magnitude of impact from orientation varies as distributor types change, and it is affected by the operating conditions as well. This paper presents an evaluation of the performance of a specific type of distributor at three different orientations: horizontal, vertical upwards, and downwards. The distributor performance is evaluated quantitively and visually in an attempt to understand the two-phase flow behavior in the distribution.

2. EXPERIMENT

2.1 Facility

The experiments for this work are performed in a real 4-5 kW R134a system, as shown schematically in Figure 2. It is composed of two major parts: the condensing unit and the test section. Refrigerant exiting the test section (from evaporator) will pass through the accumulator, compressor, condenser, receiver, and sub-cooler before returning to the test section again. Two flexible hoses connect the condensing unit and the test section. It allows the test section to be positioned in any orientations (Figure 3) with no need to change the connection between any components. To make the test section more compact, the evaporator in this system is an electrically heated evaporator (Figure 4), instead of the conventional wind tunnel type. We control the capacity of each circuit by adjusting the power of the electrical heaters through variacs individually. Four watt transmitters measure the heating power of each heater. T-type thermocouples, pressure transducers, and mass flow meters measure the temperature, pressure, and mass flow rate at the evaporator exits. Based on the measured parameters, we calculate the refrigerant qualities at distributor outlets (or evaporator inlets). The mass flow rate at the distributor inlet is controlled by changing the speed of the compressor, and the desired inlet quality is achieved by adjusting the flow rate of cooling water in the sub-cooler.
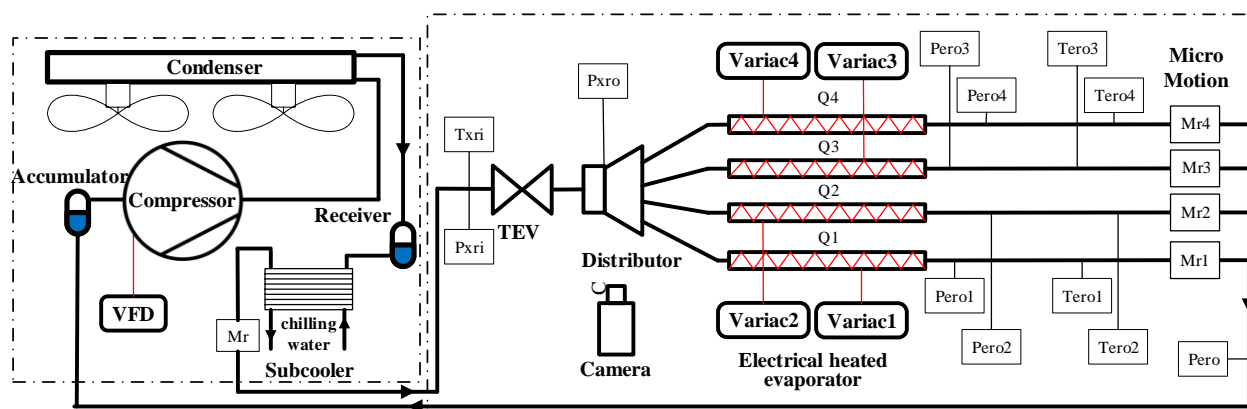

