Recent Development in Heat pump Technology in Japan

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Abstract: Since the nuclear disaster caused by the Great East Japan Earthquake in 2011, energy supply problem in Japan has been grave. Currently all nuclear power plants are out of operation, majority of power supply are by-fired power generation by fossil fuel. Under this situation the compatibility with environmental issues, energy saving strategy is very important. In this article, the recent progress of heat pump technology following Japanese policy of energy saving including the elements fundamental research is described. As a conclusion, it should be noted that the future development efforts more research is needed, but the seedlings of technology breakthrough is expected to realize in basic research.

Key Words: heat pump technology, state-of –the-art research progress in Japan

1 INTRODUCTION

Since the nuclear disaster caused by the Great East Japan Earthquake in 2011, energy supply problem in our country has been grave. Currently all nuclear power plants are out of operation, majority of power supply are by-fired power generation by fossil fuel. The compatibility with environmental issues, energy saving strategy is very important in this situation. In Fig.1, the tendency in final energy consumption in Japan is shown. The final energy consumption of Japan has basically consistently increased, except for periods immediately following the two oil crisis and the recent economic down turn. It is also recognized from this Figure that until 2012 the GDP continued increasing to about 2.4 times the 1973 level and the consumption of energy for individual sectors significantly increased with consumer sector increasing to about 2.4 times, while the transportation sector increased about 1.9 times, whereas the industrial sector decreased to about 0.85 times (Fukuda A. (November 2013)).

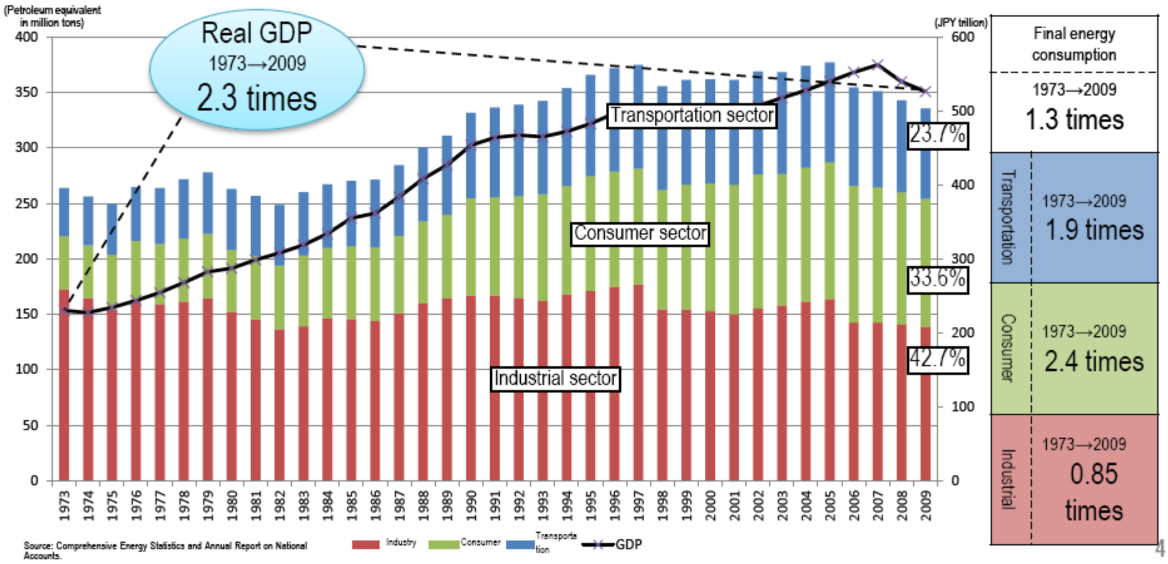


Figure 1: Transition of Final Energy Consumption in Japan (Fukuda A. (November 2013))

Our country has improved energy efficiency by approximately 40% after the oil crises in the 1970's as a result of actions by both public and private industrial sectors as shown in Fig. 2. Due to the various actions based on "Energy Management System based on Energy Conservation Law", Japan achieved the lowest level of energy consumption per GDP in the world. The innovative energy and environmental strategy, which were formulated after the earthquake, it has the goal to achieve a reduction of more than 72 million kL in 2030 on the basis of the 2010 in the final energy consumption. Heat pump technology, is shown in several sectors as a technology of energy savings is position as an important technology for energy saving to achieve this goal.

