12th IEA Heat Pump Conference 2017

Latest heat pump technologies in Japan

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Abstract

In Japan, we have to reduce CO_2 emissions by 26% by 2030, and an 80% reduction is expected by 2050. To realize this strict target, the heat pump is still believed to be a promising key technology in Japan, and an increasing number of heat-pump-related technologies have appeared. In this paper, as Japan's representative, I will share the latest information on these new technologies and the future prospects for heat pumps.

Examples of new heat-pump-related technologies include the following. For a domestic heat-pump water heater that uses CO_2 as a refrigerant, a new higher-performance double-stage evaporator with an ejector has been developed to reduce the frost formation on the windward side of the heat exchanger. In addition, a four-stage high-performance compressor has been introduced.

A VRF system that uses a heat exchanger with a flat multiport microchannel pipe has been developed for air conditioners. A human motion detector was added to supply comfortable air to individual occupants. A small compact-type adsorption air conditioner has been developed for the automotive use. For industrial use, a compression heat pump system that can supply heat at 200 °C is under development with the assistance of national funding. An absorption transformer that can supply heat at 180 °C has already been developed.

The market has seen an increase in the number of air conditioning systems that use R32 as a refrigerant because of its lower global warming potential (GWP), and an R32 heat-pump water heater is also being developed. A centrifugal chiller that uses HFO-1233zd(E), which has a GWP of only one, was also introduced into the market. A refrigerating showcase that uses a new refrigeration cycle with CO_2 as a refrigerant is being developed.

To predict the performance of a compression cycle using various types of refrigerants, including completely new refrigerants, without experiments, a general-purpose energy system analysis simulator called "Energy flow +M" was developed by Waseda University. This has become a common simulation tool for the Japan Refrigeration and Air Conditioning Industry Association. The following can also be investigated using this simulator: the static and dynamic performances, the effect of refrigerant leakage and so on.

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1. Introduction

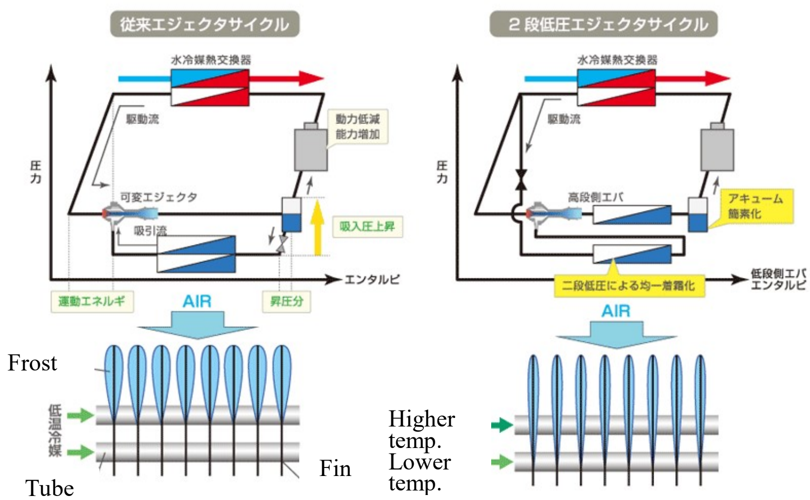
In Japan, heat pump technologies are evolving and have already achieved a very high performance. For example, the annual performance factor (APF) has already reached 7.4, which is thought to be almost the performance limit. Because of this, system R&D efforts have been made to improve the comfortableness using human detectors, improve the frost and defrost performance to widen the utilization range, and supply higher temperatures using absorption and compression systems.

In addition, a system that uses a lower global warming potential (GWP) refrigerant has been developed, along with a simulator that can predict and compare the performances of various refrigerants. After introducing these Japanese efforts, I will introduce my views on the future of air-conditioning and heat pump systems.

2. Domestic heat pump

The development of a CO_2 heat-pump water heater began in 2011, and in the 15 years since then, 5 million systems have already entered the market in Japan. I truly appreciate the great effort of the manufacturers. Because this system uses the supercritical region of CO_2, the high-side pressure reaches 10 MPa. Therefore, new technologies such as double-stage compressors and new heat exchangers that are suitable for a higher refrigerant pressure were developed.

As shown in Fig. 1(a), the performance of the system decreases greatly in the cold region because frost blocks the air flow. However, as shown in Fig. 1(b), using an ejector makes it possible to realize a double-stage evaporator with a higher temperature refrigerant side heat exchanger for the air inflow side. This reduces the frost formation on the air inflow side, which lengthens the frost time. This consequently decreases the defrost time, and increases the system performance.



(a) Conventional (b) Two stage

Fig. 1. Two stage evaporator with ejector produced by Denso [1]

On the other hand, the extremely high refrigerant pressure of the CO_2 heat-pump water heater significantly increases the cost of the heat exchanger and compressor. A heat-pump water heater that uses R32 as a refrigerant was developed to alleviate this problem, as shown in Fig. 2. This system can reduce the pressure on the high-pressure refrigerant side and thus reduce the cost.