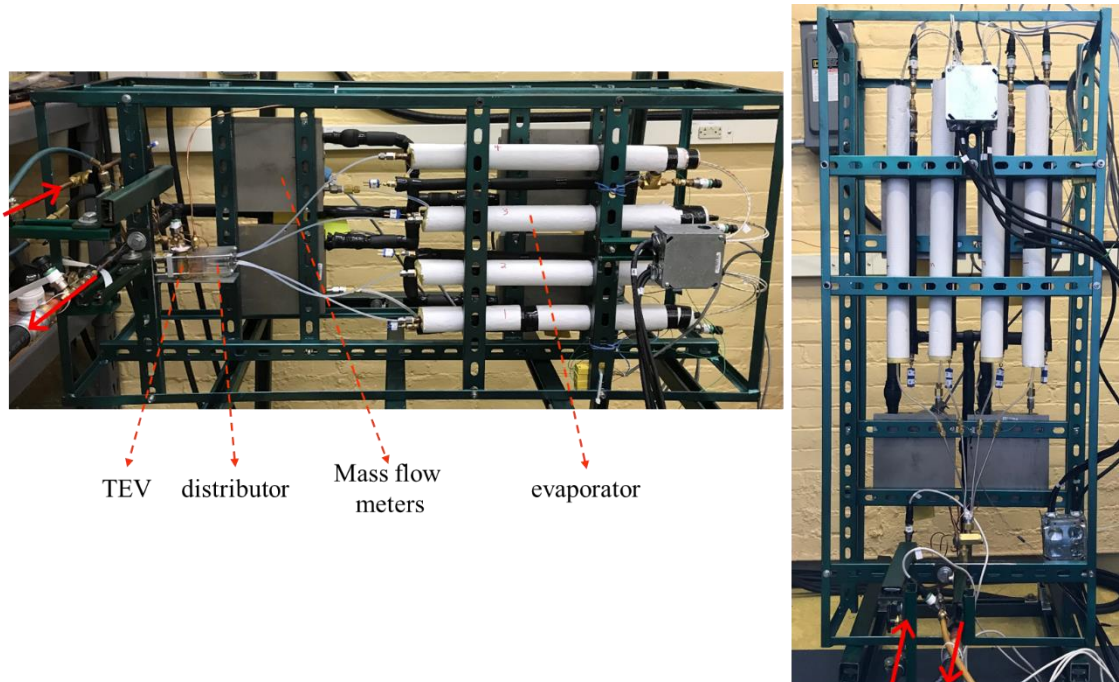**Figure 2:** Schematic of the experimental facility

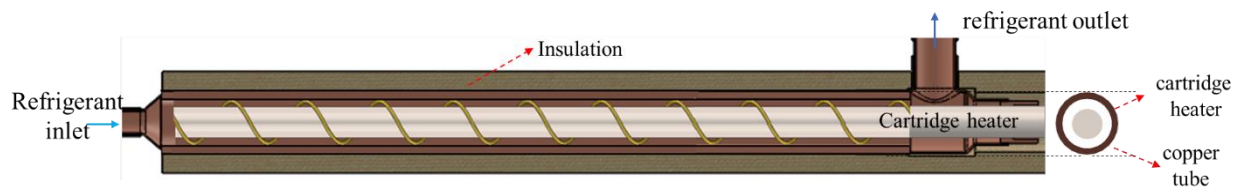**Figure 3:** Test section in different orientations

Figure 4: Structure of the evaporator (there are four evaporators)

Two distributors are used in this work: one original (Figure 5a) and one transparent (Figure 5b). The transparent distributor is built based on the exact geometry of the original one to visualize two-phase flow regimes exiting the expansion device and entering the distributor. We also check the effect of manufacture and test facility on distributor performance by comparing the experimental results of the two distributors.
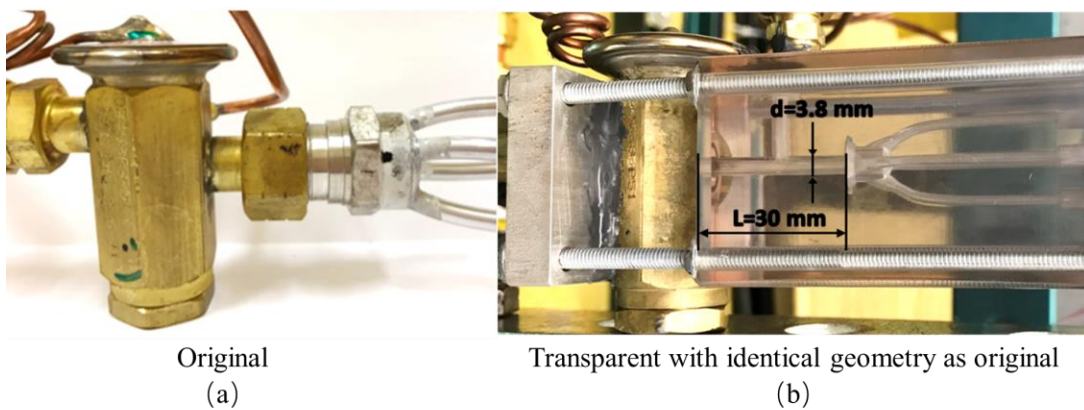

