STUDY ON THE HYBRID WATER HEATER WITH ADSORPTION HEAT PUMP

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List

Chapter 1　Introduction

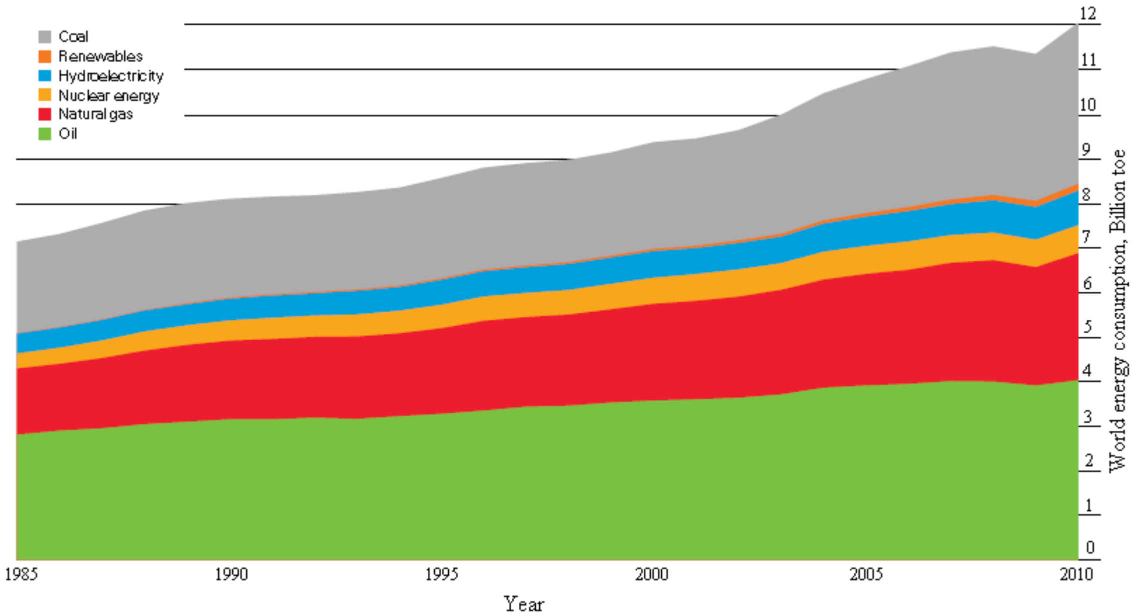
1 General background information

1.1 Energy situation and environment problems

1.1.1 World's energy situation

Energy is the vital force powering business, manufacturing, and the transportation of goods and services to serve world economies. Energy supply and demand play increasingly vital roles in national security and economic output of a nation.

In daily life, clothing, food and housing are the most basic necessities of life. More heat energy for hot water and cooking, more electrical energy for lighting and air conditioning, and more energy for transport and movement have been consumed with the growth of population. At the global level, the rapid population growth means that the production and consumption of energy will rise. Energy consumptions by fuel type are shown in Figure 1 (BP Statistical Review of World Energy, 2011).



Source: BP Statistical Review of World Energy, 2011

Figure 1 Energy consumptions by fuel type

According to data shows, energy consumption soared by more than 5% in 2010, after the decrease of 2009. Amid growing energy demand worldwide, particularly in Asia, where it is expected to increase against a background of rapid population growth, the world energy supply-demand situation is likely to tighten in the future. In the future it is expected that energy demand will increase based on economic growth of emerging market countries like China, India, and the Middle East. Furthermore, the same review is made by Morita and Matuoka (2002). So far, the majority of energy consumption is still coal, oil and natural gas. The reserves of these fossil fuels are distributed unevenly throughout the world. And more importantly, Coal, oil and natural gas are not infinite resources. World proved reserves of coal in 2010 were sufficient to meet 118 years of global production - by far the largest reserves-to-production ratio of any fossil fuel. World proved oil reserves in 2010 were sufficient to meet 46.2 years of global production. World natural gas proved reserves in 2010 were sufficient to meet 58.6 years of global production.

If the current energy demand increases substantially, depletion of energy resources will accelerate at a geometric rate. In other words, energy supply will become the only real issue in our society.

1.1.2 Global Environmental Problems

In recent years, with the overpopulation, economic growth and living standard improvement, the increase of energy consumption is also increasingly obvious. Meanwhile, environmental problems become more outstanding because of lots of waste in the process of energy consumption. Relationships among Environment, Economy and Energy are shown by Figure 2. They have closely relations. In order to maintain economic growth, lots of energy and resources will consume, and along with a great deal of energy consumption, the deterioration of the environment is caused. Balance development among economy, environment and energy is very important for the purpose of making the human survive on earth.