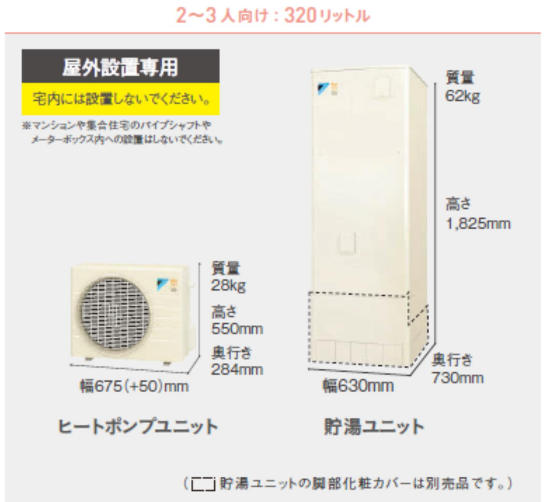
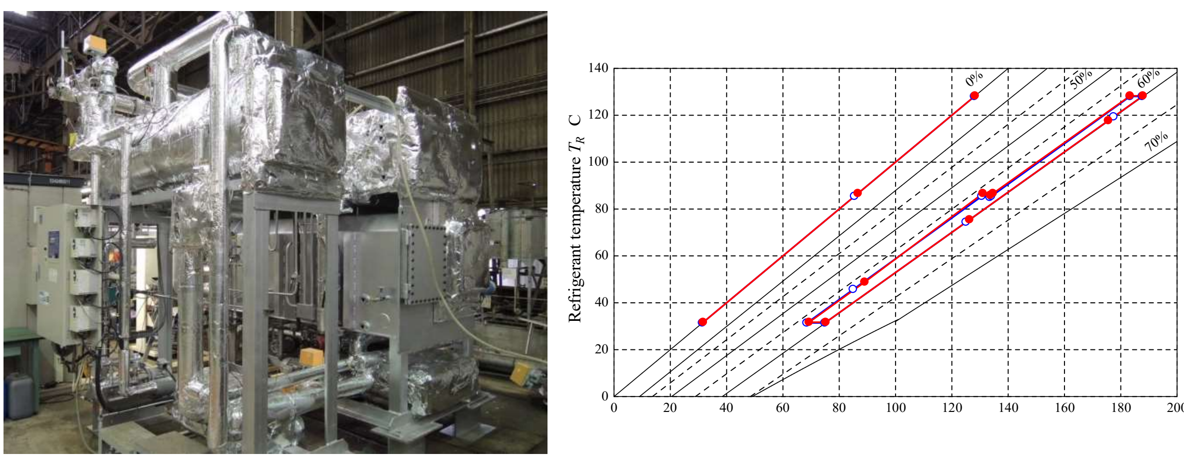


Fig. 2. R32 heat-pump water heater produced by Daikin [2]

3. Industrial heat pump

The development of industrial-use heat pump systems has continued. Various heat pump systems such as air heaters and simultaneous heating and cooling systems have appeared in the market. For example, factories normally use an 8 kgf/cm^2 steam piping network to supply steam at a temperature of approximately 180 °C. Therefore, a heat pump system that can produce steam at this temperature is in great demand. To realize 180 °C steam generation, we developed double- and triple-stage absorption heat transformers.

Normally, the absorption cycle is used for cooling, and although there are many applications, few involve heat pumps. Moreover, when a conventional single-stage absorption heat transformer is used, steam can only be generated at approximately 120 °C. By developing the double- and triple-stage systems, 180 °C steam generation was realized. Finally, a practical system could be developed. Fig. 3 shows the double-stage system that we developed.



Item		Unit	rated condition	Measurements
Steam	Capacity	kW	200	208.0
	Temp.	°C	180	179.8
	Pressure	MPa(A)	1.0	0.984
Cooling Water	Inlet Temp.	°C	25	25.0
	Flow rate	L/min	1800	1798.6
Hot Water	Inlet Temp.	°C	88	88.3
	Flow Rate	L/min	2000	2008.4
COP		-	0.27	0.278

Fig. 3. Double-stage absorption heat transformer produced by Ebara and Waseda University [3]

We are also developing a 200 °C high-temperature compression-type heat pump system. As a first step, we are developing a 165 °C heat pump system, as shown in Fig. 4. In this compression cycle, we optimized the cycle and components using a theoretical analysis and experiment. In addition, we finished designing the 3-stage compressor using a computational fluid dynamics analysis. Starting next year, we will begin the experimental testing of the whole system. We are still investigating the optimum control method using the available simulation technology, and the results will be introduced in the near future.

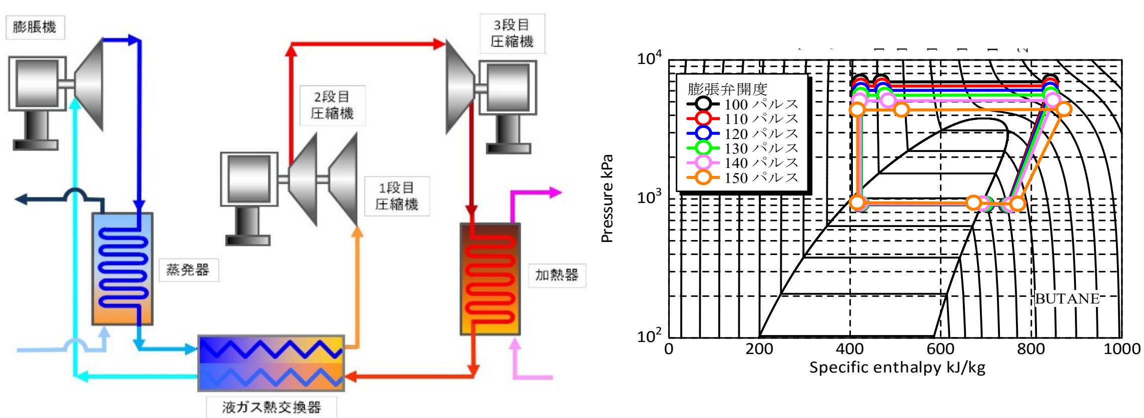


Fig. 4. Higher temperature heat pump system produced by Mayekawa and Waseda University [4]

In addition to these higher-temperature technologies, new cooling technologies have appeared. Conventionally, the temperature of the heat source used to drive an absorption cooling cycle is approximately 90 °C. However, as shown in Fig. 5, a 60 °C heat-driven absorption chiller is now under developed. The details of this technology will be introduced in this conference.