Original
(a)

Transparent with identical geometry as original
(b)

Figure 5: TEV and distributor assembly

2.2 Operating Conditions and Data Reduction

Table 1 lists the experimental conditions. For each operating condition, we conducted the experiments at three orientations: horizontal, vertical upwards, and vertical downwards. The distributor performance is evaluated by the uniformity of mass flow rate, evaporator inlet quality, and capacity among each circuit. To calculate the refrigerant qualities at evaporator inlets, refrigerant properties at evaporator outlets and the heat loads are necessary. The heating power provided to each circuit is different to achieve the same superheat (10°C), allowing the calculation of the refrigerant enthalpies at the evaporator exits. Equations 1-5 show the procedure to calculate the evaporator inlet qualities for each circuit.

$$h_{ero,i} = f(T_{ero,i}, P_{ero,i}) \tag{1}$$

$$h_{l,i} = f(P_{ero,i}) \tag{2}$$

$$h_{g,i} = f(P_{ero,i}) \tag{3}$$

$$h_{eri,i} = h_{ero,i} - Q_i/m_i \tag{4}$$

$$x_i = \frac{(h_{eri,i} - h_{l,i})}{(h_{g,i} - h_{l,i})} \tag{5}$$

where i represents the circuit number (i=1-4); T_{ero} and P_{ero} are the temperature and pressure at evaporator outlet; h_{ero} and h_{eri} are the specific enthalpies of the refrigerant at the evaporator outlet and inlet; h_l and h_g are the specific enthalpies of saturated liquid and vapor at the evaporating pressure; Q is heat load provided to each circuit; m is refrigerant mass flow rate; x is vapor quality of each circuit at evaporator inlet. The specific enthalpies are obtained from REFPROP.

Table 1: Working conditions

Working fluid	R134a with oil
Mass flow rate [g/s]	15, 20, 25
Distributor inlet quality [-]	0.23
Orientations	Horizontal, Vertical upwards & downwards
Superheat at evaporator exit [°C]	10

Table 2 lists uncertainties of all the instruments used in this study.

Table 2: Uncertainties of the instruments

Measurement	Instrument	Uncertainty
Pressure	Sporlan pressure transducer (PSPT0150SVSP-S)	±3.56kPa
Temperature	T-type thermocouple	±0.1K
Mass flow rate	Coriolis mass flow meter	±0.2% of reading
Heating power	Ohio Semitronics watt transducer (PC5-002E)	±0.5% FS

3. EXPERIMENTAL RESULTS

The distributor performance is evaluated by the uniformity of mass flow rate, liquid quality, and capacity among each circuit. We use liquid instead of vapor quality because liquid refrigerant is the useful part for cooling capacity. To compare the results from various working conditions fairly, all the parameters are normalized, as defined by the following equations:

$$m_i^* = \frac{m_i}{(\sum_{i=1}^4 m_i)/4} \tag{6}$$

$$(1 - x_i)^* = \frac{1 - x_i}{(\sum_{i=1}^4 (1 - x_i))/4} \tag{7}$$

$$Q_i^* = \frac{Q_i}{(\sum_{i=1}^4 Q_i)/4} \tag{8}$$

where m_i^*, $(1-x_i)^*$, Q_i^* are the normalized mass flow rate, liquid quality, and capacity of circuit i (i=1-4).

