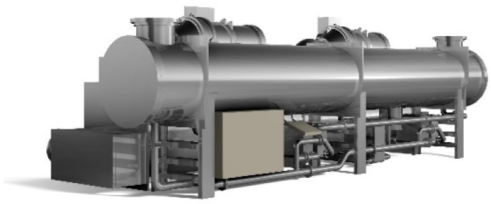
# Large-capacity, High-efficiency Centrifugal Chiller that Enables Significant Reduction in $CO_2$ Emissions



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*Although the Kigali Amendment to the Montreal Protocol has made progress with the regulation of HFC refrigerants, emerging countries are still exempt from the reduction scheme. The increase in the air conditioning demand resulting from economic growth is expected to increase both amounts of HFC and HFO refrigerants in use. Therefore, we have developed large-capacity centrifugal chillers with a maximum capacity of 5,000 refrigeration tons (RT) which share most of the equipment configurations in either HFC or HFO refrigerant. Retaining the same configurations in most parts, these chillers for the two types of refrigerants are characterized by the high efficiency enabled by a series counterflow (SCF) configuration in which a single chiller has two serially arranged compressors, and the capability of easily handling the change in the refrigerant type in use owing to the same built-in control system despite the differences between HFC and HFO refrigerants.*

*Moreover, the high-efficiency operation of plant facilities has been enabled by adopting the SCF configuration of two chillers and by controlling the number of units in operation through the dedicated control panel. This article presents the technologies applied for the development of high-efficiency large-capacity centrifugal chillers.*

## 1. Introduction

The global situation surrounding the Earth's environment revolves around the main themes of ozone layer protection and mitigating global warming. The Kigali Amendment to the Montreal Protocol, which was ratified in 2016, has set the world to phase in tougher regulations on HFC (hydrofluorocarbon) refrigerants which are alternatives to specified CFCs (Chlorofluoro carbon). While the reduction effort has been ongoing since 2019 in developed countries, with a reduction target of 85% by 2036, it is scheduled to begin in 2029 in emerging countries, with a reduction target of 80% by 2045. The demand for air conditioning resulting from economic growth in emerging countries is expected to increase by the time the scheduled start year comes. It is considered that there will be a certain level of continued demand for HFC refrigerants in addition to HFO (Hydrofluoroolefin) refrigerants which are double-bonded fluorine compound. The need for large-capacity centrifugal chillers is also growing because of the increased number of large buildings in urban areas causing air conditioning demand to rise. Introducing high-efficiency large-capacity centrifugal chillers with less environmental impact in Southeast Asia, the Middle East and East Asia will help cut $CO_2$ emissions and running costs by reducing energy consumption in urban areas.

Mitsubishi Heavy Industries Thermal Systems, Ltd. has therefore developed high-efficiency large-capacity centrifugal chillers that can operate with either HFC refrigerants or HFO refrigerants.

## 2. Comparison of HFC refrigerant and HFO refrigerants

When replacing the HFC refrigerant in use for centrifugal chillers (i.e., HFC-134a) with HFO refrigerants of a low global warming potential (GWP) (i.e., HFO-1234ze(E) or HFO-1234yf), for selection, we assessed and compared the following issues. Specifically they are: environmental integrity (not destructive to the ozone layer and having a GWP of 150 or lower), physical properties

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(having a refrigeration cycle efficiency as good as that of HFC-134a do not require extremely high design pressure in any chiller components), availability (having applications other than centrifugal chiller, so that a certain level of production is expected), and safety (able to be handled as non-flammable as per the High Pressure Gas Safety Act of Japan and having low toxicity). Each of the issues was assessed comprehensively to determine which low-GWP refrigerants should be used. The selected refrigerants of HFO-1234yf and HFO-1234ze(E) have relatively similar physical properties to HFC-134a. Their GWPs are as low as less than 1, exhibiting superior environmental compatibility.

