Development of Gas-Liquid Two-Phase Flow Distributor for Improving Energy Efficiency in Air-Conditioners

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As a means to reduce environmental impact, regulations for the energy conservation of air conditioners are being reinforced in many countries. As part of this campaign, it is becoming common to assess energy-saving performance as annual energy consumption efficiency by including intermediate seasons (i.e., spring and fall) in addition to summer and winter. One key solution to this movement lies in the method of distributing the gas-liquid two-phase refrigerant to several paths in the heat exchanger. To offer the maximum heat-exchange performance throughout the year, we have developed a new distributor which can retain the distribution characteristics of gas-liquid two-phase refrigerant against a wide range of conditions with variable loads (low to high).

1. Introduction

Regulations for the energy conservation of air conditioners and air-to-water heat pumps are being reinforced in Japan as well as in other countries. Considering the frequent use of such installations and the popularity of variable-capacity types, annual energy consumption efficiency is becoming increasingly common as an assessment index of energy efficiency. In addition to summer and winter (which have been commonly assessed), it also includes intermediate seasons (i.e., spring and fall) and their temperature conditions are newly set for assessment. The result for each season is weighted based on the operating hours in that particular season.

To achieve higher energy efficiency, the major components of air conditioners such as compressors, heat exchangers and fans have been subject to improvement. Recently, how these components can maintain optimum performance throughout the year is an issue of increasing importance. One key to the solution is technology to distribute the gas-liquid two-phase refrigerant to several paths in the heat exchanger.

2. Necessity of distribution technology of gas-liquid two-phase refrigerant

The performance of air conditioners can be improved by preventing pressure drop of the refrigerant flowing in the heat exchanger. Because of this, the refrigerant in the heat exchanger is designed not to follow a single flow, but to take several separate paths. When the heat exchanger functions as an evaporator (i.e., the indoor heat exchanger when cooling, or the outdoor heat exchanger when heating), the "gas-liquid two-phase" refrigerant, which has passed through the expansion valve, will be distributed to these paths before entering the heat exchanger using a distributor. The heat exchanger cannot fully exert its capability if the distributed flow rate of the refrigerant is not in accordance with the heat load of each path, which is determined based on the air-flow velocity. **Figure 1** illustrates this logic. Failing to be distributed properly, some paths excessively take in the refrigerant of a liquid phase. In other paths, the superheated vapor area increases. Since superheated vapor takes no part in heat exchange, the performance of the heat exchanger will decrease. Especially in packaged air-conditioners, there are approximately 10

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separate paths in the heat exchanger. The flow patterns of gas-liquid two-phase refrigerant in the diverging process are complicated, and therefore proper distribution cannot be easily achieved.

Conventionally, the distributor designs were experimentally determined to successfully distribute the refrigerant under the rated condition with a relatively high air-conditioning load in summer or winter, by means of adopting various inventions such as an orifice created immediately before the diverging paths to facilitate the gas/liquid mixing. However, under conditions that differ from the rated ones, the amount of refrigerant distributed to each path can vary greatly. It would be incorrect to say that the proper distribution of refrigerant was retained against a wide range of conditions including intermediate seasons.

Thus, to obtain the optimum performance of the heat exchanger throughout the year, it is necessary to develop a distributor design technology that can maintain the proper distribution regardless of any change in the flow rate, quality or pressure of the gas-liquid two-phase refrigerant inflow.