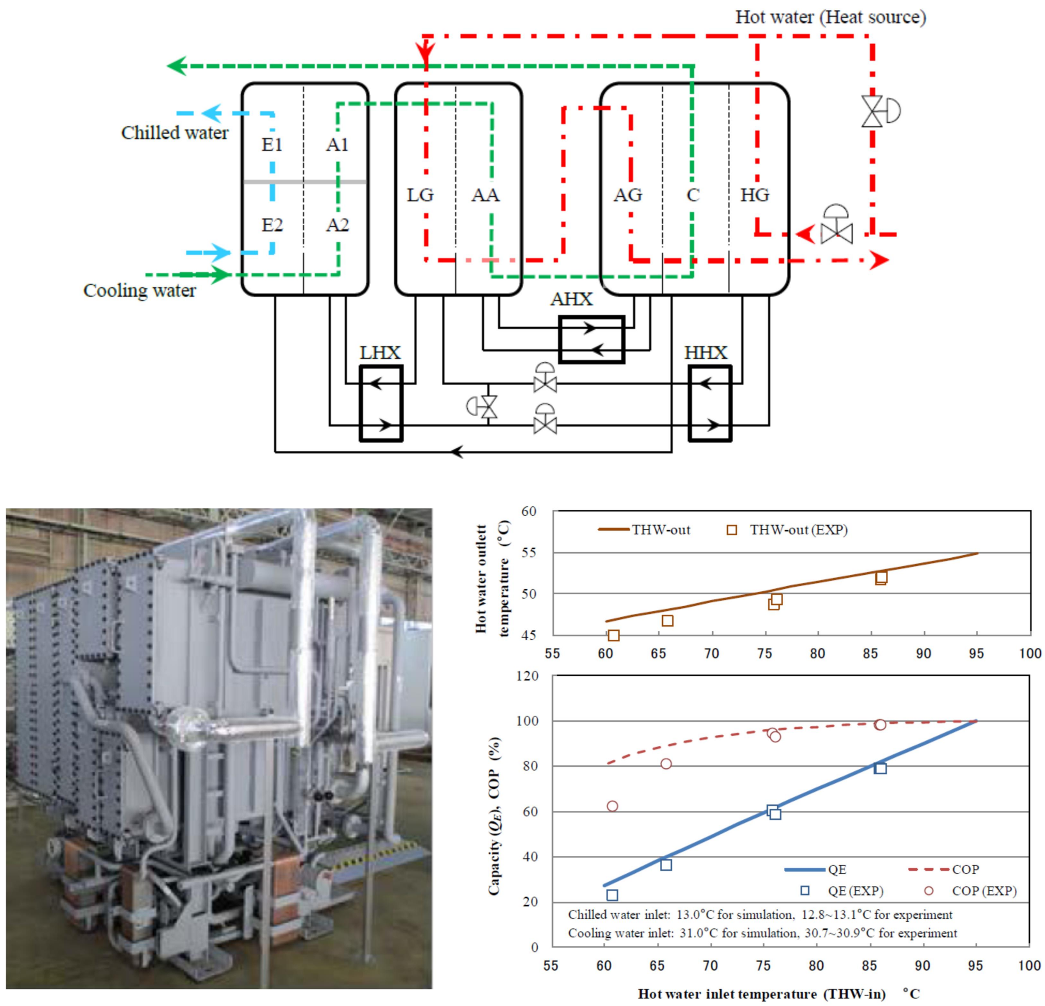


Fig. 5. Low-temperature-driven absorption chiller produced by Hitachi [5]

A very compact 120 °C steam generator heat pump system with a heat capacity of approximately 30 kW was developed, as shown in Fig. 6. The heat-source temperature has a range of 60–80 °C. Because 10 systems can be driven simultaneously, many types of steam applications in factories can be realized using this system.

4. Air-conditioner

A very-high-performance system has already been developed for a room air-conditioner. Therefore, systems to improve comfort are being developed. As shown in Fig. 7, a system with two propeller fans and an occupant detector has been developed. This system can supply air at two different comfortable temperatures for two separate occupants.

The room air-conditioner is equipped with an image recognition system utilizing near-infrared light images. As shown in Fig. 8, the shapes and positions of the furniture can be detected using this system.

