2002

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R12-7

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ABSTRACT

CFD was applied to evaluate the performance of both existing and improved designs for refrigerant distributors. In general, it is better to utilize a spherical base as compared with other shapes and to locate the orifice close to distributor base. These changes tend to improve the robustness of the distributor in terms of providing even flow and phase distribution in different outlet branches when the orifice and/or distributor are not oriented optimally. In addition, experiments were performed that tend to validate the general trends associated with the CFD results.

Introduction

Two-phase refrigerant is generally distributed to individual circuits within the evaporator of a vapor compression air conditioner or refrigerator. Often times, an orifice is integrated into a distributor housing to provide a low cost method for expansion and refrigerant distribution. Ideally, the mass flow rates and qualities of the refrigerant exiting the different branches of the distributor should be equal in order to obtain the best performance for the evaporator and the system as a whole. However, this is generally not the case.

Very little has been published regarding the analysis of refrigerant flow distributors. Generally, refrigerant flow distributors are designed using a trial-and-error process. Nakayama (2000) did experimental investigations involving a refrigerant distributor and proposed a new distributor that was claimed to have better performance with respect to flow distribution. The improved design utilized a capillary mixing space rather than an orifice. This design resulted in much more even flow rates for the individual branches within the refrigerant distributor.

In a companion paper, Li et. al (2002) demonstrated that commercially available CFD tools can be used to analyze the phase distribution and separation phenomena in refrigerant distributors. The current paper describes results of the application of CFD to evaluate the performance of both existing and improved designs for refrigerant distributors. In addition, experiments were performed to validate the general trends associated with the CFD simulations.

Distributor Geometries and Performance Criteria

Table 1 and Figures 1 – 5 describe geometries that were considered in this study. The figures are drawn to scale and show the internal volumes where refrigerant flows. Each of the distributors has four branches and an orifice that is located at the centerline of the inlet to the distributor. The Type 1 and Type 3 geometries are commercially available, while the other 3 incorporate design modifications. In the Type 1 geometry, the base of the distributor is convex with respect to the flow and comes to a point. This design was conceived so as to provide a single point of contact for separation of the flow. The Type 3 design uses a cone-shaped base that is concave with respect to the flow and was conceived so as to provide a mixing chamber for distribution of refrigerant. Type 2 and 4 are the same as Type 3, except the cone is replaced with flat and spherical surfaces, respectively. The Type 5 design is a modification of Type 4 where the orifice has been moved closer to the distributor base and the depth of the chamber has been reduced. For all of the distributors, the center of the base is on the centerline of the distributor along with the center of the orifice.

Results are presented in terms of uneven flow and quality distribution performance indices. For a given branch i, the uneven flow and quality indices are

$$\varepsilon_{m,i} = \frac{\dot{m}_i - \overline{\dot{m}}}{\overline{\dot{m}}} \tag{1}$$

$$\varepsilon_{x,i} = \frac{x_i - \bar{x}}{\bar{x}} \tag{2}$$

where $\varepsilon_{m,i}$ and $\varepsilon_{x,i}$ are the indices for uneven flow and quality, $\dot{m}_i$ and x_i are individual branch flow rates and qualities, and $\bar{\dot{m}}$ and $\bar{x}$ are average mass flow rates and qualities for all four branches.

For a given distributor, average performance indices for uneven flow and quality are defined as

$$\bar{\varepsilon}_m = \frac{\sqrt{\sum_{i=1}^{4} \left(\dot{m}_i - \bar{\dot{m}}\right)^2}}{\bar{\dot{m}}} \tag{3}$$

$$\bar{\varepsilon}_x = \frac{\sqrt{\sum_{i=1}^{4} \left(x_i - \bar{x}\right)^2}}{\bar{x}} \tag{4}$$

Refrigerant Distributor Modeling

In a companion paper, Li et. al., (2002) demonstrated that FLUENT 5.5 is applicable for flow conditions encountered in refrigerant distributors. Therefore, this CFD modeling tool was used to investigate the performance of the distributors described in Table 1 and Figures 1 – 5. The inflow boundary had specified inlet velocity with uniform void fractions at conditions associated with the outlet of the orifice. Constant and uniform pressures were specified for all outflow boundaries. A three-dimensional incompressible adiabatic flow was assumed with no phase change.