3.1 Two-phase Flow Distribution at the Horizontal Orientation (Transparent Distributor)
Figure 6 presents the flow distribution in terms of the normalized mass flow rate, liquid quality, and capacity. Each circuit is represented by one line with different colors and symbols. In horizontal orientation, circuits 1 and 4 are located at the bottom and the top, while circuits 2 and 3 are at the middle. According to Figure 6, more vapor is distributed to circuits 2 and 3 for all the working conditions. Accordingly, they get less flow rate than the other two circuits. It is because the pressure drop of each circuit should be the same. The capacity is determined by both the mass flow rate and quality. Therefore, the capacity of circuits 1 and 4 are higher than the other two because of the high flow rate and high liquid quality.

The result that circuit 4 always has a high mass flow rate also indicates flow distribution is not affected by the gravity under the tested working conditions. It is because the velocity of the two-phase refrigerant flow at the distributor inlet is relatively high. As a consequence, the inertia of the refrigerant flow is stronger than the gravity.
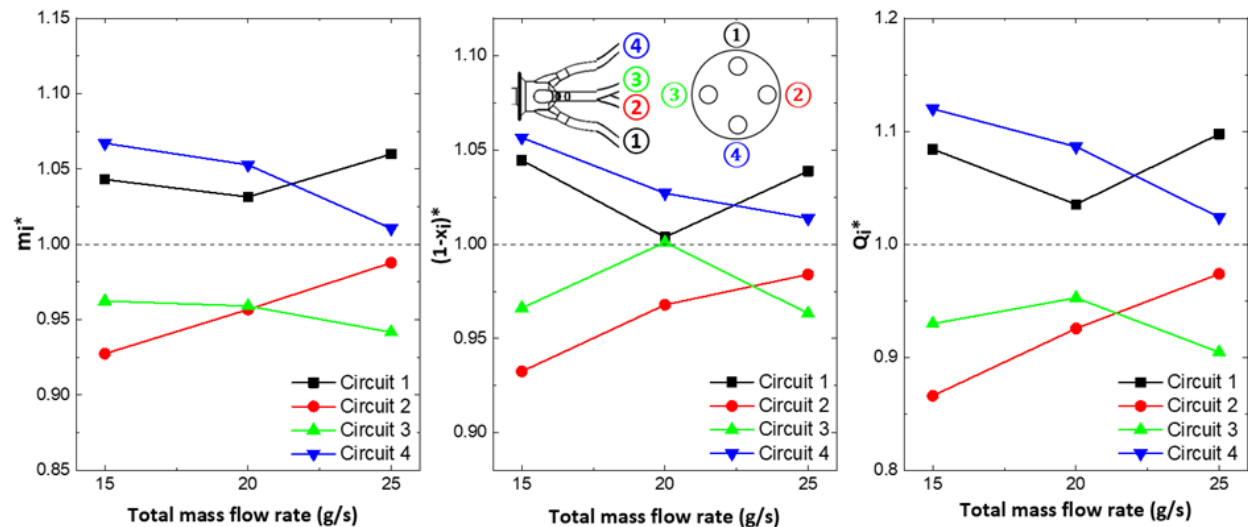

Figure 6: Distribution of normalized mass flow rate - m_i^*, liquid quality - $(1-x_i)^*$ and capacity – Q_i^* at horizontal orientation, $x_{dri}=0.23$

3.2 Effect of Orientation on the Distributor Performance (Transparent Distributor)
It is well known that gravity plays an important role in phase separation when it comes to the two-phase flow distribution. And its impact is different as the flow direction changes. To investigate the effect of orientation on the performance of the refrigerant distributor, all the experiments performed at horizontal condition are also conducted at vertical upwards and downwards directions. Standard deviation, as defined in equation 9, is used to analyze the uniformity of the flow distribution. It integrates the normalized parameters of each circuit into one single number and indicates the averaged diversion of each circuit from the mean. For a completely uniform distribution, the standard

deviation should be zero. In this work, the standard deviation of capacity is used because capacity is a synthetical effect of mass flow rate and quality.

$$STD_Q = \sqrt{\frac{\sum_{i=1}^{4}(Q_i^* - 1)^2}{4}} \qquad (9)$$

where STD_Q is the standard deviation of capacity; Q_i^* is the normalized capacity of circuit i (i=1-4).