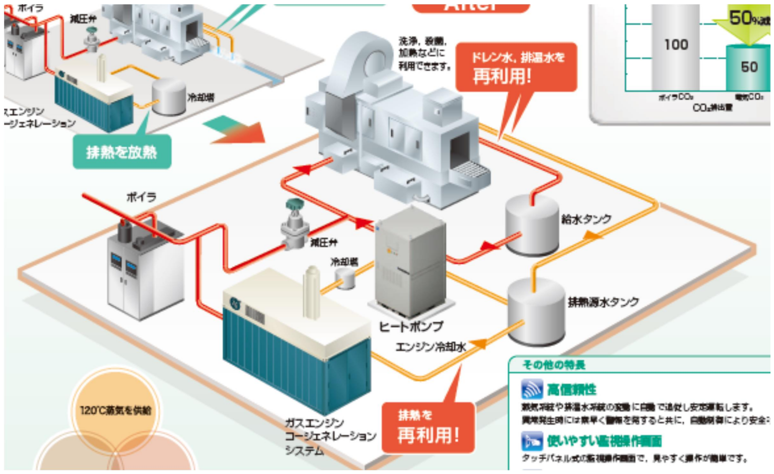


Fig. 6. Small steam generator produced by Fuji Electric Company [6]

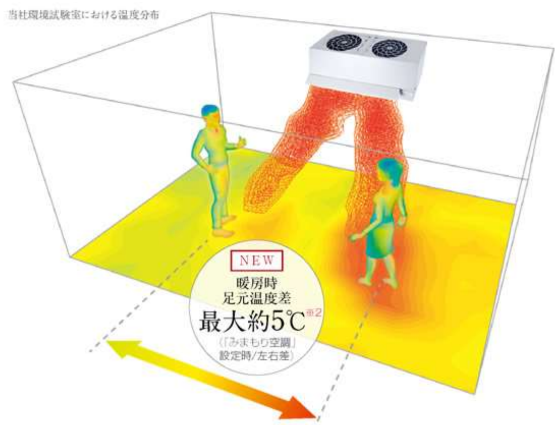


Fig. 7. Air-conditioning system supplying air at two different temperatures produced by Mitsubishi Electric [7]

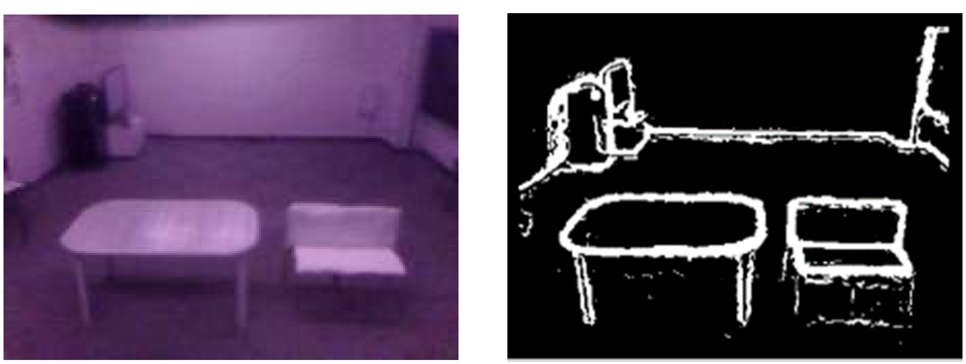


Fig. 8. Furniture shape and position detection system by Hitachi [8]

Using this detection system, an experimental test was performed using furniture positioned as shown in Fig. 9. For this furniture arrangement, a 24% energy saving could be realized because the air was supplied to the best area considering the furniture positions.

"Air-Flow-Paths"	OFF	ON
Foot Temperature	24.1℃	24.2℃
Setting Temperature	26.5℃	23.0℃
Electric Energy per one hour	790Wh	597Wh

-3.5℃

Effect of Power Saving 24.4%

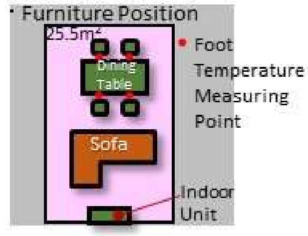
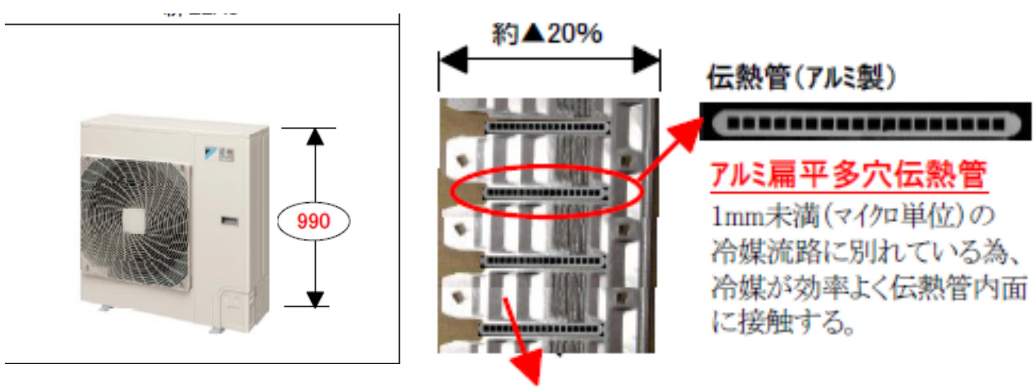


Fig. 9. Energy saving with furniture shape and position detection system

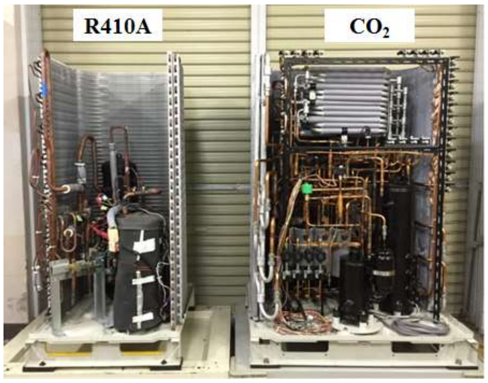
As shown in Fig. 10, multi-hole flat tubes were used for a package air-conditioner to improve the heat exchanger performance and realize a compact design. This heat exchanger was applied to an outdoor unit, and the refrigerant charge could also be reduced.