The goal of the simulations was to evaluate the robustness of each of the distributors with respect to manufacturing and installation defects. For vertically installed distributors with no manufacturing defects, all of the distributor designs would produce even flow and phase distributions in each of the branches since the outlet branches are located symmetrically about the centerline of the distributor. However, it is difficult to orient the orifice perfectly and as a result the refrigerant will exit the orifice in direction that is not along the centerline of the distributor. To simulate this effect, the direction of refrigerant flow was considered to be off the centerline by an angle of 3.7^o. In addition, gravity effects will affect the flow and phase distributions when the distributor is oriented horizontally. This case was also considered.

As a first step to eliminate the poorer performing devices, single-phase simulations were performed. Under the assumption of homogeneous equilibrium flow, two-phase flow can be simplified to single-phase flow with proper averaging methods used for the properties of the fluids. From a cycle analysis of a 3-ton capacity refrigeration application, average property values for the pseudo-fluid entering the distributor were obtained for the CFD simulation, as well as boundary conditions and operating conditions. The density and viscosity for this pseudo-fluid were taken to be 58.34 kg/m^3 and 2.3×10^{-4} kg/m-s, respectively, corresponding to an evaporating temperature of 0^0C and a quality of 0.35. The outlet reference pressure was 5 atm, which is close to the evaporating pressure for this specific application.

Figure 6 shows flow distribution results for the single-phase simulations applied to distributor Types 1– 4, all oriented upwards in the vertical direction with an orifice tilted 3.7^o towards branch 1. The x and y components of the inlet velocity were 50.79 m/s and 3 m/s. For this situation, the sharp-end (Type 1) distributor performed considerably worse than the other 3 designs. The maximum flow rate for the sharp-end distributor occurs in branch 1, which is the direction of orientation of the orifice. On the other hand, the blunt-end designs tend to recirculate refrigerant prior to distribution so the maximum flow rate occurs in other branches and the flow rate is more evenly distributed. In general, the sharp-end design is very sensitive to orifice orientation and was not considered in two-phase simulations.

Figures 7 and 8 show flow and quality distribution results for two-phase simulations applied to distributor Types 2– 5, all oriented upwards in the vertical direction with an orifice tilted 3.7^o towards branch 1. The boundary conditions for two-phase flow were the same as for the single-phase simulations except there was a uniform void fraction specified at the inlet assuming a no slip condition. For these blunt end distributors, the shape of the base plays an important role in terms of flow recirculation and distribution. Types 2 – 4 have similar overall performance, but result in different flow and quality distributions for individual branches. The Type 5 distributor is much less sensitive to orifice orientation and has much more uniform flow and quality among the different branches.

Figures 9 and 10 show velocity vectors and void fraction contours for a plane that goes through the center of the distributor, branch 1, and branch 3 for the Type 3 and 5 distributors (oriented upwards in the vertical direction with an orifice tilted 3.7^{o} towards branch 1). For the cone-shaped base (Type 3), more of the higher-momentum liquid refrigerant flows through branch 1 than branch 3 leading to larger total flow and lower quality (see Figures 7 and 8) through this branch. However, as shown in Figures 7, the largest flows occur in branch 2 and 4 even though there is a slight increase in quality of the refrigerant in these branches (Figure 8). The complex recirculation patterns produced by this shape result in relatively asymmetric velocity and phase distributions in all three dimensions. On the other hand, the Type 5 design (spherical base with a closer orifice location) results in more symmetric recirculation patterns and velocity and phase distributions.

Figures 11 and 12 show flow and quality distribution results for the distributors mounted in a horizontal direction with perfect orifice orientations. The flow and quality distributions are uneven due to the effects of gravity. The spherically-shaped bases have more even flow and phase distributions than the cone and flat bases. In particular, the flat base has much worse phase distribution than the other designs.

Table 2 summarizes the overall performance of the Type 2 – 5 distributors in terms of mass flow and quality distributions at the outlet branches. The Type 5 distributor is much more robust with respect to imperfections in orifice and distributor installation as compared with the other designs.