Although HFO-1234ze(E), which is used in the centrifugal chillers addressed in this report, has almost the same theoretical COP (Coefficient of Performance) as HFC-134a, the specific gas volume is roughly 20% larger. It naturally becomes necessary to increase the volume of components such as the compressor, heat exchanger and pipes, if the same level of cooling capacity is to be output. However, the consequent increase in the required installation area will be disadvantageous from a cost perspective and will also make it difficult to replace the earlier models as alternative new models. We therefore reconsidered the designs as described below, especially focusing on the component designs for space-saving/compactness features and their combinations, in addition to improved performance. The centrifugal chillers in which HFO-1234yf is used are presented in a separate report of MHI Technical Review: New “JHT-Y” Series of Centrifugal Chillers with Low-GWP Refrigerants Contributing to Carbon Neutrality[2].

(1) Compressor: improved performance and downsizing

To accommodate the increased specific volume of gaseous refrigerant, we focused on the aerodynamic design that makes it possible to withstand a larger gas flow compared to the conventional impellers. However, because of the tendency for the increased gas flow to impair the adiabatic efficiency, the shapes of the front and rear edge of impeller blade, blade angle distribution, and the inlet guide vanes were optimized using CFD (Computational Fluid Dynamics) analysis. As a result, we have successfully increased the gas flow by 23% while retaining the same adiabatic efficiency with the same impeller diameter as the existing models. The volume of the compressor has thus been reduced, when compared at the same gas flow. In downsizing the compressor, the components such as bearings, seals and gears were also optimized, resulting in reduced loss and improved reliability.

(2) Heat exchanger: improved performance and downsizing

For the heat exchanger, the shell-and-tube type is used to handle large capacity. The following points were noted to improve the performance of the heat exchanger.

- In the evaporator, dryout lowers the heat exchange efficiency of heat exchanger tubes. To prevent it from happening, CFD analysis was conducted to determine the heat exchanger tube layout that prevents a local increase in heat flux and realizes even distribution. Moreover, the tube bundle configuration (i.e., the gap between the adjacent subsets of tubes in the evaporator) and the shape and positioning of the demister are optimized, in order to prevent refrigerant liquid droplets from being carried with gaseous refrigerant into the compressor because of the gaseous refrigerant bursting from the outlet at the top of the tube bundle.
- The performance of the heat exchanger is lowered by the increased pressure loss due to a local increase in the flow rate inside the condenser. To prevent it from happening, CFD analysis was also conducted, as in the case of the evaporator, to determine the heat exchanger tube layout and the shape of the components inside the condenser.
- The shape of the bellmouth was optimized to reduce the pressure loss in the areas with a high velocity of gaseous refrigerant flow at the evaporator’s outlet and the condenser’s inlet.

As described above, the heat exchanger was downsized and the area required for installing a chiller was reduced.

(3) Combination of heat exchanger and compressor

In designing our chiller series, we decided to use a heat exchanger shell with the same diameter for the models of both refrigerants of HFC-134a and HFO-1234ze(E), and optimized the number of tubes in the heat exchanger and their layout according to each capacity range and the type of refrigerant. This has enabled the chiller series to have the same design in terms of piping layout and auxiliary equipment except for the heat exchanger. Simplification of each piece of auxiliary equipment and the piping configuration has successfully reduced the costs. Furthermore, it has also become possible to choose the optimal equipment configuration depending on the capacity and refrigerant from the perspectives of efficiency and cost by changing the compressor for combining while the diameter of the shell remains the same.

(4) Control system handling three types of refrigerants

With the aim of handling three types of refrigerants, we organized as dimensionless quantities the characteristics of parameters to control the compressor and expansion valves. Thus, if there arises a difference in the amount of circulating refrigerant or physical properties, optimal control is possible for each refrigerant, ensuring a wide operation range and high-efficiency features.

(5) COP improvement through SCF configuration

Conventionally, the parallel configuration is adopted when a large-capacity chiller has two compressors. In our chillers, however, the components with compressors are arranged in SCF. This increases in stages the adiabatic head for the upstream and downstream compressors of a chiller, achieving the improved COP of the entire chiller. The following chapter details the principles and effects.