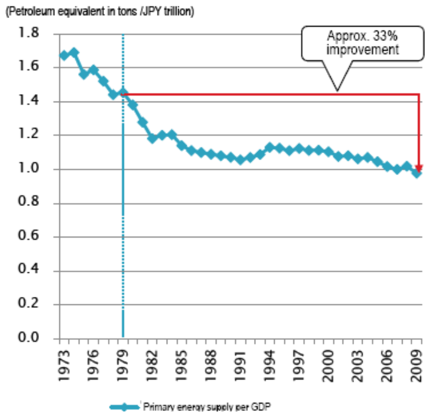


Figure 2: Energy Conservation Efforts in Japan since Oil Crisis (Fukuda A. (November 2013))

In future, to reduce the CO_2 emission and to achieve the high efficiency and low cost, not only the development of high efficiency refrigeration cycle system and brand new low GWP refrigerant but also innovative element technology for high performance heat exchanger and compressor will be required. Another important aspect is as follows: the integrated technology including the secure of heat source and secondary control method together with thermal storage system and expansion power recovery technology. NEDO defined these refrigeration systems as "Heat Pump System in Next Generation". And the 2030 goal of this strategy will be 3/4 manufacturing current cost（2008 level） and improving the overall efficiency 1.5 times that of 2008 level (COOL EARTH strategy) The deployment scenarios related to the heat pump is shown in Figure 3 (Amari T. (September 2013)).

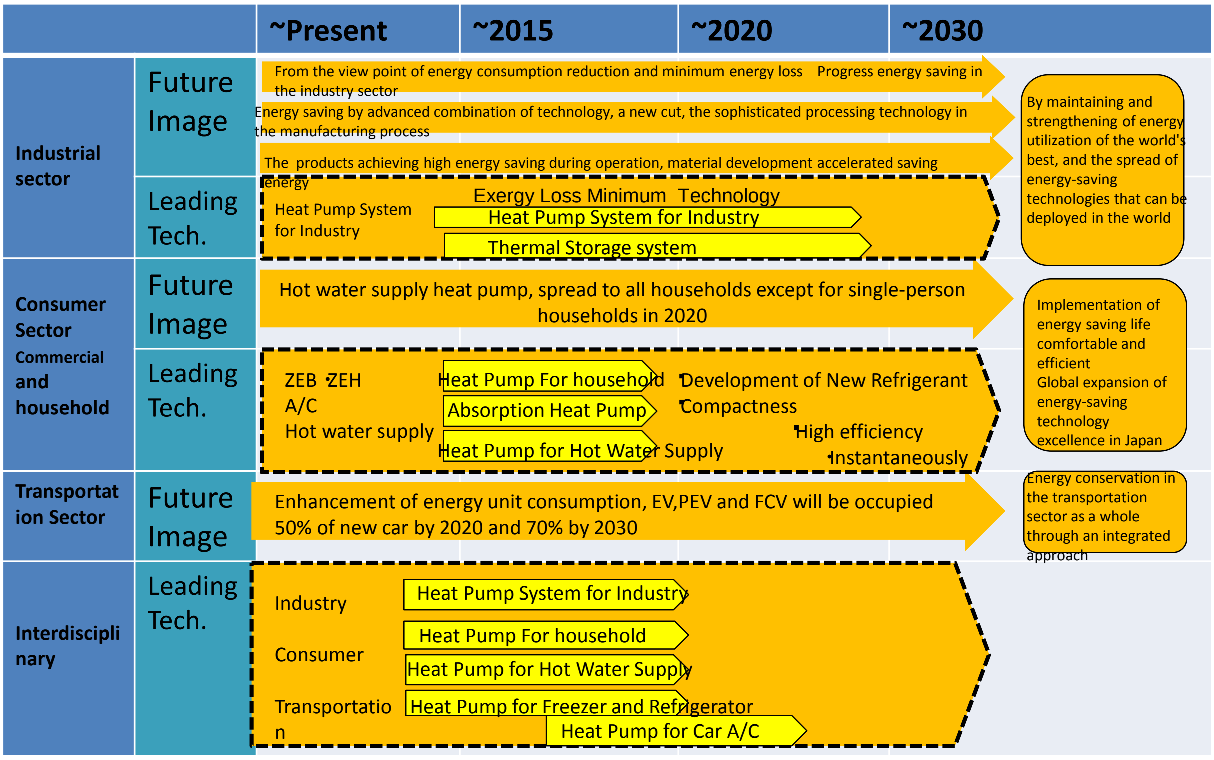


Figure 3: Heat Pump Deployment Scenarios by Strategy of Energy Conservation 2011 (Amari T. (September 2013))

Since mentioning briefly Japanese policy of energy saving including the elements fundamental research, the research and development recent trends in each sector will be discussed.