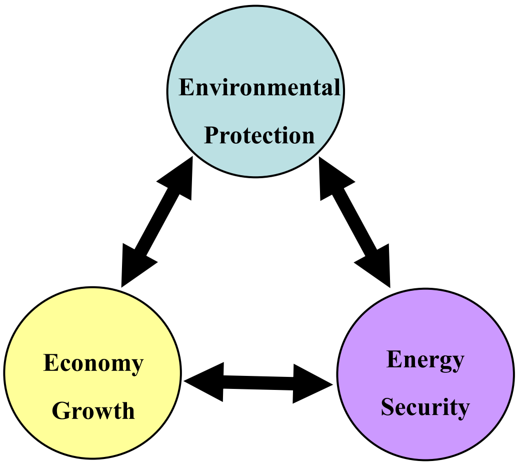
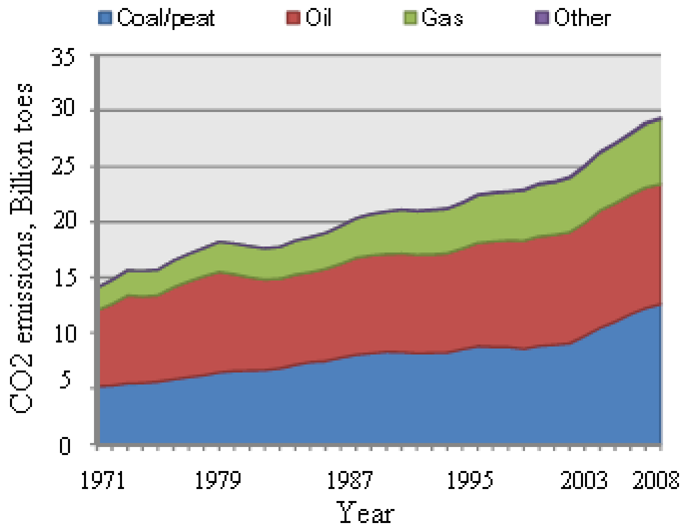


Figure 2 Relationships among Environment, Economy and Energy

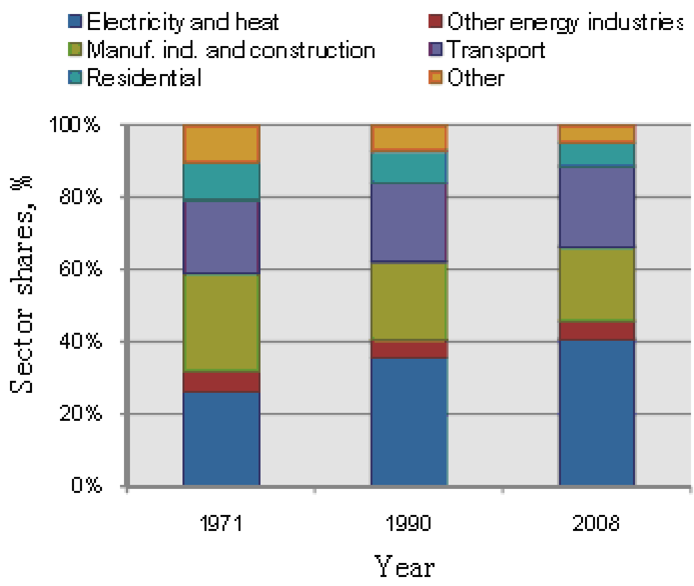
It is now a scientifically accepted fact that global warming is indeed occurring and that it will have long-ranging impacts on the earth's ecosystems (IPCC Fourth Assessment Report, 2007; Anthony et al., 2008; Arnold et al., 2009 and Abbasi et al., 2010). There is no longer any significant disagreement on the existence of global warming; if there is disagreement, it is on the extent of harm global warming will cause. The use of energy represents by far the largest source of emissions among the many human activities that produce greenhouse gases. Use of fossil fuels is the principal cause of global warming. With the combustion of fossil fuels all amounts of carbon dioxide, oxynitride, sulfur dioxide and so on are emitted, the former of them cause global warming, the latter two are the main cause of acid rain, and the seriousness of environmental damage which are caused by these pollutants brought from high energy consumption lasted half a century is well known. CO_2 emissions therefore are the most important cause of global warming. And unless the emissions to atmosphere of CO_2 and other greenhouse gases are drastically reduced, global warming will progressively increase and lead the world to extinction. Growing world energy demand from fossil fuels plays a key role in the upward trend in CO_2 emissions (Figure 3). Since 1971, annual CO_2 emissions from fuel combustion dramatically increased from near 15 to 29 billion toes in 2008.