## 3. SCF configuration for enhanced efficiency

The COP of a chiller is represented by the following formula.

$$COP^{*}(-) = \frac{Cooling\ capacity\ (kW)}{Motor\ input\ (kW)}$$

To improve the chiller COP, it is necessary to reduce the input power of the compressor, as indicated by above formula. The input of the compressor motor is proportional to the amount of gas taken into the compressor and the adiabatic head. The adiabatic head is nearly equal to the saturation pressure corresponding to the difference between the cooling water outlet temperature and the chilled water outlet temperature. Therefore, as this temperature difference becomes smaller, the COP of a chiller will get higher.

**Figure 1** is a conceptual schematic of the compressors arranged in parallel (hereafter the latter is referred to as the parallel model) and those arranged in SCF (hereafter the latter is referred to as the SCF model). In the parallel model, two compressors share the evaporator and the condenser resulting in the same adiabatic head for each compressor. The adiabatic head is then approximated by the difference between the cooling water outlet temperature and the chilled water outlet temperature.

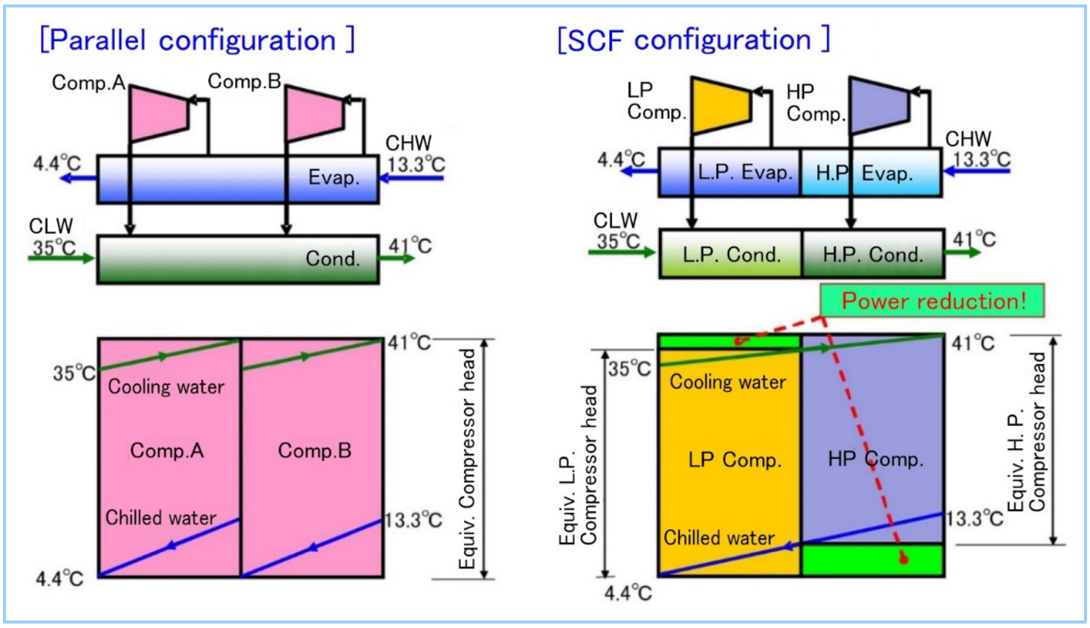


**Figure 1 Conceptual schematic for comparison between parallel configuration and SCF configuration**

In the SCF model, on the other hand, there is a partition in the middle of both the evaporator and the condenser. This decreases the difference between the cooling water outlet temperature and the chilled water outlet temperature of the upstream or downstream heat exchanger. The adiabatic head for either compressor becomes smaller, compared with the parallel model. The resulting reduction in motor input, which is indicated by the lime green color in the figure, leads to a COP improvement.

In a specific example considering temperature conditions for the Middle East region are generally as follows: the chilled water inlet temperature is 13.3°C, the chilled water outlet temperature is 4.4°C, the cooling water inlet temperature is 35.0°C, and the cooling water outlet temperature is 41.0°C. The COPs are compared between the parallel model and the SCF model, when the cooling capacity of a single compressor is 2,400 RT and the total thermal load is 4,800 RT.