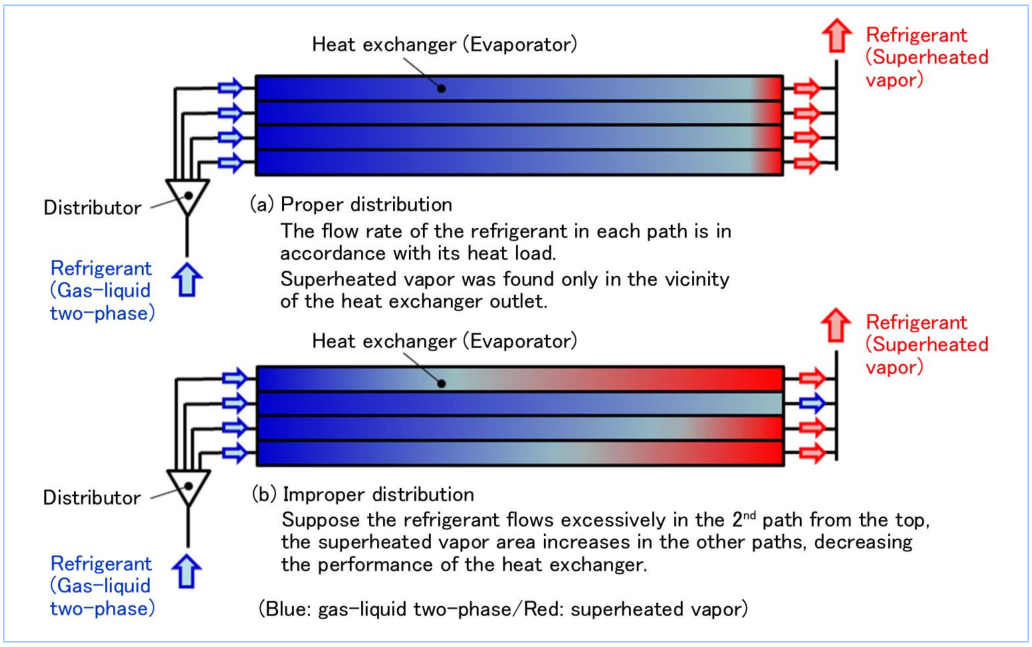

Figure 1 Proper/improper distribution of gas-liquid two-phase refrigerant
When distributed improperly, the superheated vapor area expands.

3. Distributor geometry optimization based on quality engineering

The change in distributor geometry affects flow patterns, consequently changing the amount of refrigerant distributed to each path in the heat exchanger (i.e., distribution characteristics). The geometric parameters of the distributor are complicatedly associated with the distribution characteristics. Even if we find a way to obtain better distribution characteristics in one parameter, a change in another parameter may induce a negative effect. Therefore, the geometric parameters that can produce offsetting effects were examined and their influence was assessed from the perspective of quality engineering (Taguchi Method). The Taguchi Method is a method of conducting the minimal number of experiments to determine the sensitivity of each parameter (i.e., the degree of influence on the variation of the distributed flow rate).

3.1 Structure of the distributor

Figure 2 shows the basic structure of the distributor. It consists of a gas-liquid mixing chamber and the diverging paths radiating upward from the upper surface of the chamber. In the chamber, the two phases of refrigerant (i.e., gas and liquid) are homogeneously mixed before being led to the diverging paths. The distributor is placed vertically to prevent gravitational influence on the liquid refrigerant (which can cause deviation) and the refrigerant flows from the bottom to the top. To reduce uneven inflow of liquid refrigerant and facilitate homogeneity in the chamber, mesh is attached upstream from the chamber and creates flow resistance. In the heat exchanger, the heat load of each path varies depending on the velocity of air flowing into it. Therefore, by adjusting the inner diameter and length of the branch pipes that are installed up to the inlet of the heat exchanger (i.e., adjusting the resistance in the path), refrigerant flow can be provided in accordance with the heat load of each path in the heat exchanger.

This report addresses a distributor with eight diverging paths. The inner diameter and the length of the branch pipes and those of the following paths in the heat exchanger are the same. In this case, the proper distribution means the refrigerant flow rate of each of the eight diverging paths is the same.

3.2 Sensitivity analysis and optimization of geometry

There are many geometric parameters in the distributor. Of these, the four parameters which are considered to have a significant impact on flow patterns were selected, and their sensitivities were examined using the Taguchi Method (L18 orthogonal array). The selected parameters are the (1) inner diameter of the gas-liquid mixing chamber, (2) inner diameter of diverging paths, (3) distance between the mesh and the upper surface of the chamber, and (4) mesh size. For each parameter, three levels (with the conventional value as the median) were used for examination.

Conditions such as flow rate and pressure of the refrigerant flowing in the distributor correspond to those of the distributor installed in the indoor heat exchanger during the cooling operation in summer or intermediate seasons. For the variation assessment of the distributed flow rate, the amounts of both liquid- and gas-phase flows in each of the eight diverging paths were measured.