Experimental Testing

In order to validate the trends associated with the CFD modeling, experiments were performed for 3 of the geometries: sharp-end base (Type 1), cone-shaped base (Type 3), and spherical base with closer orifice location (Type 5). Type 1 and 3 were commercially available, whereas Type 5 had to be specially built for this project. Different orifices were investigated, but only the best flow distribution results are presented for each distributor.

Figure 13 shows the experimental test stand that was developed for testing. The inlet pressure and temperature to the orifice and the pressures at the outlets of the branches are controlled using adjustable valves. For each test, the pressures at the outlet of each branch were controlled to the same value. The refrigerant mass flow rate through an individual distributor branch is estimated from an energy balance on an electrically powered superheater located after the evaporator that follows that branch. Measurements of power input and refrigerant inlet and outlet temperature and pressure are used along with property data to estimate mass flow rate through that branch. The quality of the refrigerant leaving each branch is estimated from an energy balance on the evaporator associated with that branch. The evaporators are water-cooled and heat transfer rates are determined from water-side flow rates and temperatures. The evaporator inlet enthalpy is determined from a refrigerant-side energy balance using the water-side heat transfer rate and refrigerant outlet state measurements. The inlet quality is then determined from refrigerant property data with the estimated inlet enthalpy and measured pressure. Based upon an uncertainty analysis, the uncertainty in the mass flow measurements ranges from about 5 to 10%, whereas the uncertainty in the quality measurements is between about 10 and 20%.

The distributors were tested in a vertical, downward flowing orientation. Tests were performed at high, medium, and low condenser pressures and repeated twice at each condition. In addition, each of the tests was repeated with the distributor rotated through all four possible arrangements of the outlet branches feeding the different evaporator circuits of the test stand. This was done in order to eliminate any bias associated with orifice orientation and the test stand. Average performance indices for uneven flow and quality (equations 3 and 4) were determined for each distributor by averaging results obtained for all conditions and distributor orientations (24 tests for each distributor).

Figure 14 shows test results for the different distributors considered. Consistent with the CFD simulations, the sharp-end distributor had the worst performance of those considered. The performance of the spherical-base distributor was slightly better than the cone-base distributor. However, the differences were smaller than those determined through simulation. Several factors could have led to these differences. The actual orientation of the orifice within the distributor housing was unknown and has a major impact on flow distribution. The experimental results were averaged for several different tests where the orifice orientation could have changed. The uncertainty in the flow measurements can be as high as 10%. The simulations assumed a uniform void fraction at the outlet of the orifice. The actual void fraction distribution at the orifice outlet was unknown and a non-uniform distribution would impact the flow distribution at the branch outlets.

Conclusions

Experimental results confirmed some general trends arising from CFD simulations of existing and improved refrigerant distributors. In general, it is better to utilize a spherical base as compared with other shapes and to locate the orifice close to distributor base. These changes tend to improve the robustness of the distributor in terms of providing even flow and phase distribution in different branches when the orifice and/or distributor are not oriented in an optimal fashion.

References

G. Li, S. Frankel, J.E. Braun, and E.A. Groll, Application of CFD models to two-phase flow in refrigerant distributors, 2002 International Refrigeration Conference at Purdue, (2002).

M. Nakayama, Y. Sumida, S. Hirakuni, and A. Mochizuki, Development of a refrigerant two-phase flow distributor for a room air conditioner, International Refrigeration Conference at Purdue (2000) pp. 313-319.