Source: CO_2 Emissions from Fuel Combustion, 2010

Figure 3 CO_2 emissions by fuel

In recent years, carbon dioxide as greenhouse gas contributes to global warming, and global temperature rise causes the problem of sea surface rise and the drought, etc. Therefore, the energy problem has been shifted from fossil resources exhaustion to global warming. In everyday life, the energy consumption which consists of thermal energy for hot water and cooking, electrical energy for lighting and air conditioning, energy for movement and transportation and so on can be imagined easily, but maintaining the current level of life is difficult without the benefits of energy. CO_2 emissions by sector are shown in Figure 4. Figure 4 shows that generation of electricity and heat was by far the largest producer of CO_2 emissions and was responsible for 41% of the world CO_2 emissions in 2008. In the meantime, a large amount of heat energy, which accounts for more than 60% of primary energy, is not used effectively and discharged into the atmosphere as waste heat. In particular, approximately 80% of the waste heat is below 100°C (Hirota et al., 2008). Due to the discharge of waste heat, greenhouse gases such as carbon dioxide contribute to global warming. The future development of the emissions intensity of this sector depends strongly on the fuels used to generate the electricity and on the share of non-emitting sources, such as renewable energy sources, and so on.



Source: CO_2 Emissions from Fuel Combustion, 2010

Figure 4 CO_2 emissions by sector

In view of the actuality of global warming at present, for two big problems of energy and environment, to construct positively new energy conservation and resource recycling society is strongly required for the human.