2 PRESENT STATUA AND PROSPECT HEAT PUMP

In this section, the recent developments of heat pump for each sectors are described and discussion is also made about the outlook for the future.

2.1 Residential Sector

In recent years, environmental and energy problems such as global warming are becoming important and ways to tackle greenhouse gas emissions on a global scale are required. Looking at the sector CO_2 emissions growth rate from 1990, CO_2 emissions of so-called consumer sector, residential sector and commercial sector are increasing significantly, there is as urgent need for effective measures in this sector. When attention is focused on the usage of the energy in the residential sector, the hot water supply and the heating are occupied 55% (Fig.4). Looking in more detail, 84% of the energy used for heating hot water supply is direct fired fossil fuel city gas, LPG, and kerosene. It is possible to approach the low-carbon society is in fossil fuels by replacing the heat pump with high efficiency in this area. Japanese energy conservation evaluation criteria for air conditioning system are also unified in an APF from COP and 2010 performance objectives have been established.

The transition of seasonal energy consumption from 1995 is shown in Figure 5. Top runner method is introduced in 1999, about 40% of energy saving was achieved in air conditioning area. APF of energy-saving top-class machine currently has achieved 7.2 (cooling capacity 2.8kW), 7.0 (cooling capacity 4.0kW) (Nishiwaki F. (September 2013)).

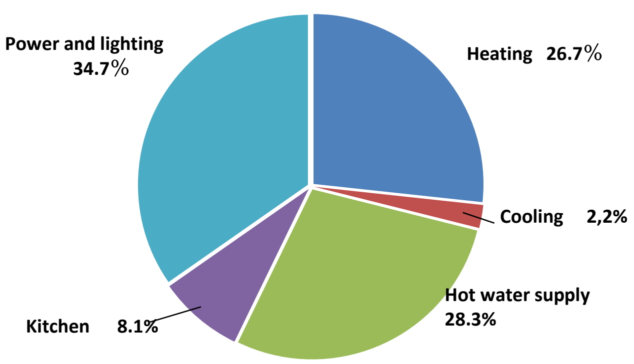


Figure 4: Residential Sector Energy Consumption Classified by Use

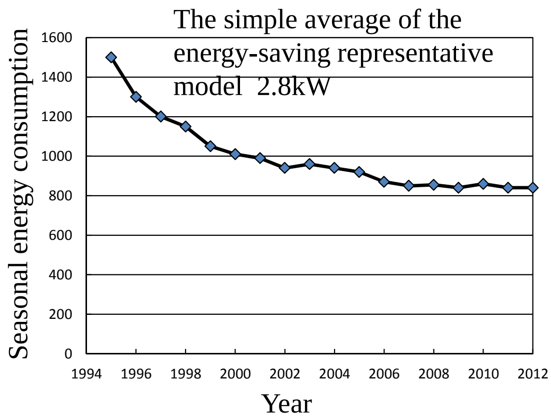
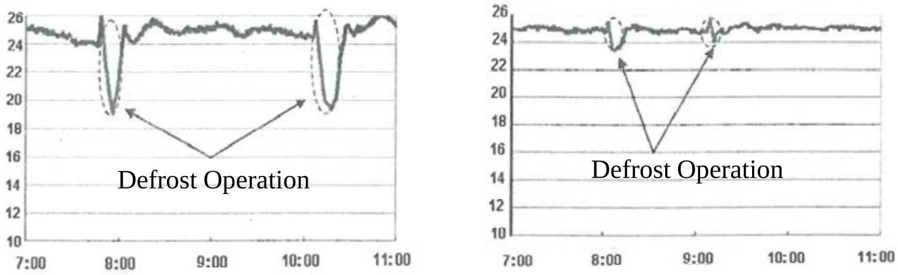


Figure 5: Transition of Seasonal Energy Consumption (Residential Air Conditioning System)

Currently, we are making efforts to improve the following element techniques expecting further improvement;

・Use of the compressor waste heat
・Partial load corresponding technology
・The energy conservation and comfort technology by sensor and airflow control
・Temperature and humidity control technology

In a conventional air conditioner, when the outside air temperature is low, a phenomenon that is frosted to the outdoor heat exchanger, capacity may decrease in heating operation. In this case, defrosting process is started by switching the cooling cycle from the heating cycle and the flow direction of refrigerant, but there is the problem of the room temperature is going down. Therefore, the compressor waste heat is focused on the thermal energy which has been abandoned in the outdoor environment of the compressor, stored in the heat storage medium and the exhaust heat by utilizing the heat in the defrosting operation, it does not prevent the heating and defrosting of utilization system has also been developed.