Table 1 Description of the refrigerant distributors

<table>
<tr><td>Sharp-end distributor</td><td></td><td>Commercially available design</td><td>Type 1</td></tr>
<tr><td rowspan="4">Blunt-end distributors</td><td>Flat base</td><td>Same as Type 3 except base surface is flat</td><td>Type 2</td></tr>
<tr><td>Cone base</td><td>Commercially available design</td><td>Type 3</td></tr>
<tr><td rowspan="2">Round base
(base surface center at the center of the orifice)</td><td>Same as Type 3 except base surface is a spherical</td><td>Type 4</td></tr>
<tr><td>Same as Type 3 except orifice position is moved closer to chamber end; chamber depth is reduced</td><td>Type 5</td></tr>
</table>

Table 2 CFD results for average two-phase unevenness distributions for different distributors

	Horizontal installation		Vertical installation with tilted inlet velocity	
	$\bar{\varepsilon}_m$	$\bar{\varepsilon}_x$	$\bar{\varepsilon}_m$	$\bar{\varepsilon}_x$
Type 2	23.48%	13.89%	27.09%	13.48%
Type 3	17.59%	6.77%	48.23%	16.02%
Type 4	2.66%	2.67%	26.87%	11.26%
Type 5	0.91%	2.57%	1.02%	2.25%