Figure 3 gives the results of the Taguchi Method assessment (as a graph of factorial effects), which shows each parameter's sensitivity of influencing variation in the distributed flow rate. It therefore has been demonstrated that the inner diameter of the gas-liquid mixing chamber has the highest sensitivity and the variation can be reduced by making the inner diameter smaller. Regarding the other geometric parameters, the levels to produce minimal variation were selected to optimize the geometry of the distributor.

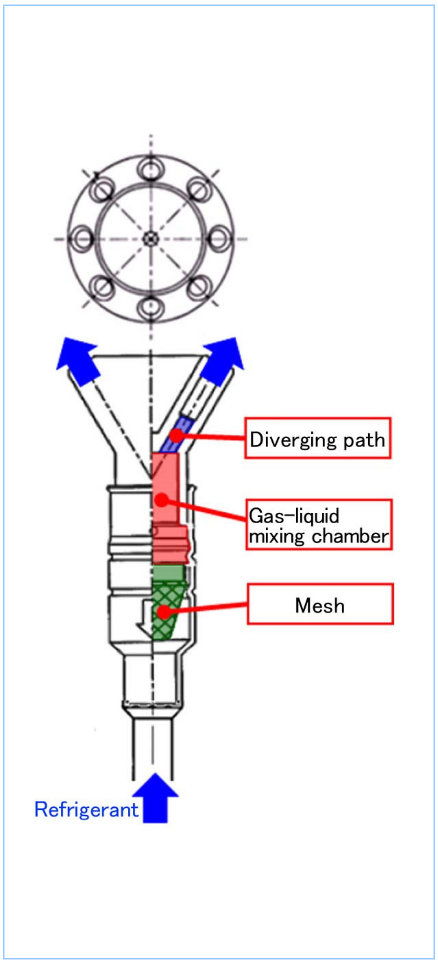

Figure 2 Structure of the distributor
A distributor with diverging paths radiating from the gas-liquid mixing chamber

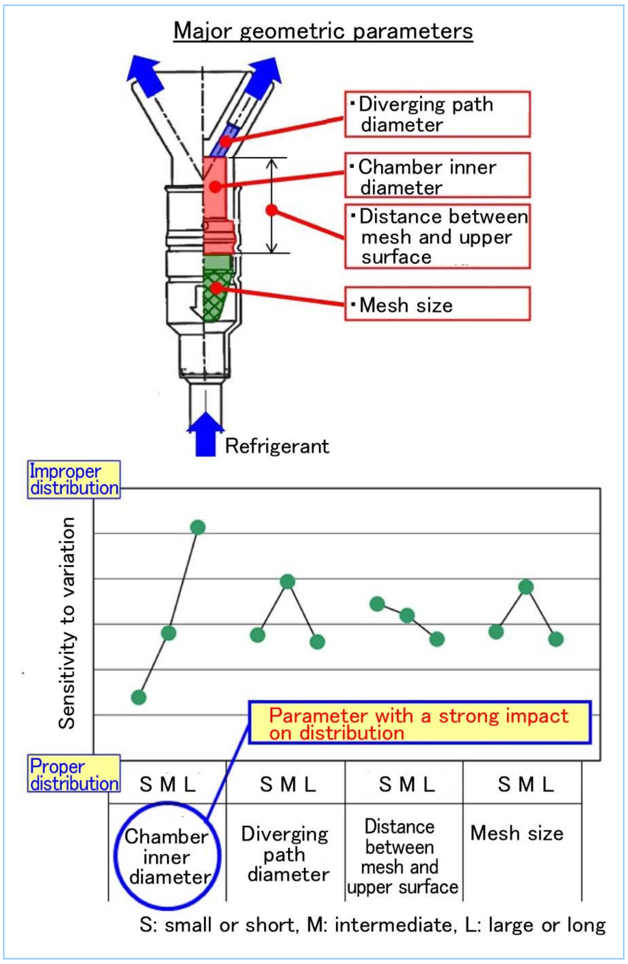

Figure 3 Graph of factorial effects
How the four major geometric parameters influence the variation of the distributed flow rate.