(i) VRF system produced by Mitsubishi electric [7]

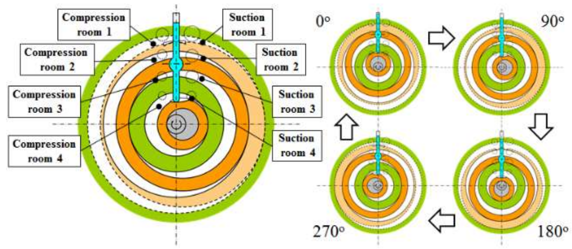


(ii) VRF system produced by Daikin [2]
Fig. 10. VRF systems with multi-hole flat tubes

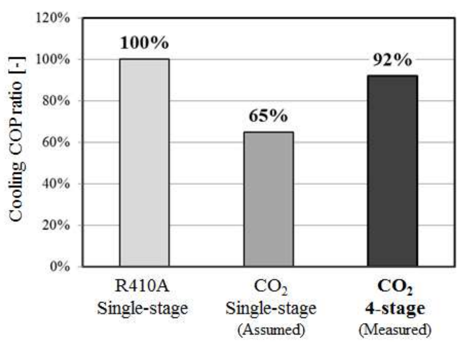
As shown in Fig. 11, a 4-stage compressor was developed to further improve the performance of the cooling cycle when using CO_2 as the refrigerant. This compressor seems to be the optimum device.



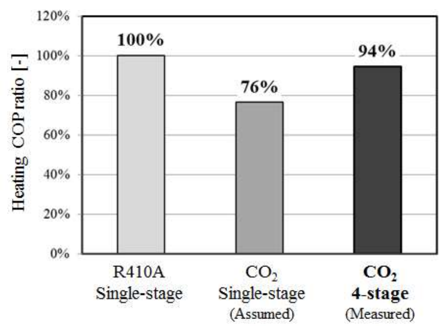
(a) Outdoor unit



(b) Four-stage compressor



(c) Performance of cooling operation



(d) Performance of heating operation

Fig. 11. Four-stage compressor produced by Daikin [9]

Automotive air-conditioning systems are rapidly being developed. As shown in Fig. 12, an adsorption system for an automotive use was developed because of the convenience of using the waste heat from the engine.

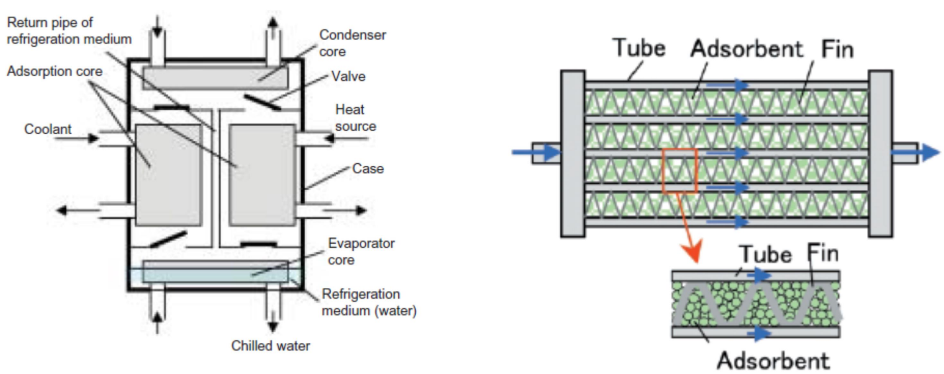


Fig. 12. Adsorption system for automotive use produced by Denso [10]

As shown in Fig. 13, a new higher-performance automotive air-conditioner that uses an ejector was developed. A coefficient of performance (COP) enhancement of approximately 50% can be realized with this ejector.

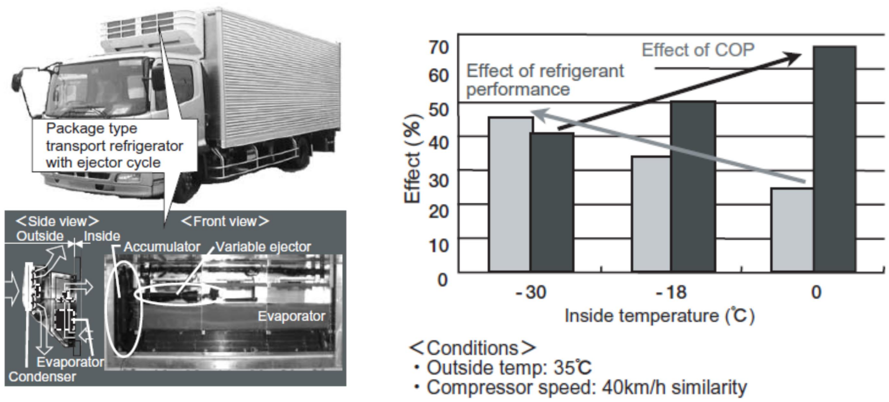


Fig. 13. Refrigeration system with ejector for automotive use produced by Denso [11]

5. Refrigerant

As shown in Fig. 14, to realize a low GWP, room air-conditioners that use R32 instead of R410A have been developed.