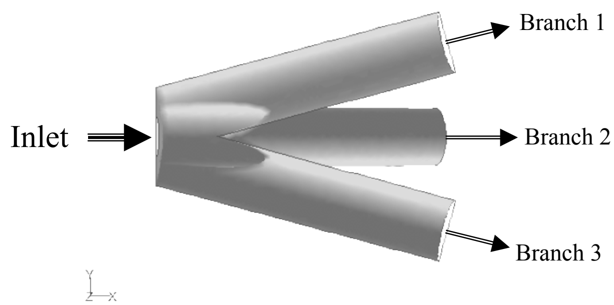

Figure 1: Type 1 distributor (half shown) with pointed base

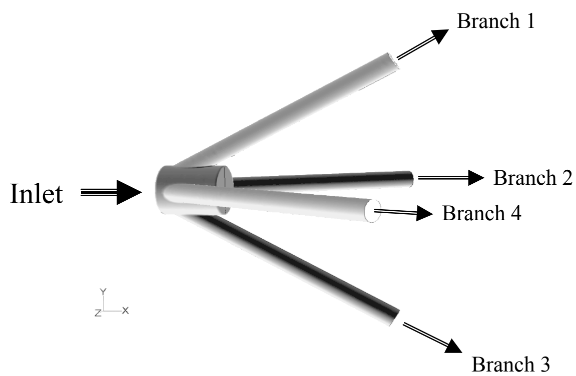

Figure 2: Type 2 distributor with flat base

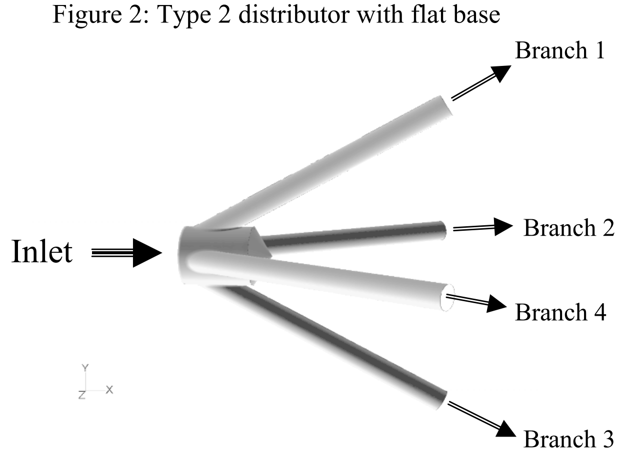

Figure 3: Type 3 distributor with cone base

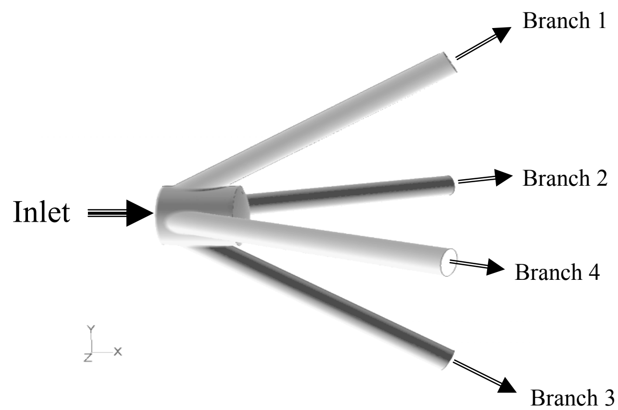

Figure 4: Type 4 distributor with spherical base

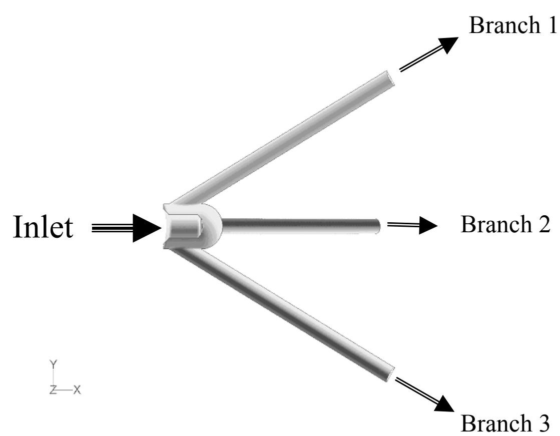

Figure 5: Type 5 distributor (half shown) with spherical base and orifice moved closer to base

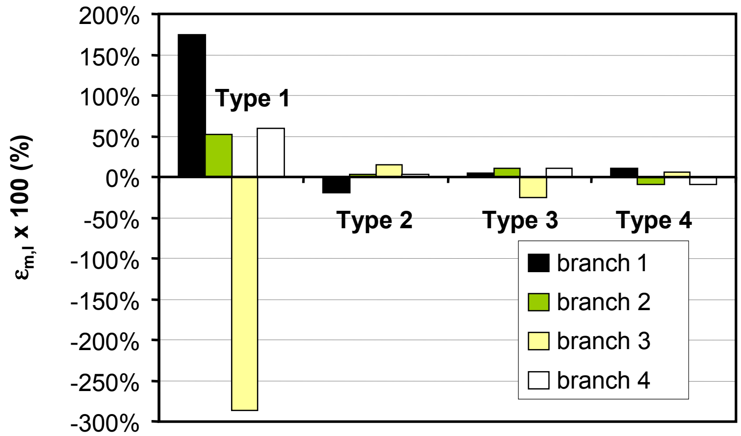

Figure 6: Single-phase simulation results for mass flow distribution in vertically installed distributors with imperfect orifice orientations

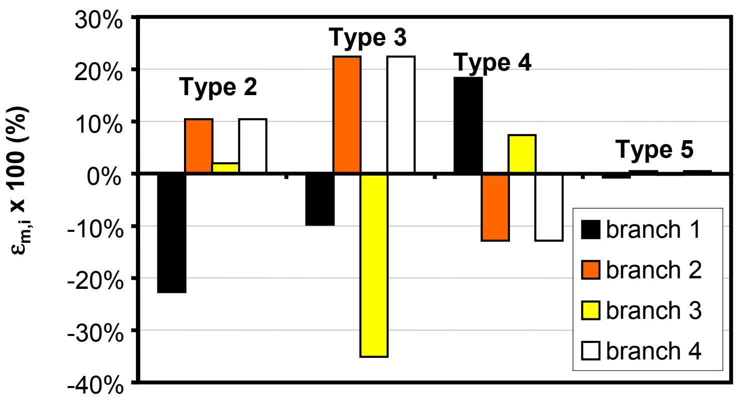

Figure 7: Two-phase simulation results for mass flow distribution in vertically installed distributors with imperfect orifice orientations

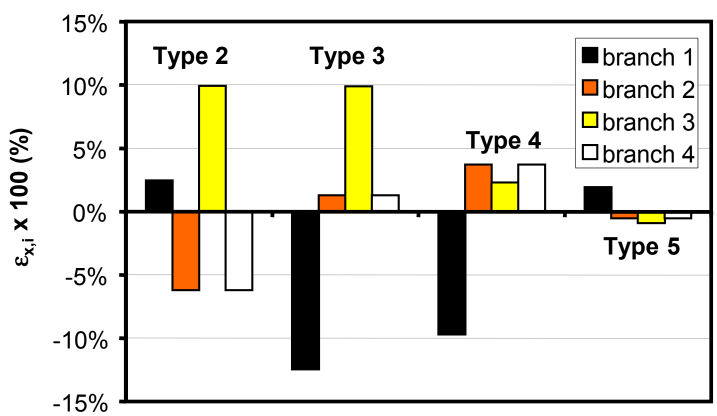

Figure 8: Two-phase simulation results for quality distribution in vertically installed distributors with imperfect orifice orientations