4. Successful reduction of distributed flow rate variation based on flow pattern observation

Using the Taguchi Method, the parameter levels with minimal variation in the distributed flow rate were identified. This was followed by visualization to observe how these parameters affect flow patterns in the distributor. Described below are the visualization results of two components: the gas-liquid mixing chamber (which has a high sensitivity) and the inlet pipe attached to the distributor.

4.1 Flow patterns in the gas-liquid mixing chamber

The fluid used is R410A, which is the refrigerant used in packaged air-conditioners. As the operating pressure of R410A refrigerant is high, flow-pattern observations in the distributor are rare and therefore how it actually flowed was unknown. We used synthetic silica glass with excellent strength to make a gas-liquid mixing chamber. With this chamber, a test piece for visualization that enables the observation of the R410A flow condition was built. Lighting was also placed behind on both sides of the test piece, enabling frontal images to be taken by digital camera and video to be recorded by high-speed camera. Test conditions such as the flow rate, quality and pressure of the inlet refrigerant were set to cover a wide range of loads (low to high) during cooling operation, and for each condition clear images and videos were recorded. In addition, the flow rate of each diverging path was simultaneously measured to examine the relationship between the flow pattern and the variation of the flow rate distribution.

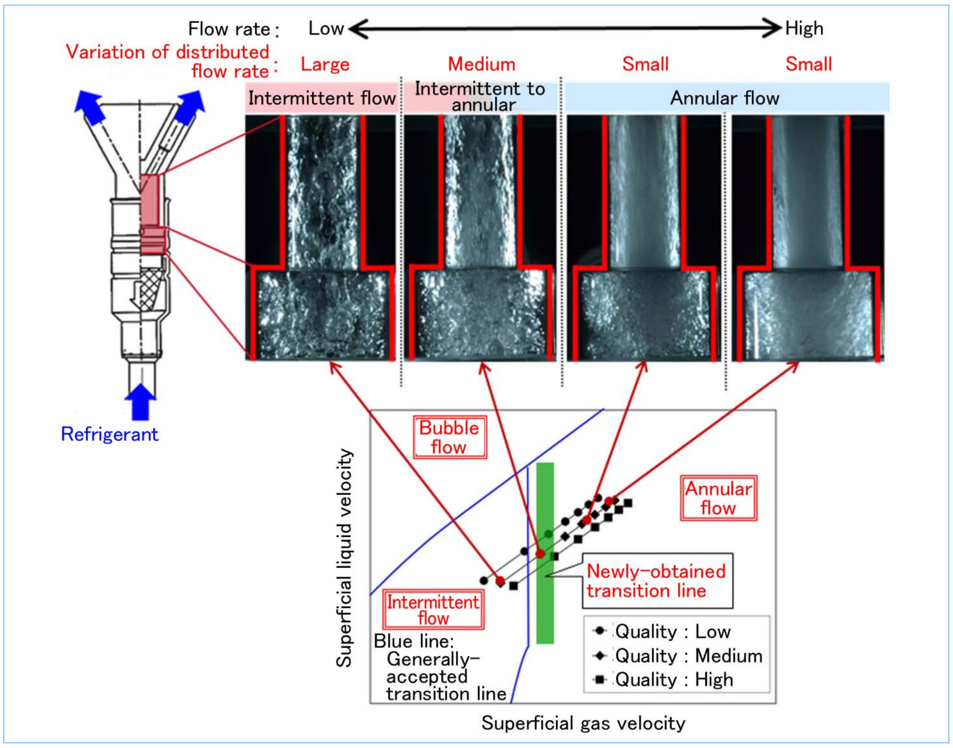

Figure 4 Visualization results of flow patterns in gas-liquid mixing chamber
The relationship between the flow pattern and the variation of the distributed flow rate is shown.