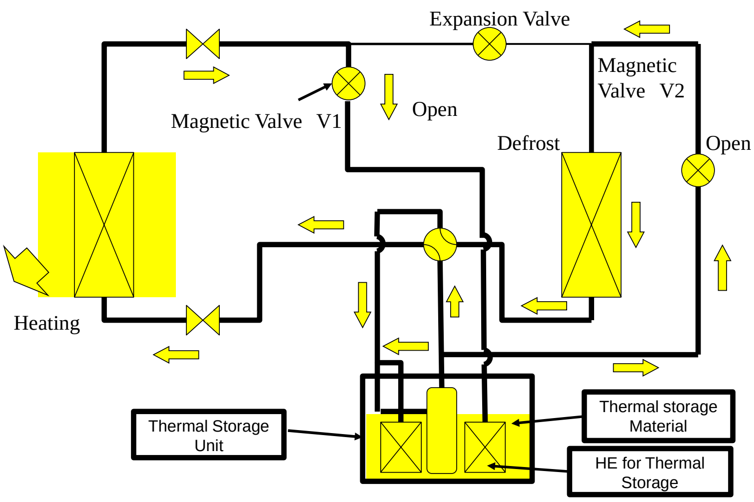


(a) Conventional defrost process (b) Defrost process by using recovered waste heat

Figure 6: Indoor Temperature Variation of the Defrosting Operation (**Nishiwaki F. (September 2013))**

The indoor temperature variation of the defrosting operation is shown in the Figure 6. The average temperature drop during operation is reduced to about 1 ℃ and when the comparison is made with the conventional system, this temperature drop is significantly improved . Figure 7 shows flow diagram of defrosting cycle using compressor waste heat.

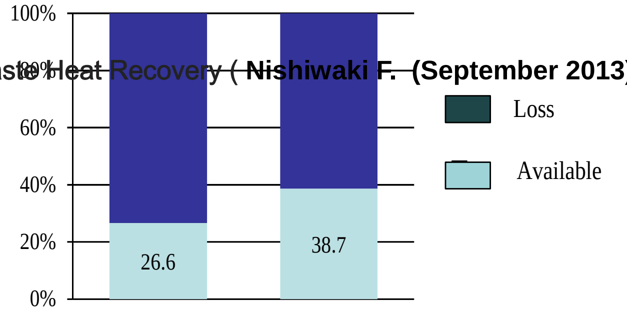
On the other hand, development to balance comfort and energy savings by utilizing the airflow sensor and control is in progress. This sensor suppresses unnecessary heating and cooling energy, both improvement of energy saving performance and keeping of the comfort can be realized.



Since the remarkable progress of airtight and high thermal insulation is achieved, part-load operation of a small capacity range near at set temperature tends to increased. The variable-cylinder systems which can be reduced to half of capacity using one cylinder operation have been developed.

Figure 7: Defrosting Cycle using Compressor Waste Heat Recovery (**Nishiwaki F. (September 2013))**

2.2 Industrial Sector



Larger industrial applications of the heat pump is important in order to enhance the energy saving and to reduce CO_2 emissions. In particular, the high temperature heat pump, hot water circulation heating, hot-air generator, and the steam production, is expected as to achieve significant energy savings in industry (Watanabe C. (September 2013).

It supplies the steam energy centres in automobile, machinery and food plant, is used for heating in the manufacturing process in many cases. Nowadays, overall efficiency of the steam infrastructure is very low.

As shown in the Figure 8, there is the example in which the overall efficiency improved from 22.6% to 38.7%. In addition, the research is reported the most of steam use temperature zone is from 55 ℃ to 80 ℃, less than 5kW often use steam heat load. The manufacturing process, use of an electric heater is popular so that the energy efficiency of primary energy conversion is low.
By replacing the heat pump an electric heater or steam infrastructure,
the significant energy savings can be
expected. It should be considered a heat recovery arrangement and distributed heat pump.