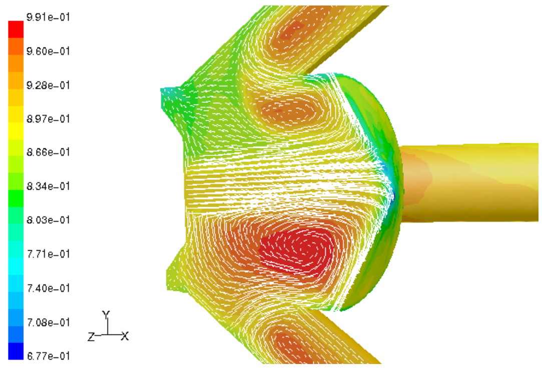

Figure 9: Velocity vectors superimposed on void fraction contours for Type 3 distributor

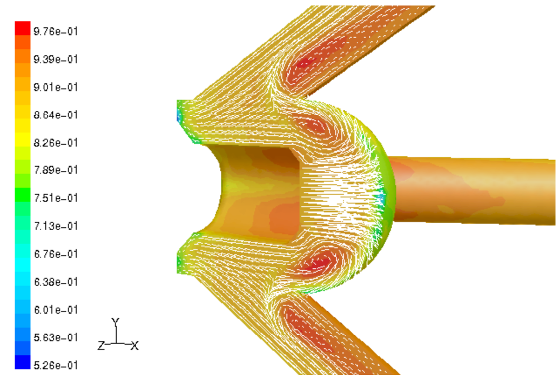

Figure 10: Velocity vectors superimposed on void fraction contours for Type 5 distributor

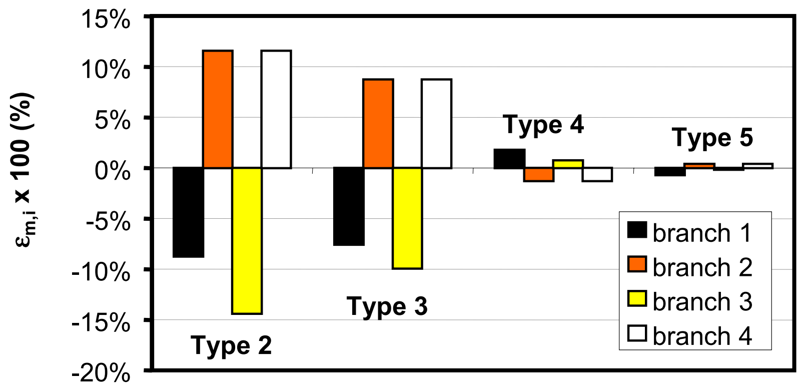

Figure 11: Two-phase simulation results for mass flow distribution in horizontally installed distributors with perfect orifice orientations

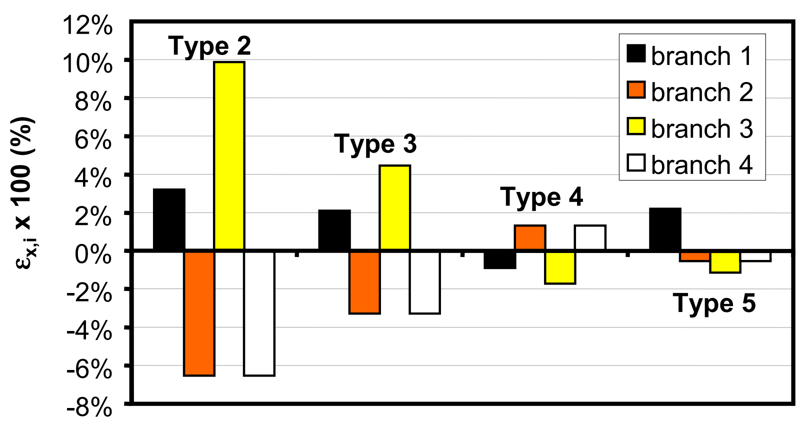

Figure 12: Two-phase simulation results for quality distribution in horizontally installed distributors with perfect orifice orientations