Figure 4 is an example of the visualization test results of the conventional distributor with varying refrigerant flow rates. The flow-rate measurement results of the diverging paths, which were simultaneously obtained during the visualization test, indicate that the formation of stable annular flows is associated with small variation in the distributed flow rate. As the inlet flow rate decreases, intermittent flows such as slug flows are observed, which is then associated with large variation in the distributed flow rate. When the inlet flow rate is low, the distributed flow rate of each diverging path may vary because of temporal changes/migration of intermittent flows or the uneven spread of liquid film. The same results were obtained with other inner diameters of the gas-liquid mixing chamber. At the bottom of Figure 4 is a flow pattern map with the x axis being the superficial gas velocity and the y axis being the superficial liquid velocity. Based on the results, the transition line between intermittent flows and annular flows can be drawn in an area of higher velocities than generally considered. This newly obtained line and annular flow formation area will be a useful design guideline on the inner diameter of the gas-liquid mixing chamber in order to achieve minimal variation in the distributed flow rate against varying conditions of refrigerant inflow.

4.2 Inlet pipe geometry

From the visualization test results, it is clear that the uneven spread of liquid film considerably affects the variation of the distributed flow rate. The geometry of the inlet pipe attached to the distributor, which is the cause of such uneven spread of liquid film, was examined. Because there is a certain vertical limit in the dimensions of air conditioners wherein the distributor is installed, the inlet pipe takes an L shape. Therefore, when flowing along the curve, liquid refrigerant is affected by centrifugal force and becomes concentrated outward in a radial direction, and in this state, refrigerant flows in the distributor. It is considered that the mesh, which is installed upstream from the gas-liquid mixing chamber, may not sufficiently reduce this uneven deviation in some cases. When intermittent flows are formed at a low flow rate, homogeneity in the chamber is also insufficient. Thus, the geometry of the inlet pipe was reviewed to reduce the uneven deviation of liquid refrigerant at the entry to the distributor.

Figure 5 shows an example of the flow-pattern visualization test results of the existing L-shape inlet pipe and the T-shape inlet pipe, which was newly developed by combining a horizontal tube with a vertical riser tube. The fluids used in this test are water and air. As shown in Figure 5, the T-shape inlet pipe can allow liquid refrigerant to spread all around the inner wall of the vertical riser tube without causing unevenness regardless of whether the tube is short.

Thereafter, the flow rate of each diverging path was measured using the T-shape inlet pipe and the expected results were obtained. The variation of the distributed flow rate was reduced.

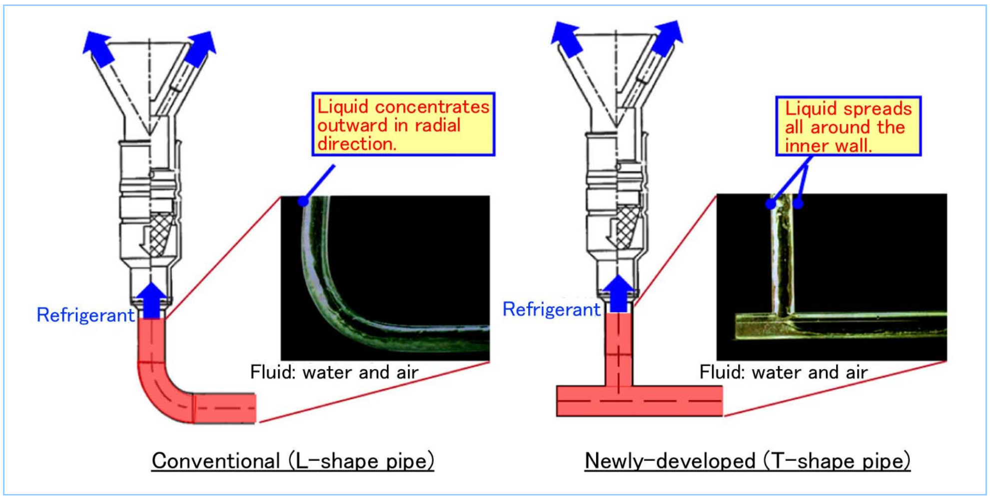

Figure 5 Visualization results of flow patterns in the inlet pipe
Difference in the geometry of inlet pipe results in different deviation of liquid refrigerant.

5. Improved result of distributed flow rate using the new distributor

By integrating all the results (i.e., the optimized geometry of diverging paths in the distributor through quality engineering (Taguchi Method), the inner diameter of the gas-liquid mixing chamber based on the flow pattern map obtained by the visualization test, and the adoption of a T-shape inlet pipe), we built a new distributor and measured the variation in the distributed flow rate of each path under varying conditions of refrigerant inflow. Specifically, there were eight conditions in total, which were set based on parameters such as flow rate and quality.