Figure 9 shows a flowchart of the heat pump to generate steam 165 ℃. After generating steam of 110 ℃ from heat pump unit, to increase the temperature and pressure of the steam in the steam compressor further. In order to increase the capacity per unit flow rate, this system is used a mixed refrigerant HFC134a based HFC245fa. A single stage compressor is used

Figure 8: Total Energy Efficiency of Steam Generation **(Watanabe C. (September 2013))**

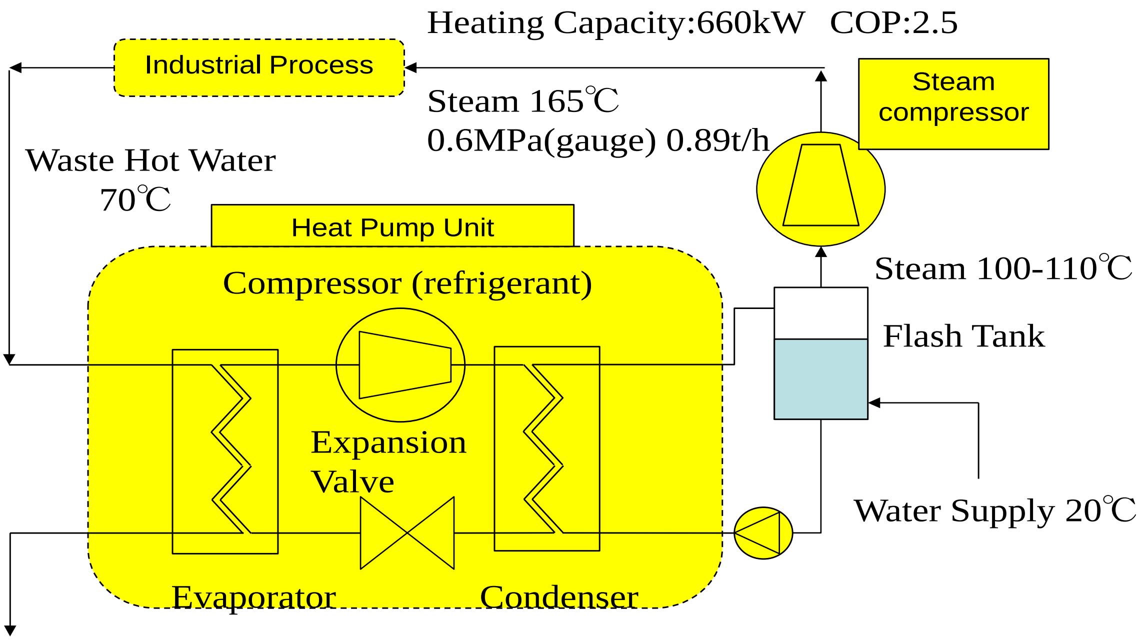


Figure 9: Flow Diagram of Heat Pump for 165℃ Steam Generator
Watanabe C. (September 2013)

It is an important issue which refrigerant should be used for high-temperature heat pump. Currently applied refrigerant, for example HFC-134a and HFC-245fa, has high critical temperature, it is suitable for heat pump to generate steam or hot water at temperature 60C or more, except for disadvantage of high GWP as shown in Table. Although the HFO refrigerants have a mild-flammability, because of its low GWP, these are attractive candidates of HFC134a and HFC-245fa alternatives.

Table 1 High-temperature heat pump refrigerant

Working-fluid	GWP	Critical temperature ℃	Critical Pressure MPa	Boiling Point℃
HFO-1234yf	4	94.7	3.382	-29.48
HFC-134a	1430	101.06	4.0593	-26.07
HFO-1234ze(E)	6	109.37	3.636	-18.96
HFO-1234ze(Z)	<10	153.7	3.97	9.76
HFC-245fa	1030	154.01	3.651	15.14

2.3 Recent Progress in Basic Research in JAPAN

This paper describes the development and research trends founded in recent JSRAE annual conference presentation papers. This annual conference started in 1997 and there were only 25 presentations at the first conference; however the number of presentations increased gradually. Because the organized committee system had started since 2002, the number of presentations dramatically increased to 165. And right now, over 10% of total society members constantly attend this conference.

Contents primarily picked up are as follows; (1) heat transfer with phase change, (2) all-aluminium heat exchanger, (3) the distribution of two-phase flow in multi-ports heat exchanger and (4) frost problems.