**Figure 2** shows a comparison of COPs between the parallel and the SCF model. In the case of the parallel model, both compressors have the same temperature conditions. The difference between the cooling water outlet temperature and the chilled water outlet temperature is 36.6°C. As the COP at the full load is 5.16, the system COP is also 5.16. In the case of the SCF model, however, the temperatures of the chilled water and the cooling water at the intermediate place of the chiller are 8.6°C and 37.9°C, respectively. The differences between the cooling water outlet temperature and the chilled water outlet temperature in the upstream and downstream chillers are 32.4°C and 33.5°C, respectively. These obtained temperature differences are smaller, when compared with the parallel model. The COP of the upstream chiller is 5.67, whereas that of the downstream chiller is 5.41. As such, it was confirmed that both chillers improved in performance. The system COP is estimated at 5.54, which indicates that the performance of the SCF model has been enhanced by 7.3% from the level obtained by the parallel model.

In addition to the COP advantage, the SCF model also has the following advantages over the parallel model.

- Smaller area required for installation
- Simplified layout of equipment piping

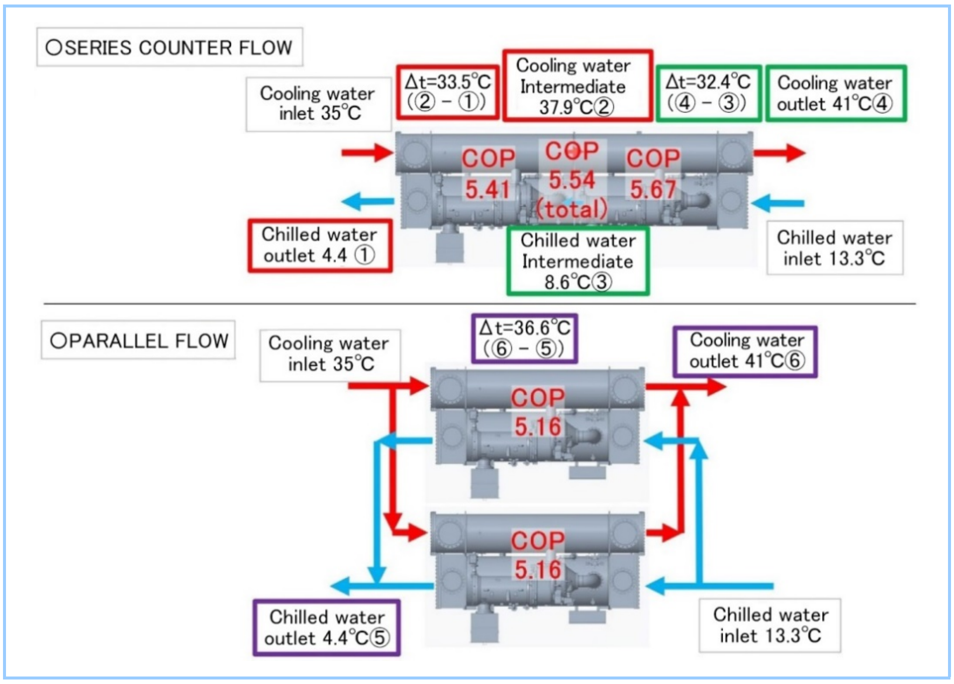


**Figure 2 COP comparison between SCF configuration and parallel configuration**

The effect can also be expected when the SCF models are further arranged in SCF. **Figure 3** compares COPs between the SCF models arranged in SCF and those arranged in parallel, when the temperature conditions for chilled water and cooling water are the same as the previous example and the total thermal load is 9,800 RT. The COP of the SCF models arranged in SCF is 5.90, whereas that of the SCF models arranged in parallel is 5.54. A nearly 6.5% improvement in performance is indicated, which shows the effectiveness of the SCF configuration.