Fig. 14. Room air-conditioner that uses R32 produced by Daikin [2]

Table 1. Manufacturers that uses R32 [12]

Manufacturers that use R32 as refrigerant			
Room Type		**Package Type**	
1. Daikin 2. Hitachi 3. Mitsubishi 4. Panasonic	5. Sharp 6. Fujitsu General 7. Toshiba Carrier 8. Other【Corona】	1. Daikin 2. Mitsubishi 3. Toshiba Carrier	4. Panasonic 5. Other

Most manufacturers already used R32 for room and package-type air-conditioners, as listed in Table 1. The flammability of R32 is mild and far less than that of others such as hydrocarbon (HC) refrigerants. A risk assessment was already performed by the Japan Society of Refrigeration and Air-conditioning Engineers (JSRAE), and a safety standard was established. Therefore, it is safe to use this refrigerant.

As shown in Fig. 15, a centrifugal chiller was developed that used HFO-1233zd(E), which has a rated COP of 6.3, instead of R134a or R245fa. The GWP values of R134a and R245fa are very high at 1430 and 1030, respectively. In contrast, the GWP of this refrigerant is approximately one. This refrigerant will be the main refrigerant of the centrifugal chiller.

Fig. 15. Centrifugal chiller that uses HFO-1233zd(E) produced by Mitsubishi Heavy Industries [13]

A refrigerated display case that uses CO_2 as a refrigerant was developed, as shown in Fig. 16. The cycle of this system was improved, which makes it possible to obtain a higher annual performance.

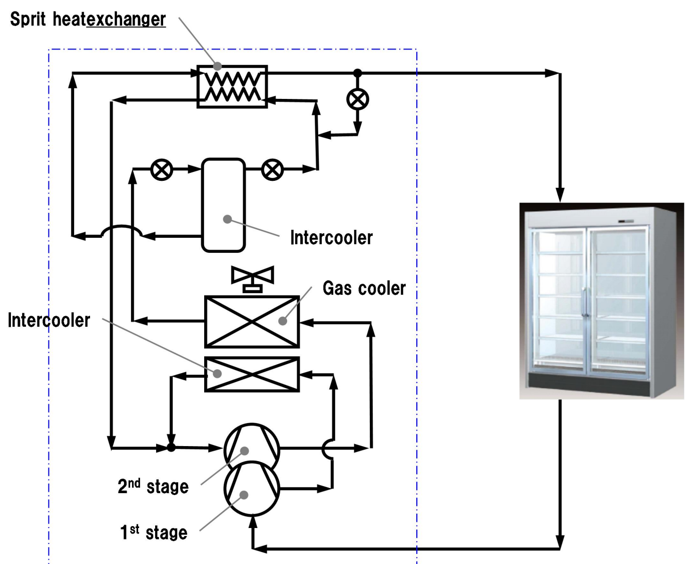


Fig. 16. Refrigerated display case that uses CO_2 as refrigerant produced by Panasonic [14]

6. Simulation technologies

6.1 Introduction of simulator "ENERGY FLOW +M"

"Energy flow +M" is a general purpose energy system analysis simulator that uses modular analysis theory. Using this simulator eliminates the need for users to consider the calculation algorithms of the analysis.

In this simulator, element modules that express the input–output relations are connected to each other, and analysis code for the entire system can be developed.

As shown in Fig. 17, the compression refrigerant cycle consists of the evaporator, condenser, expansion valve, accumulator, and reversing valve.

Fig. 18 shows how this cycle is described in "Energy flow +M." It is only necessary to select the modules we need and connect them to each other. Of course, various refrigerant and input calculation conditions can be selected, and some of the parameters needed for the simulation can be changed.

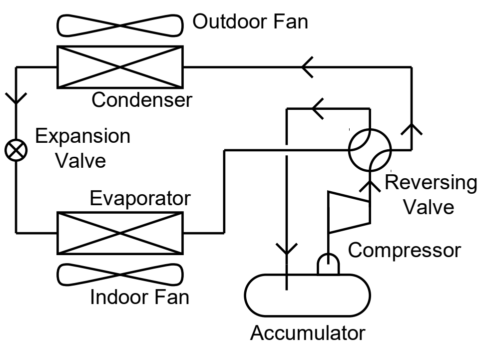


Fig. 17. Compression-type refrigeration cycle

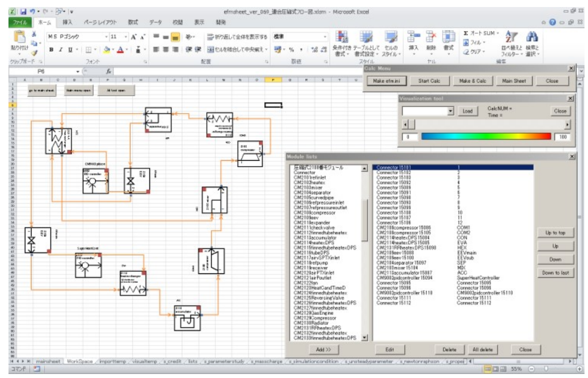


Fig. 18. Energy flow +M [15]

Because the modules are independent, this simulator makes it possible to easily remake the new system simply by changing the module connection conditions.

We have already developed the modules needed for the calculations of the VRF system, GHP, and absorption system. The calculations for a VRF system with four indoor units are shown in Figs. 19 to 21.