(1) Heat transfer with phase change

Kyusyu University, University of Tokyo and Waseda University Research Groups are very active in heat transfer with phase change. Their current interest focused on the new HFO refrigerants in a horizontal multi-port tube (to take into account the all-aluminium heat exchanger), including the effect of micro-channel geometry and lubricating oil on heat transfer and hydraulic characteristics. Koyama, Kyusyu University has been investigating on the pressure drop and flow boiling heat transfer characteristics of HFO 1234ze(E) in a horizontal multi-port tube with 0.85mm rectangular mini-channels. This experiment was carried out in mass velocity range of 100 to 400 kg/m^2 s and heat flux 10 to 20 kW/m^2. The frictional pressure drop on the adiabatic and boiling flow of HFO 1234ze(E) are measured and the effect of mass velocity and heat flux on the boiling heat transfer are classified. These measured data are compared to several previous correlations (Koyama S. et.al, (September 2012)).

Katsuta also has conducted research on the boiling and condensing heat transfer characteristics with using HF1234yf as refrigerant. Mass velocity range is little larger than that of Koyama and from 400 to 600 kg/m^2 s. In this experiment, the effects of

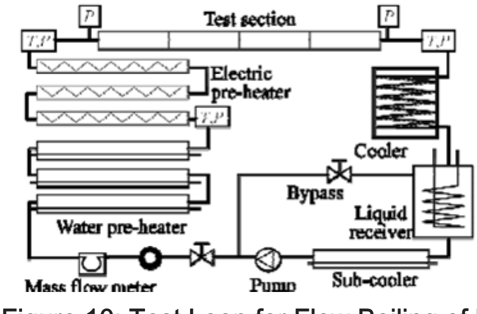


Figure 10: Test Loop for Flow Boiling of R1234ze(E) in a Multi-Port Tube Koyama S. et.al, (September 2012)

fabricated inner injection and oil contamination on heat transfer and hydraulic characteristics are also investigated. (Katsuta M. et.al, (September 2013))
With the development of all aluminium parallel flow type heat exchanger, research has been conducted on the optimal cross-sectional shape. Sumitomo Light Metal, LTD. reported that how affect micro channel tube inside geometry (Fig. 12) and louver fin pitch for all aluminium heat exchanger performance. The heat exchanger with using triangle shape micro channel tubes and narrow pitched fins showed higher performance. They also postulated that their heat exchanger showed a better corrosion resistance than that of the products in the market.

(2) All-aluminium heat exchanger

On the topics development of all-aluminium micro-channel heat exchanger for air-conditioner are reported by Daikin Industries. This heat exchanger has been used already in the car air conditioner for several decades. Recently, this is also adopted in the residential air conditioner because of the steep rise in copper prices and the reduction of the weight. Of course, heat exchanger of this type has high performance compared with a conventional fin and tube type heat exchanger due to its characteristic configuration. However, when this heat exchanger is applied to heat pump system, we should make an effort to solve several problems. One of the most difficult problems is to improve the drainage of condensed water when it is used as an evaporator. They proposed a new type fin referred as “Insertion waffle louver fin”(Figure 11). In addition, the specifications of the heat exchanger are optimized for heat pump system. As a result, this brand new heat exchanger can reduce the weight about one third and the amount of containing refrigerant about one fourth compared with a conventional fin and tube type heat exchanger (Kamada T. et.al (September 2012)).

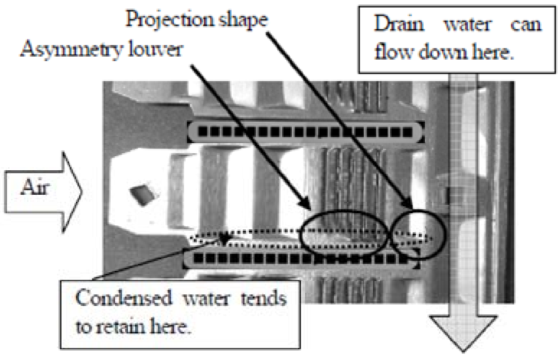


Figure 11: Improvement for Smooth Drainage on “Insertion Waffle Louver Fin” (**Kamada T. et.al (September 2012))**

On the other hand, Denso developed the new heat exchanger for automobile air conditioner so called ECS (ejector cycle system). The principle and mechanism of ejector effect as follows; the derived flow is decompressed at the nozzle to draw the refrigerant from the evaporator. This flow and intake flow are mixed, reducing the flow velocity and increasing the pressure, when it passes through the diffuser. This pressure lift can save compressor input power. Denso reported that ECS realizes a new CO_2 heat pump water heater with 30% heating capacity and COP approximately 20% higher than a conventional type. To save energy consumption and from the need of downsizing, they proposed the heat exchanger having ejector built-in in a tank as shown Figure 13 (Sato H.et.al, (September 2012)),.