Figure 6 shows the flow rate of the liquid refrigerant distributed to each path. Conventionally, this varies according to changes in conditions. That is to say, the distribution may be proper under a certain condition (as shown in Figure 1 (a)), while it may become improper under another (Figure 1 (b)). With the new distributor, however, the distributed flow rate of the liquid refrigerant remains almost the same under any of the different conditions, which indicates the realization of the refrigerant flow rate being distributed properly under a wide range of conditions.

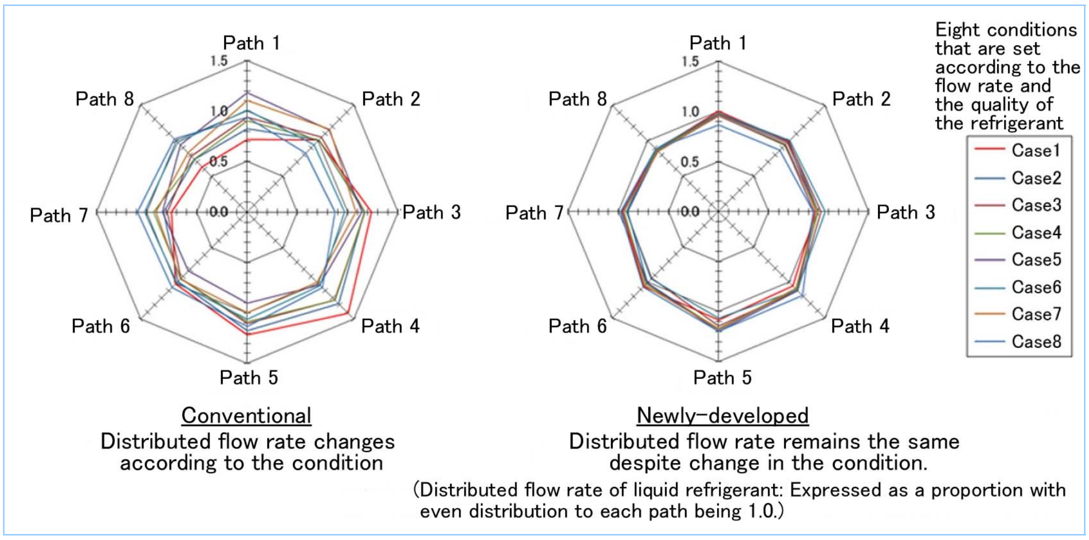

Figure 6 Flow rate of liquid refrigerant distributed to each diverging path
Difference in the refrigerant inflow condition results in different flow rates of liquid refrigerant distributed to diverging paths.

In **Figure 7,** variation in the distributed flow rate is expressed on the y axis. Our new distributor can significantly reduce the variation compared with existing products. From the air conditioners of other companies, we removed the distributors and tested them under the same conditions. The figure contains the test results. It has been demonstrated that the performance of our new distributor is as good as or superior to that of other companies.

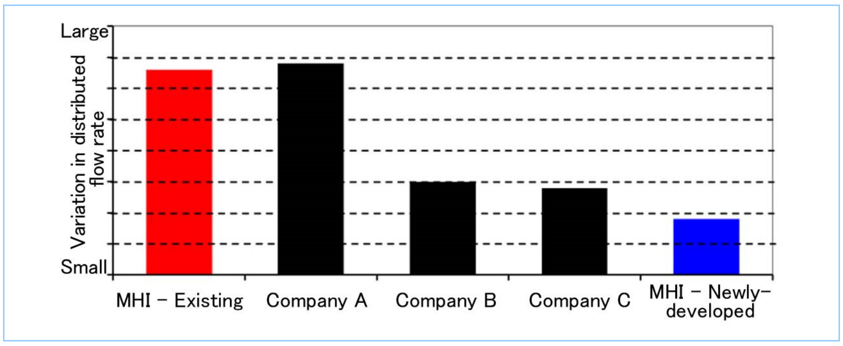

Figure 7 The improved result of variation in distributed flow rate
The variations in the distributed flow rate using the distributors from MHI and other companies are shown.