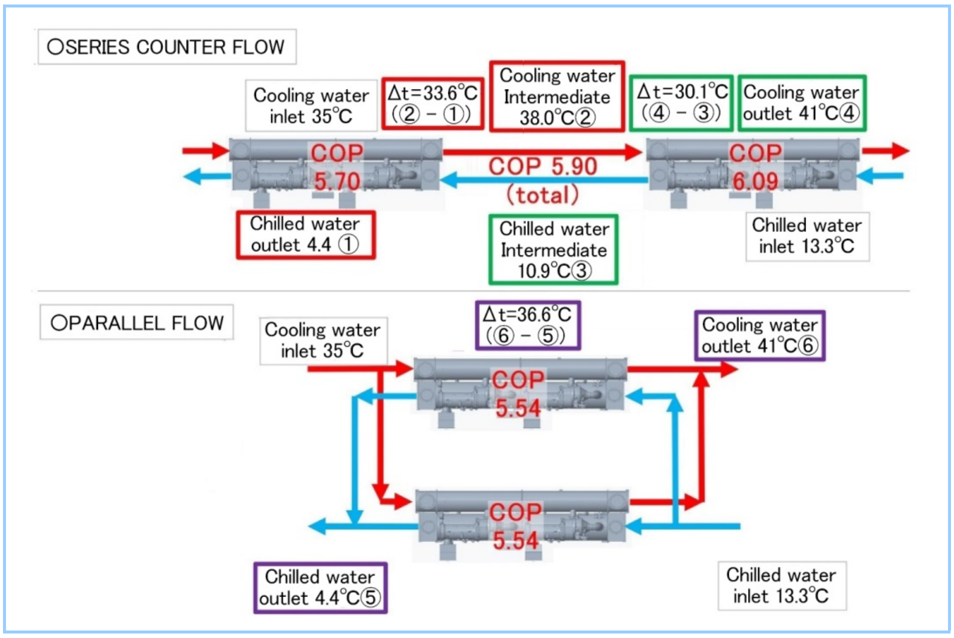


**Figure 3 COP comparison between SCF configuration in SCF model and parallel configuration**

## 4. Chiller control systems

The SCF model is equipped with the systems to control the number of compressors in operation and the supply chilled water temperature.

The system to control the number of compressors determines the required number of compressors in operation according to a given load and the operation of either one or two units of the compressors arranged in SCF is commanded by a control panel. If only one compressor operates in a chiller and some failure necessitating the shutdown of the compressor occurs, the remaining compressor will be started by the failure backup control.

In controlling the supply chilled water temperature, the setting details are determined according to the computation results based on the compressor operation conditions and load. If the temperature of chilled water at the inlet is higher than the rated level, the difference between these two temperatures will be set as the supply chilled water temperature. During the chiller operation, because all the set supply chilled water temperatures are subject to the predetermined increasing and decreasing rates, the change in the setting is controlled within these rates. **Figure 4** gives a conceptual schematic of the supply chilled water temperature setting in automatic mode. As shown in the figure, the set supply chilled water temperature at the downstream side is targeted for 4.4°C. Until the chilled water inlet temperature at the upstream side goes down to 13.3°C, the supply chilled water temperature setting will be carried out maintaining the temperature difference between the upstream and downstream rated temperature differences. When the chilled water temperature at the upstream inlet becomes less than 13.3°C, each of the set temperatures for supply chilled water is determined based on the optimal load distribution ratio.

**Figure 5** shows the actual operation results of a chiller, which indicates that the load on the chiller varied with the change in the chilled water inlet temperature. However, the chilled water outlet temperature followed the change in the set level within a short period of time, while a high COP was maintained. It has thus been demonstrated that the supply chilled water temperature is appropriately controlled.