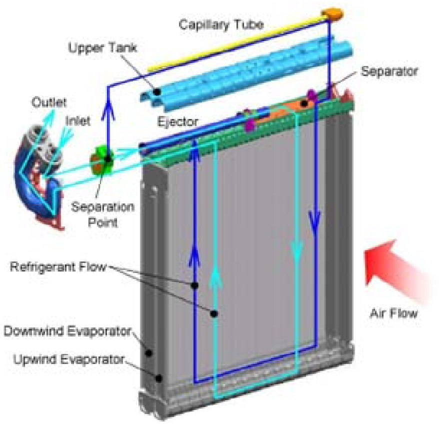


Fig.5 Structure and Refrigerant Paths of ECS Evaporator.

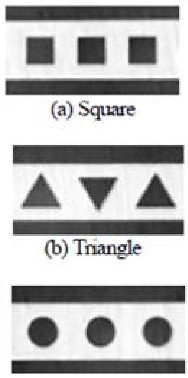


Figure 12: Cross Sectional View of Micro Channel Tube Mizuta Y. and Kakiyama S., (September 2012)

Figure 13: Structure and refrigerant Path of ECS Evaporator Sato H.et.al, (September 2012)

(3) The distribution of two-phase flow in multi-ports heat exchanger

Mal-distribution problem of two-phase flow in the evaporator is still unresolved and particularly complicated phenomena. Recently, studies that attempt to elucidate these phenomena have become very popular in Japan. Various approaches are available to quantify these phenomena; here will be featured following two interesting attempts. ①Direct observation of refrigerant behavior with using Newtron Radiography, ② Experimental research on the analogy between refrigerant and air-water two phase flow. Asano (Asano H., (September 2010)) provides the sample picture with using Neutron Radiography. This method is effective to visualize gas-liquid two-phase flows in a metallic vessel due to attenuation characteristics. He concluded that it is possible to visualize liquid behaviors and to measure 2D void fraction distribution quantitatively via image processing methods. Moreover, he made mention of 3D void fraction (Figure 14).

Hirota (Hirota M. et.al (September 2010)) made an effort using the similarity between the refrigerant flow and air-water flow. Their interests focused on the gas-liquid flow in multiple upward channels that simulate the evaporator in cooling unit. Their experimental flow loop and details test section are shown in Figure 15. They observed air-water two-phase flow under following four air and water velocity conditions at the header entrance: (ⅰ) superficial velocities equal to the refrigerant flow, (ⅱ) equal kinetic energy,(ⅲ) equal quality and mass flow rate, (ⅳ) equal Baker map parameters. They found that the condition of (ⅱ) at the header entrance could simulate the refrigerant flow closely. They made experiment on air water two-phase flow distribution ratio to branches under two conditions (ⅱ) and (ⅳ).

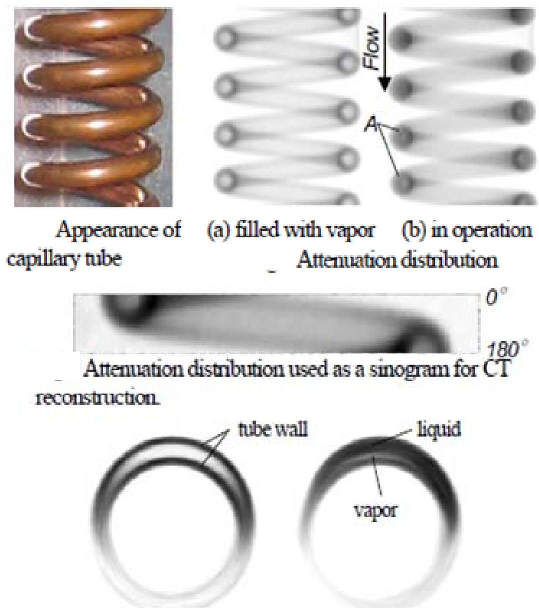


Figure14: Sample Picture of Flow Visualization by Neutron Radiography Asano H., (September 2010)