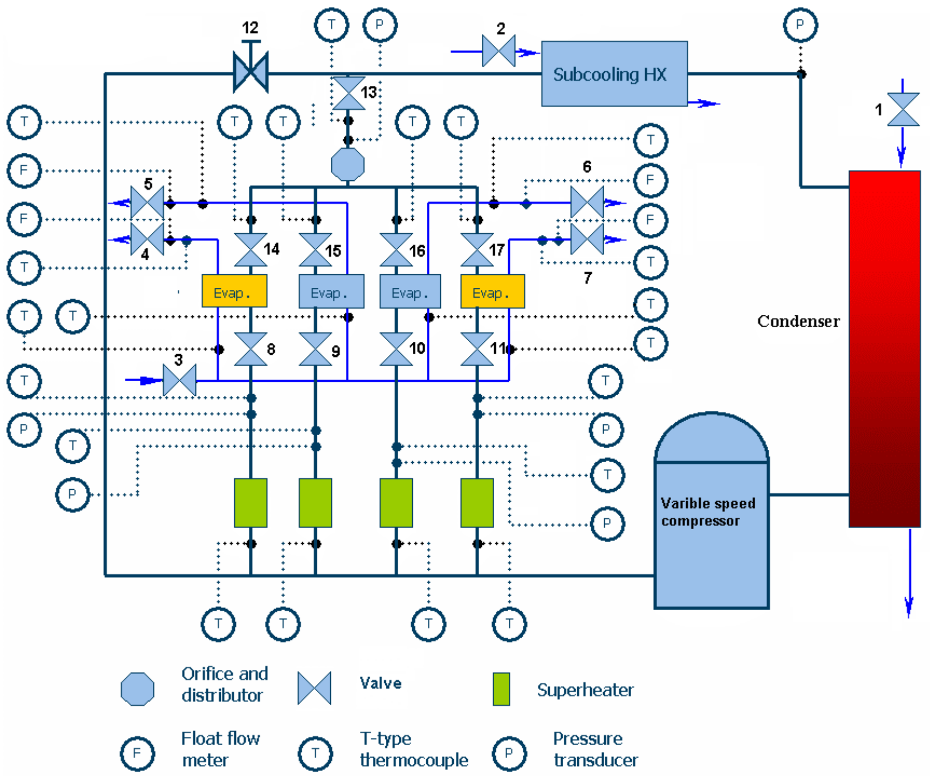

Figure 13: Experimental test stand

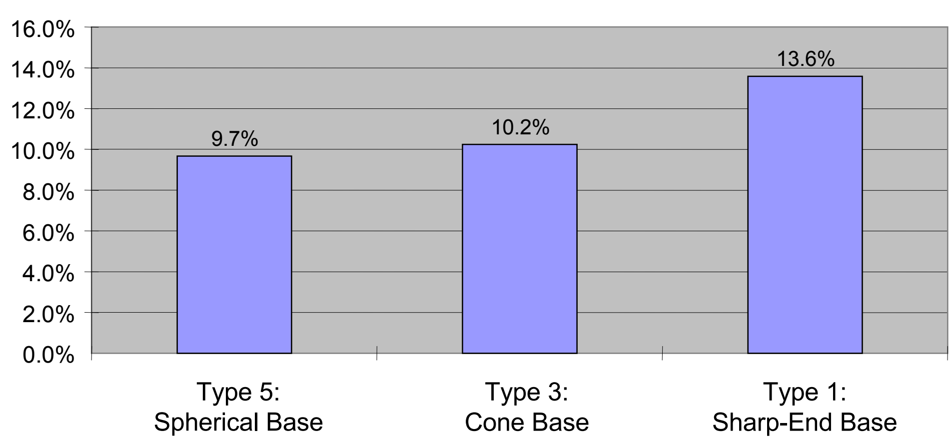

Figure 14: Comparison of average unevenness flow distributions for different types of distributors determined from experiments