Figure 7 compares the standard deviation of capacity at three orientations. In general, the distributor performance is quite similar for all three directions, although not exactly overlapped with each other. The advantage of vertical over horizontal is almost negligible. It indicates that the orientation or gravity has nearly no effect on the distributor performance under the tested operating conditions. This conclusion is also verified by the results that the circuit at the top location always gets more liquid than the circuits in the middle when the distributor is installed horizontally, as discussed in the previous section. The first reason for this is the small diameter of the inlet tube before the distributor. So, the flow velocity is high enough to make the momentum to overcome the effect of the gravity. The second reason is the short distance between the distributor and the expansion valve. The well-mixed two-phase flow generated by the expansion process in the thermostatic expansion valve has not separated at the distributor inlet, as indicated by the visualization results in Figure 8.

The nominal capacity of the distributor is 4kW, corresponding to the mass flow rate of about 25g/s. For all the tested working conditions (m=15-25g/s), no obvious phase separation is observed at the distributor inlet or inside the distributor. What's more, the flow regimes at horizontal orientation are similar to the vertical results. However, when the mass flow rate is reduced to 3-5g/s (16% of the nominal capacity), there is a clear interface between the liquid and vapor phases. For vertical orientation, the flow regime at the distributor inlet is annular. While a stratified annular flow is observed for the horizontal orientation due to the effect of gravity. In this case, it is expected that flow distribution would be affected by the distributor orientation.

Although Figure 7 has presented the similarity of standard deviation at different orientations, it is also essential to learn the detailed flow distribution in each circuit. In Figure 9, distributions of normalized mass flow rate, liquid quality, and capacity at three orientations are put together for a better comparison. For all the three plots, the black and blue lines are in the upper part while the green and red lines are in the relatively lower part. That means circuits 1 and 4 usually have a higher mass flow rate, low vapor quality, and high cooling capacity than the other two circuits regardless of the orientation. Since this similar pattern of distribution is not affected by orientation, gravity is excluded from the possible reasons. Other potential explanations may be the different resistance in each circuit due to non-ideal facility construction or the difference in distributor circuits due to manufacture. This will be discussed further in the following section.
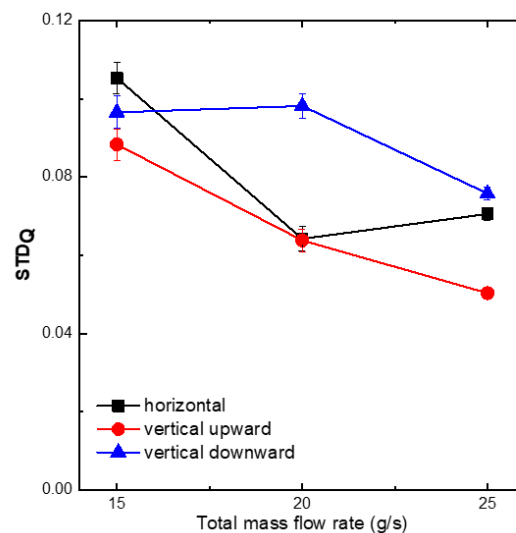