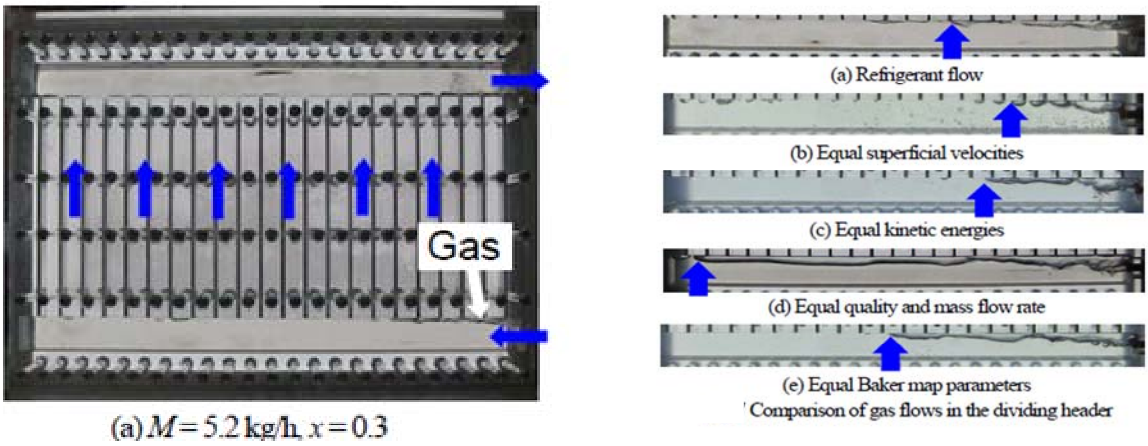


Figure 15: Two-phase Flow Distribution in Multi-pass Channels Comparison of Refrigerant Flow and Air-water Flow Hirota M. et.al (September 2010)

(4) Frost problems

Frost formation phenomenon research is also very popular in Japan. Elucidation on this phenomenon is important not only because it contribute to energy conservation, but also does to the development of heat pump for cold climate regions. Ongoing researches are as follows: To establish the fundamental frost growth model, possibility of frost control with fine surface processing and the development of heat pump system without frost. Especially featured on the second and third category, Ohkubo has been successful in achieving an area frost crystals by applying the cooling surface with fine processing surface of several hundred microns.

Central Institute of Electric Power Industry proposed frost-free air source heat pump water heater system with integrated solid desiccant, in which frosting can be retarded by dehumidifying air before entering the evaporator. They suggested various systems and recommended air recirculating desiccant type system as shown in Figure 17.The experimental results show that the COP in the range of 3.3 to 3.8, this is 10 to 20% higher than that of conventional system.

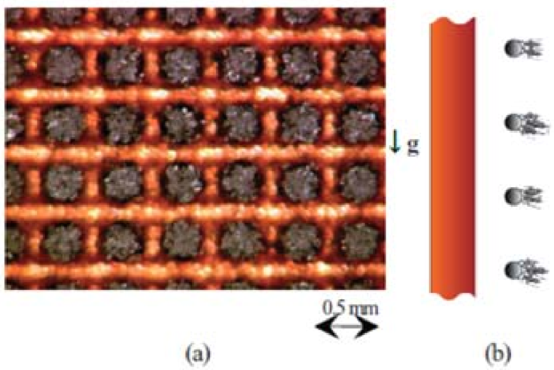


Figure 16: Control of Frost Cristal Growth

Ohkubo H. and Matsushita S (September 2013)

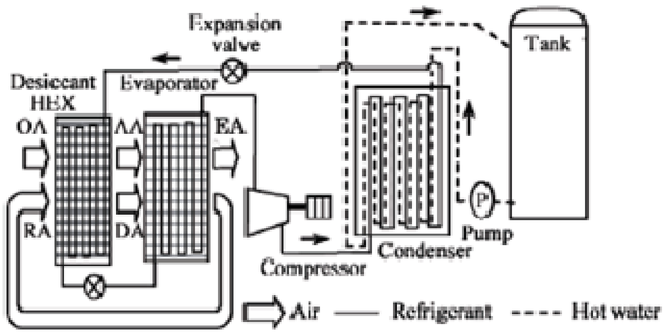


Figure 17: Air-recirculating Desiccant HEX Type Frost-free ASHPWH System

Saikawa M. et. al,(September 2013)

3 CONCLUSION

In this paper, recent progress on the development of the heat pump research in Japan is described and discussed. Heat pump is a technique which can be a trump card of CO_2 emission reduction and energy conservation. It should be noted that the future development efforts and more research is needed, but the seedlings of technology breakthrough is expected to realize in basic research.

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