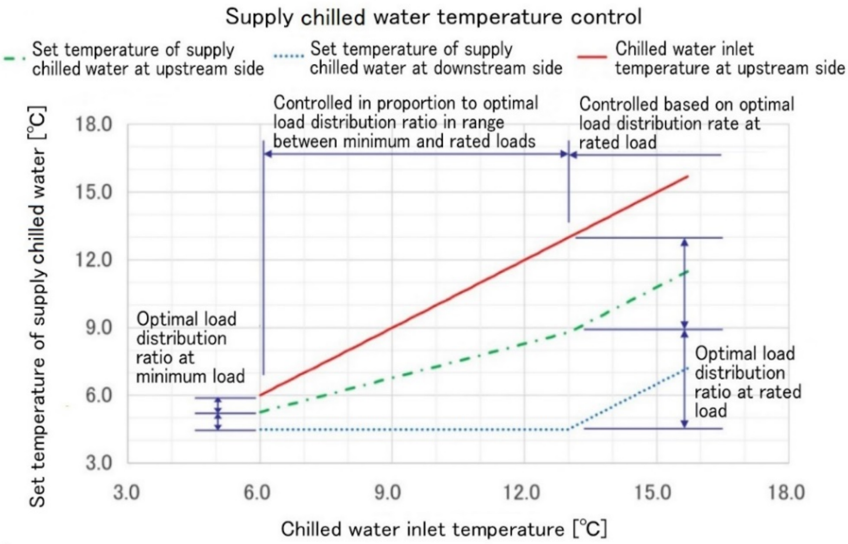


**Figure 4　Conceptual diagram of supply chilled water temperature setting**

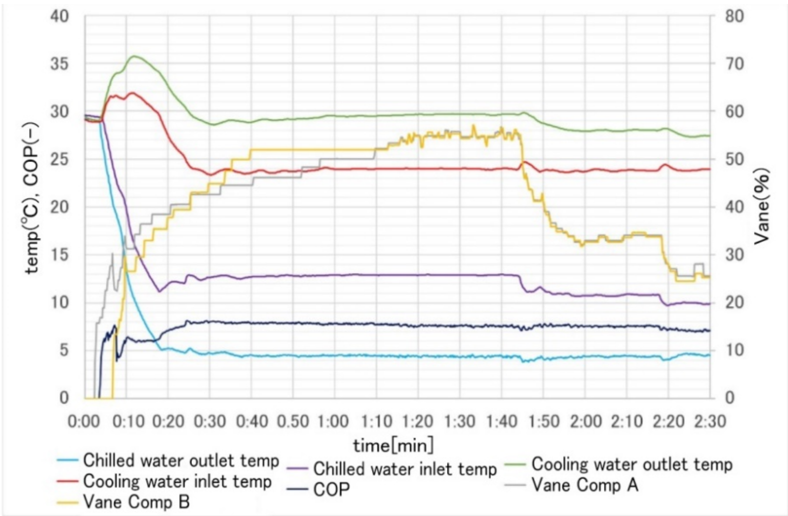


**Figure 5　Controllability against load change**

## 5. Control of number of units in operation to handle larger capacity

While a single SCF model is controlled as described in chapter 4, the SCF configuration of SCF models makes it possible to operate as a larger capacity chiller. For such operations, the SNCP (Small Number Control Panel) was developed as the dedicated control panel. The use of SNCP enables to control the start/stop processes and the supply chilled water temperature as in SCF models. Regarding the control of start/stop processes and temperature, the temperatures for supply chilled water are determined based on the predetermined optimal load distribution ratios, as in the case of controlling the number of the operating compressors arranged in the SCF model and the supply chilled water temperature. Therefore, this section describes how to control when a failure occurs and during power outages.

Furthermore, if Ene-Conductor is installed as the upper control system of SNCP, this allows multiple SCF models arranged in SCF under the control of SNCP to be handled in the same way as a single chiller as shown in **Figures 6**. Thus, it becomes possible to build an optimal heat source control system using Ene-Conductor by which a maximum of six sets of the SNCP-integration-SCF-configurations with up to 60,000 RT can be controlled.

Moreover, by combining Ene-Conductor with DIASYS Netmation® (MHI's DCSS (Distributed Control System)), it also becomes possible to control multiple. The cases that are not standard in Ene-Conductors, such as the heat source system components (such as the heat storage tanks) and the increase in the number of input/output points can be handled in a flexible manner. This removes the limitations on the amount of heat source equipment and the capacity for a single plant, making it applicable to district heating and cooling systems and large-scale factories as shown in **Figure 7**.