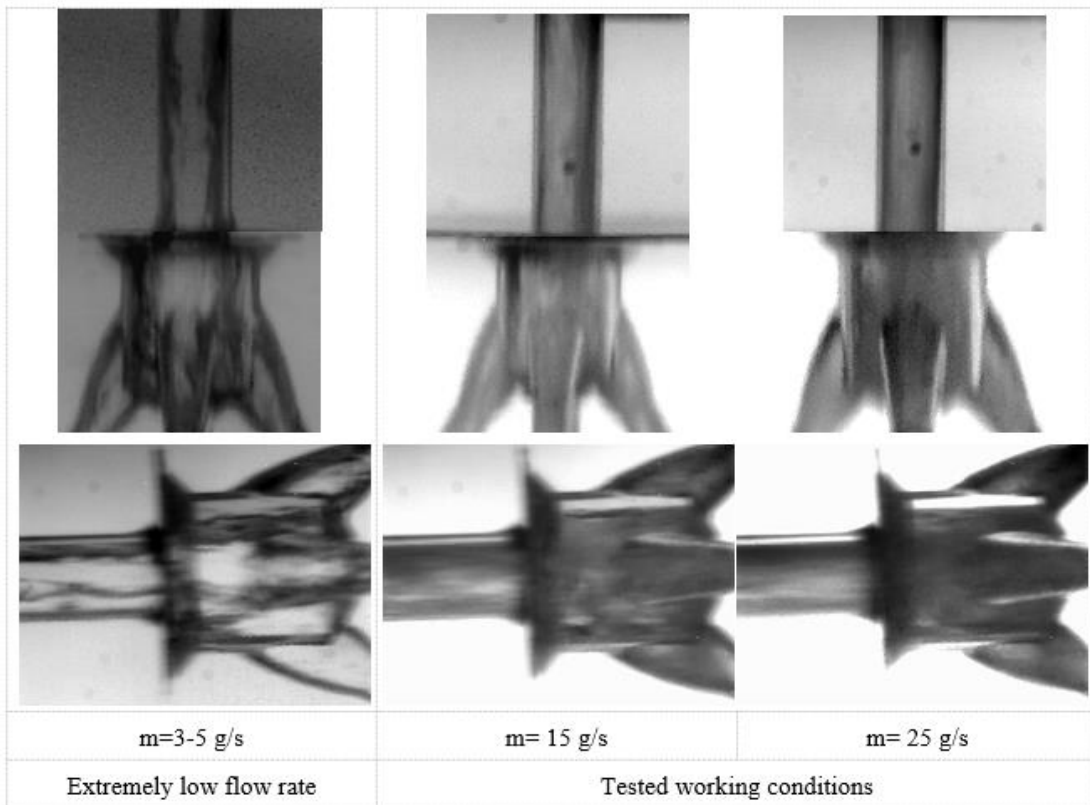**Figure 7:** Standard deviation of capacity at three orientations

Figure 8: Visualization of flow distribution at horizontal and vertical orientations
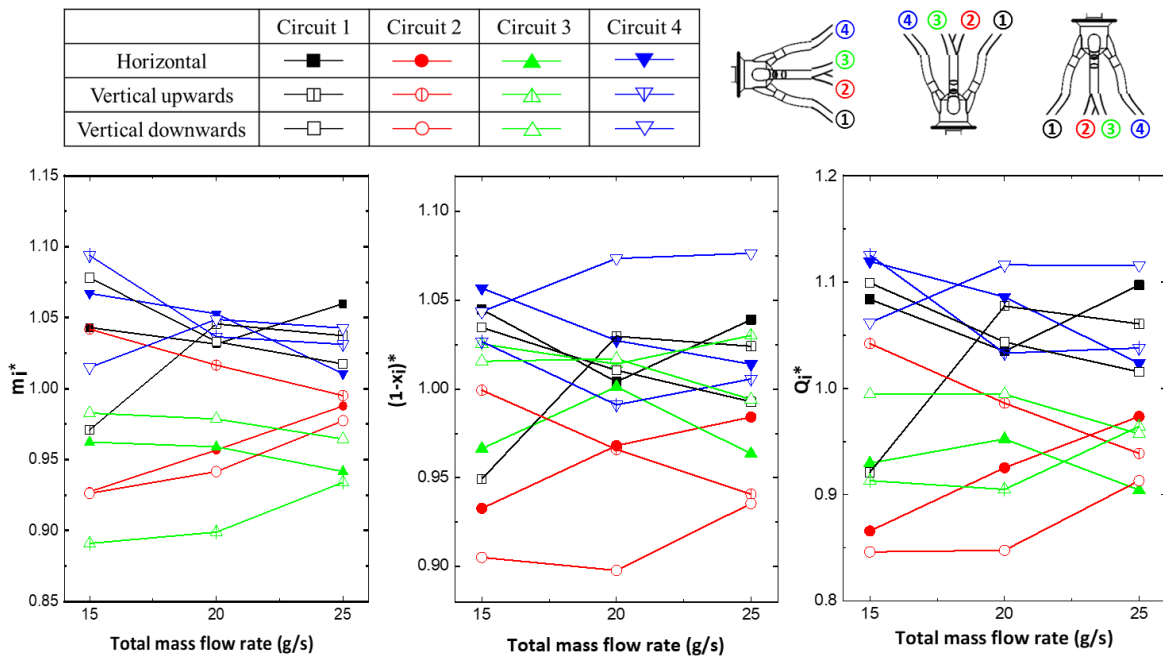