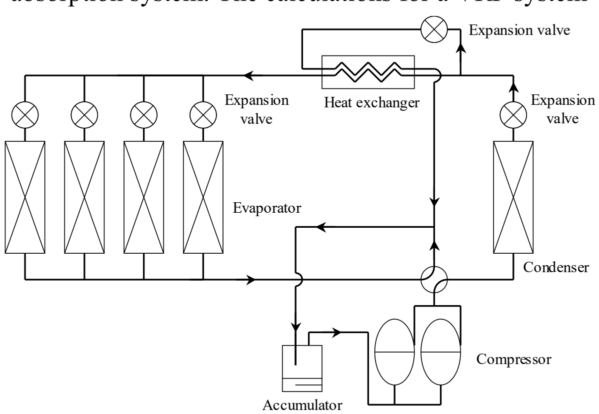


Fig. 19. VRF flow

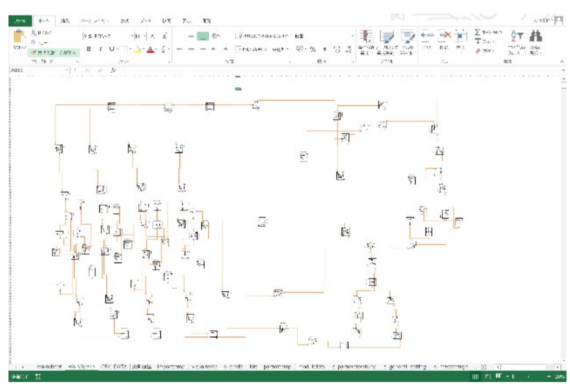


Fig. 20. VRF on Energy flow +M

The system flow is shown in Fig. 19, and the simulation code used in Energy flow +M is shown in Fig. 20, which is very complex. The calculation results for the dynamic characteristics are shown in Fig. 21. The driving of each indoor unit interferes with that of the others.

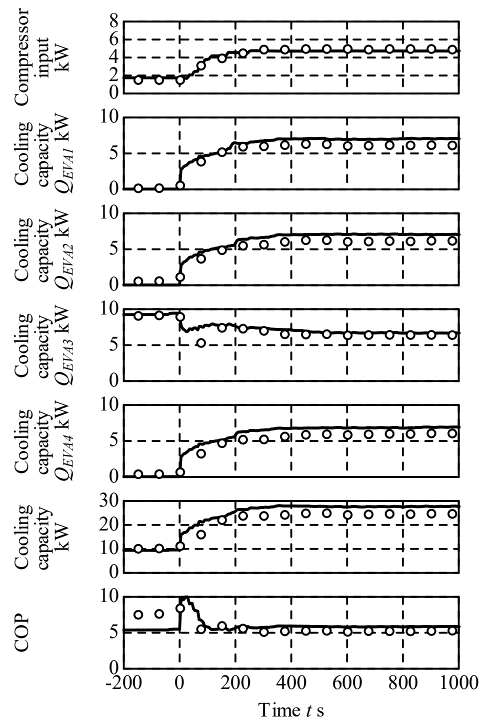


Fig. 21. Dynamic calculation of VRF system

6.2 Mathematical models

The simulator can use many kinds of correlations between the heat transfer and pressure drop. A straight pipe is divided into several parts with the same length as a control volume for the heat exchanger calculation, and we consider models of bends and U pipes.

We use iso-entropic and volumetric efficiencies for the compressor model.

6.3 Drop-in test with HC refrigerant

Because the GWP of an HFC refrigerant such as R410A is high, a drop-in test of an HC refrigerant was performed using a system that was originally developed to use another refrigerant. It was reported that this greatly reduced the electricity consumption and realized energy savings.

But it is easy to guess that only electric consumption can’t be reduced and good performance can’t acquire. Therefore, we used R600a in a room air-conditioner that was originally developed to use R410A.

Before carrying out the simulation, we compared the thermodynamic properties of R410A and R600a, as listed in Table 2. Based on this table, because of the large specific volume of R600a, it could be predicted that both the electricity consumption and cooling capacity would be reduced.

Fig. 22 shows the experimental and simulation results. These results show that under the rated conditions, the electricity consumption was greatly decreased, but the cooling capacity was also decreased.

Thus, it was found that good results could not be obtained when using R600a in a system as a drop-in that was originally designed to use R410A.

Based on these results, the simulation and experimental results agreed well with each other. It is easy to understand that the previous reports include some fatal misunderstanding.

Table 2. Theoretical compression cycle

	R410A	R600a
Evaporation temperature,□	10.0	
Condensation temperature,□	45.0	
Sub cooled temperature,□	5.0	
Super heat temperature,□	5.0	
Adiabatic efficiency,-	1.0	
Theoretical COP,-	6.40	7.13
Compressor inlet specific volume, m^3/kg	0.0248	0.174
Evaporator specific enthalpy difference, kJ/kg	164	280
Refrigerant flow rate per unit of cooling capacity, kg/(s・kW)	0.00610	0.00357