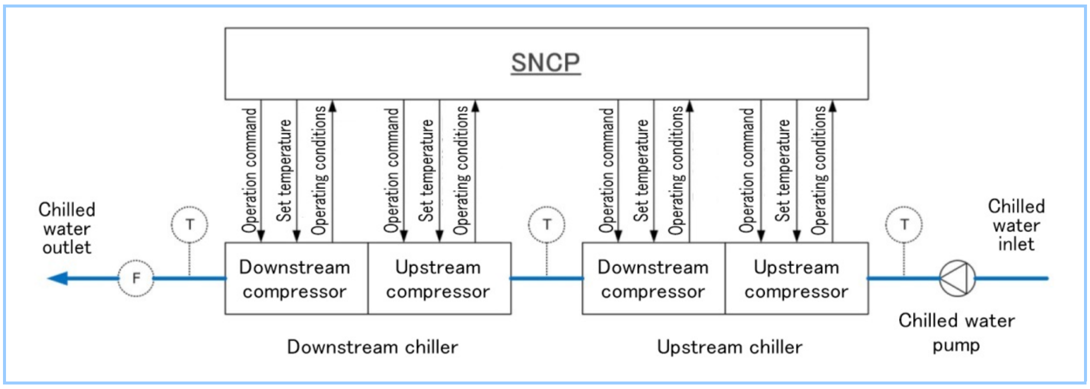


**Figure 6 SNCP integration SCF configuration**

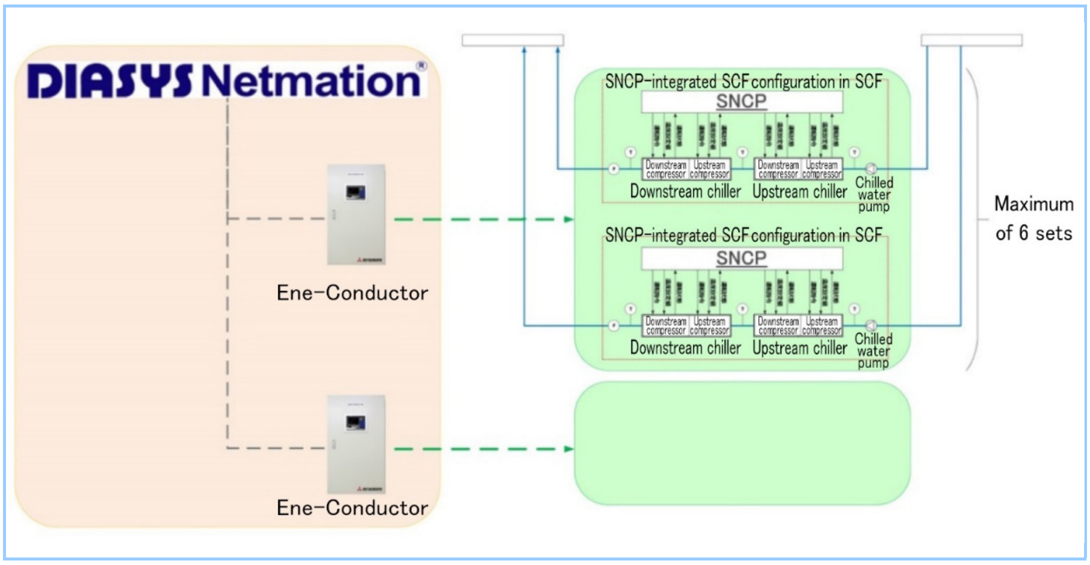


**Figure 7 Configuration of Ene-Conductor and DIASYS Netmation**

## 6. Conclusion

Our newly developed high-efficiency large-capacity centrifugal chillers have substantially improved the efficiency by adopting the SCF configuration. Owing to their small installation area and compact layout including equipment piping, these chillers are suitable as a new installation or a replacement of an earlier model with the capability of satisfying large-scale heat demand in emerging countries. Being operable with either HFC refrigerants or HFO refrigerants, our chillers have an equipment configuration that can be flexibly adapted according to future changes in the HFC refrigerant reduction schedule.

Moreover, we have established a system that allows our products to be shipped from factories in either Japan or China, enabling the selection of products that meet customer needs in terms of the delivery date and price. In addition, the installation of SNCP enables two chillers to be easily operated as a single large-capacity chiller. Further installation of Ene-Conductor as the upper control system makes it possible to control heat sources in an optimal manner, with the capability to satisfy large-scale heat demand of up to 60,000 RT. This can be expected to lead to reductions in power consumption, $CO_2$ emissions and running costs.



## References

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(2) Makoto Shimokawa, et al., New “JHT-Y” Series of Centrifugal Chillers with Low-GWP Refrigerants Contributing to Carbon Neutrality, Mitsubishi Heavy Industries Technical Review Vol.60 No.2 (2023)