Figure 9: Distribution of normalized mass flow rate - m_i*, liquid quality - $(1-x_i)*$ and capacity – Q_i* at three different orientations, $x_{dri}=0.23$

3.3 Flow Distribution of the Original Distributor

In the previous section, it has been proved that the not perfect but robust pattern of flow distribution for the transparent distributor is not a result of the orientation/gravity. To check the potential effect of the test facility on two-phase flow distribution, we also test the performance of the original distributor under the same working conditions as the transparent one. Since the transparent and the original distributor have the identical geometry, we would expect to get similar performance theoretically. Figure 10 presents the distribution of the normalized mass flow rate, liquid quality, and cooling capacity of the original distributor at three orientations. For this distributor, circuits 1 and 2 always get more liquid phase refrigerant than the others. Accordingly, they have a higher mass flow rate and larger capacity. This pattern of flow distribution is also not changed as the orientation varies.

Compared to the experiments of the transparent distributor, the only changed component is the distributor itself, while all the other parts of the test section kept exactly the same. The circuit numbers are named as indicated in Figure 2, which is also unaltered. Although each distributor has a constant pattern of flow distribution for all the operating conditions, they are different from each other. For the transparent distributor, circuit 1 has a similar behavior with circuit 4. However, a similarity between circuits 1 and 2 is observed for the original distributor. The difference between the two distributors implies that the maldistribution is not a consequence of the resistance difference among each circuit. Because in that case, the circuit with relatively larger resistance will always has a lower flow rate regardless of the distributors.