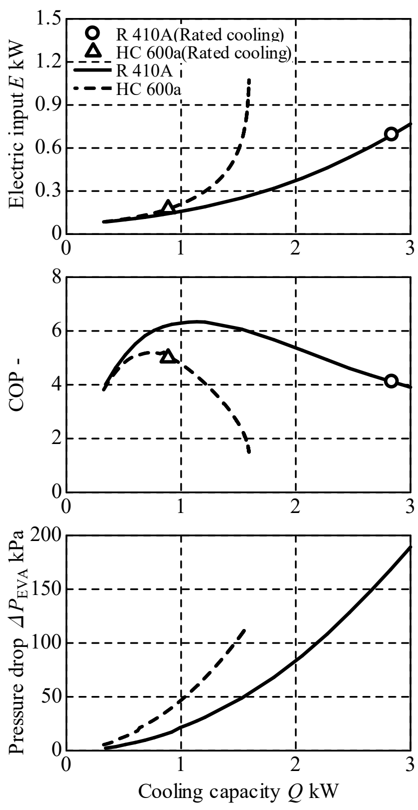


Fig. 22. Drop-in result of HC

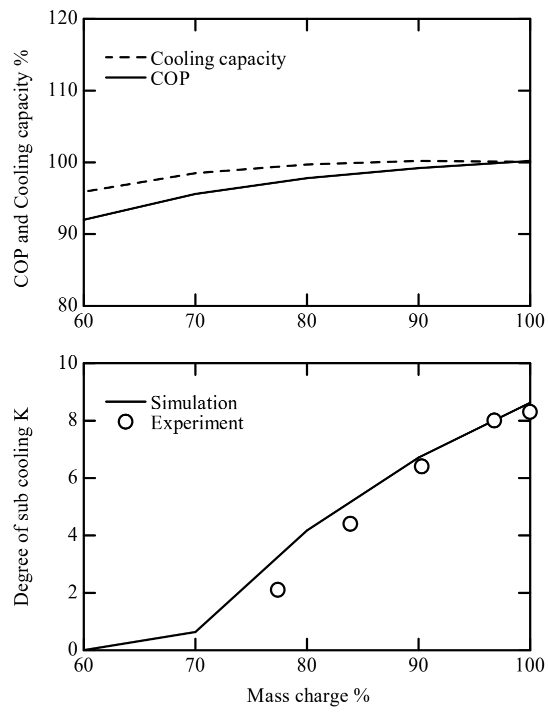


Fig. 23. Effect of refrigerant charge

6.4 Effect of refrigerant charge

The effect of the refrigerant charge on the performance of the refrigeration cycle was investigated. We had to use a low GWP refrigerant with flammability. Therefore, we had to reduce the refrigerant charge in the system, and we sometimes had to immediately predict refrigerant leakage.

In any case, we had to determine the effect of the refrigerant charge on the system performance. As shown in Fig. 23, we can easily understand the effect of the refrigerant charge on the COP and sub-cooling. It might be possible to estimate how much refrigerant is leaked based on the sub-cooling results, without measuring the refrigerant charge.

7. Future prospect

Extensive works are being performed to develop heat pump technologies for air-conditioning systems and water heater. The problems to be faced in the near future will involve refrigerants. There is still some confusion because some governments and system and refrigerant manufacturers may have different goals. Some have the goal of recovering refrigerant, whereas others have the desire to utilize natural refrigerants even if they are flammable or toxic. Finally, we have to determine the best solution for the world environment.

Recently, the smart energy and zero energy building concepts have been developed, which require the introduction of additional sources of renewable energy. Thus, because a heat pump uses renewable energy and can be used for heat and electricity conversion at low cost on site, it is a very important system. However, the system has to withstand fluctuations in the load, source, and renewable energy. Some new technologies to extend the driving range, improve the efficiency with a wide driving range, and provide stable control have to be developed.

There are still some processes that have large irreversible losses such as expansion losses and unexpected temperature increases in the compression process. Attempts have been made to recover the expansion loss using an expander and ejector, but the loss inside the compressor has not been discussed. If a two-phase flow could be directly compressed, it would be possible to prevent an unexpected temperature increase in the compressor. I hope that new technology appears with a cycle close to the Carnot cycle. In addition, when an air-conditioner is mounted on a wall, it is difficult to realize a comfortable environment in the entire space. Ten years ago, in my lab, an air-conditioning robot was developed that could move by itself to a person who wanted air-conditioning, as shown in Fig. 24.

A robot vacuum cleaner has already been developed, and robot technologies are being applied to home use. By installing an air-conditioner inside a robot, it could provide a comfortable environment for each person. The application of local air-conditioning is useful for reducing energy. Direct air-conditioning for the human body or blood will be developed.

On the other hand, there is still a vast amount of solar energy available. Although the energy density is very small, the total quantity is very large. There is a possibility that a concept will be devised for directly air-conditioning a vast area.

8. Conclusions

I introduced the latest heat pump technologies in Japan. The progress of these heat pump technologies is very slow compared to that of computer, electrical, and electronic technologies. I believe that the situation that has prevailed over the past 100 years still continues. However, we need to steadily improve the technologies for heat pumps. Of course, I will do my best to spread heat pump technologies throughout the world.

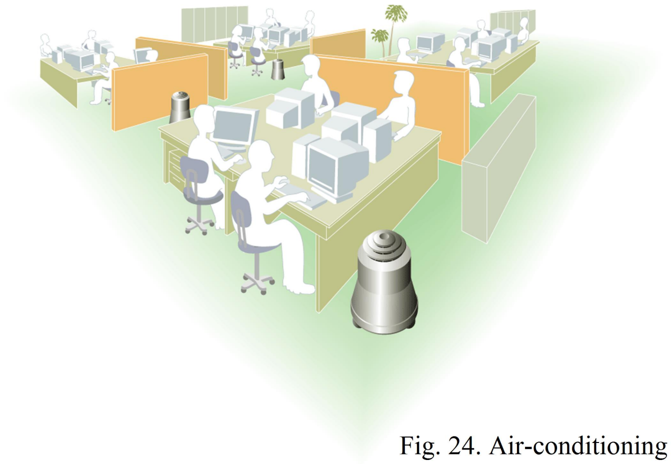


Fig. 24. Air-conditioning robot

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