6. Application to products

An application example of the new distributor to a ceiling suspended indoor unit is given in **Figure 8**. Among the indoor units of packaged air-conditioners, ceiling suspended indoor units have the most severe restrictions on the vertical dimensions and therefore, the proper distribution of the refrigerant flow rate is difficult to achieve.

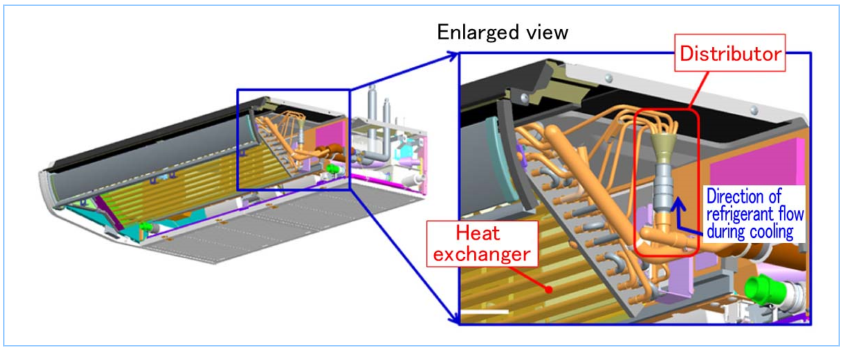

Figure 8 Internal structure of ceiling suspended indoor unit
An applied example of the new distributor in a ceiling suspended indoor unit is shown.

However, with our new distributor, which can offer the maximum heat-exchange performance throughout the year, this type of unit improved annual energy consumption efficiency. Incorporating other energy-saving effects as well, APF values of all types of ceiling suspended indoor units (from small to large capacity units) have satisfied the 2015 Standard values under the Japanese Energy-Saving Law, as shown in **Figure 9**.

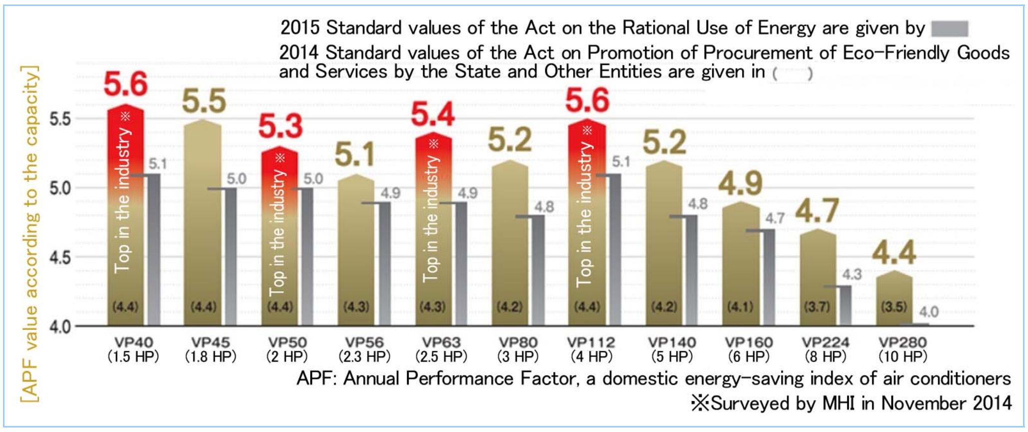

Figure 9 Annual energy consumption efficiencies of ceiling suspended air conditioners
The APF values (for annual energy consumption efficiency) according to the capacity are shown.

7. Conclusion

The distributor geometry was optimized in terms of quality engineering (Taguchi Method). The design guidelines on the inner diameter of the gas-liquid mixing chamber and the geometry of the inlet pipe were obtained based on the observed flow patterns in the distributor. Applying these results practically, we developed a new distributor which can retain the distribution characteristics of gas-liquid two-phase refrigerant regardless of changes in condition.

This newly-developed distributor has been used in a ceiling suspended indoor unit released in January 2015, enabling us to offer highly energy efficient products to our customers. The new distributor will also be applied to ceiling cassettes (four-way) indoor units and outdoor units to market new products with further improved energy consumption efficiency, whereby we will contribute to reduce the impact on the global environment.