A similar phenomenon was observed by Fay and Hrnjak (2011). They measured the superheats at evaporator exits to denote the uniformity of flow distribution for a conical type distributor with 12 circuits. It was found that the superheat profile is almost the same over a range of operating conditions with variations of inlet quality and mass flow rate. Therefore, they concluded that the superheat profile is a result of a complicated relationship between the distributor and the evaporator. Based on the results of both the transparent and original distributor in this work, it seems that the test section (including the evaporator) does not affect the flow distribution significantly. In contrast, the distributor itself is more likely to be the reason. Since the two distributors are manufactured by different methods, there may be some differences between these two distributors. More importantly, for each distributor, the individual circuits may not be identical. Some burrs on the inner surface, for instance, will cause the non-uniform flow distribution, and this kind of characteristic is not affected by the orientation.
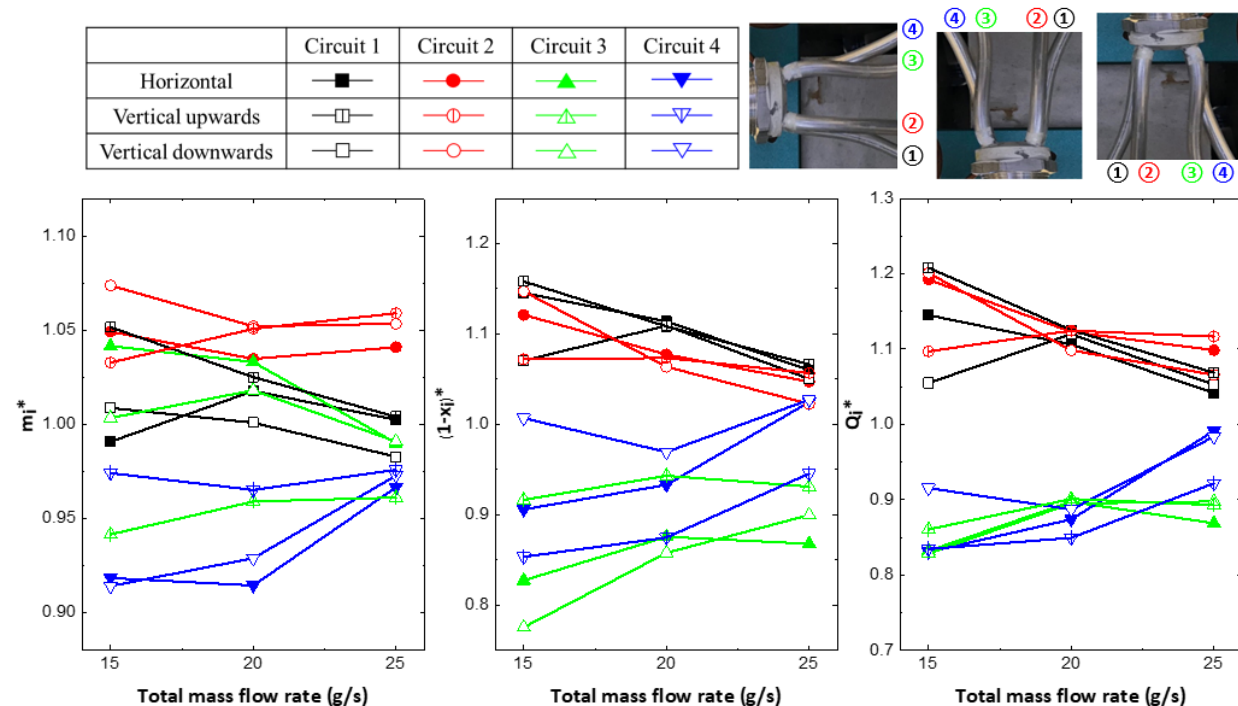

Figure 10: Distribution of normalized mass flow rate - m_i^*, liquid quality - $(1-x_i)^*$ and capacity – Q_i^* at three different orientations for the original distributor, x_{dri}=0.23

4. CONCLUSIONS

Two-phase flow distribution in a transparent and an original distributor are evaluated in a real R134a system at three orientations: horizontal, vertical upwards, and downwards. It is found that orientation/gravity has nearly no effect on the distributor performance for both cases. Visualization through the transparent distributor shows similar flow regimes between horizontal and vertical. There is no obvious phase separation for the tested operating conditions. For each distributor, the pattern of two-phase distribution is consistent as the distributor orientation varies. In other words, some circuits always get more liquid than the others, regardless of the operating conditions or the distributor orientations. However, this consistent pattern is not the same for the two distributors when nothing except the distributor is changed in the test section. Therefore, the influence of the test section, such as the resistance difference among each circuit, is nearly negligible. The non-uniform distribution is more likely caused by the difference in distributor circuits due to the manufacture.

NOMENCLATURE

h	enthalpy	kJ/kg
m	mass flow rate	g/s
P	pressure	kPa
Q	heating power	W
STD	standard deviation	-
T	temperature	°C
x	quality	-

Subscripts

dri	**d**istributor **r**efrigerant **i**nlet
eri	**e**vaporator **r**efrigerant **i**nlet
ero	**e**vaporator **r**efrigerant **o**utlet
i	circuit number i
l	liquid
v	vapor

Superscripts

*	normalized parameter

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