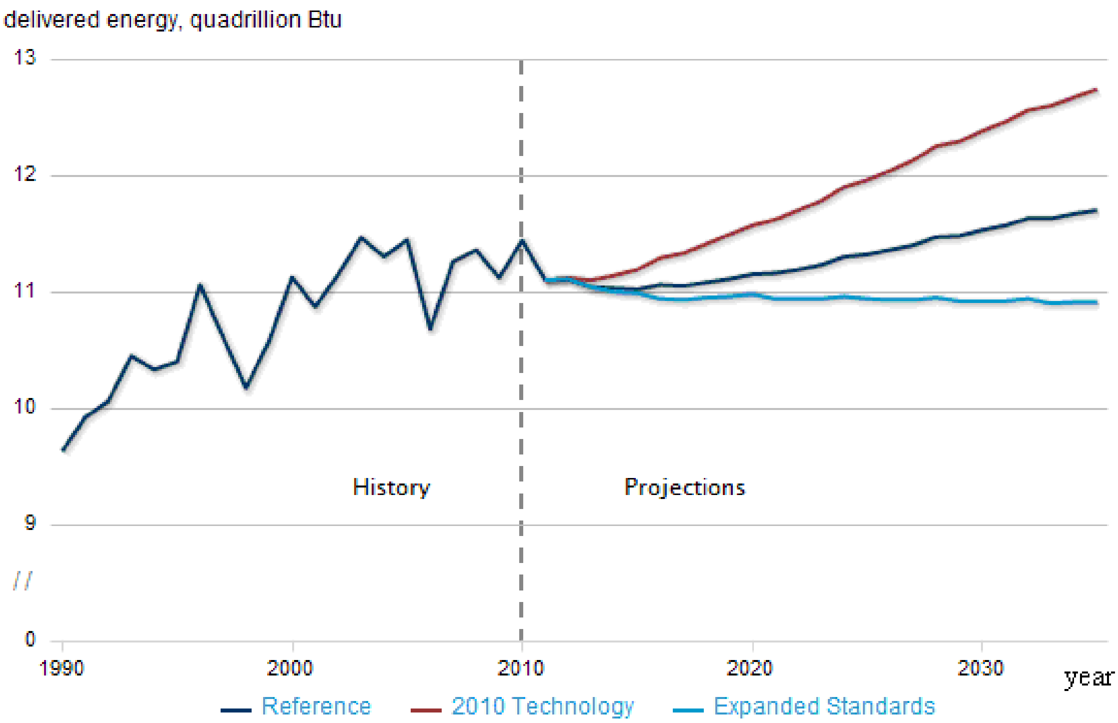
1.2 Efficient energy use

Energy efficiency and renewable energy are said to be the “twin pillars” of a sustainable energy policy. Both strategies must be developed concurrently in order to stabilize and reduce carbon dioxide emissions (American Council for an Energy-Efficient Economy). Efficient energy use is essential to slowing the energy demand growth so that rising clean energy supplies can make deep cuts in fossil fuel use. If energy use grows too rapidly, renewable energy development will chase a receding target. Likewise, unless clean energy supplies come online rapidly, slowing demand growth will only begin to reduce total carbon emissions; a reduction in the carbon content of energy sources is also needed. A sustainable energy economy thus requires major commitments to both efficiency and renewable energy sources. In many countries energy efficiency is also seen to have a national security benefit because it can be used to reduce the level of energy imports from foreign countries and may slow down the rate at which domestic energy resources are depleted (The Twin Pillars of Sustainable Energy, 2008). The Vienna Climate Change Talks 2007 Report (United nations, 2007), under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), clearly shows "that energy efficiency can achieve real emission reductions at low cost." According to the International Energy Agency, improved energy efficiency in buildings, industrial processes and transportation could reduce the world's energy needs in 2050 by one third, and help control global emissions of greenhouse gases(Hebden, 2010).

2 Hot water demand and current status of water heaters

2.1 Hot water demand

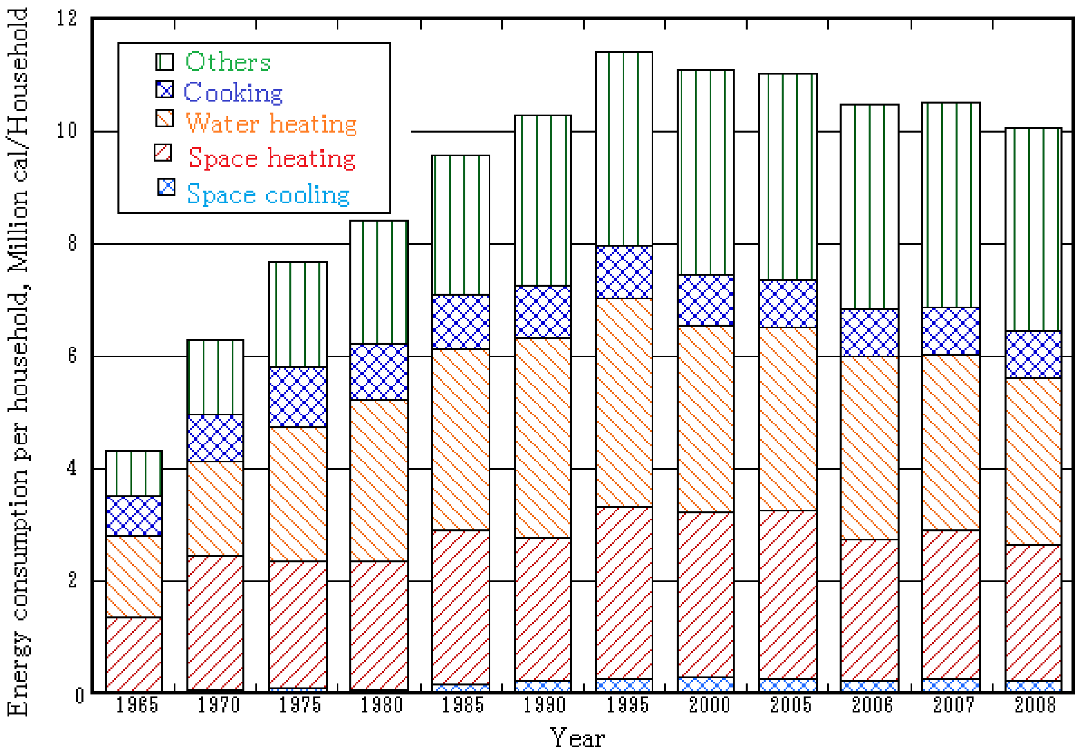
The data from U.S. energy information administration (U.S. Energy Information Administration, 2011) show that the increase of energy uses in the residential sector is more distinct. Energy use in the residential sector is shown in Figure 5. Heating and cooling in the residential, industrial, and commercial sectors constitute around 40~50% of global final energy demands (Seyboth et al., 2007).



Source: Today in Energy, 2011

Figure 5 Energy use in the residential sector

For a household, when the need to conserve energy is considered, the focus should be mainly on water heating and space heating processes. (EDMC Handbook of Energy & Economic Statistics, 2009) Energy consumption per household in the residential sector is shown in Figure 6. In Figure 6, water heating and space heating are the major uses of energy. And water heating is a sizable use of energy. Water heating is a thermodynamic process using an energy source to heat water above its initial temperature. Typical domestic uses of hot water are for shower, bath, and so on. The data from U.S. department of energy shows that hot water use in bath account for 41.8% of total hot water use (U.S. department of energy, 2010).



Source: EDMC Handbook of Energy and Economic Statistics, 2009

Figure 6 Energy consumptions per household in residential sector

2.2 Various water heaters

Domestically, water is traditionally heated in vessels known such as pots. These metal vessels heat a batch of water but do not produce a continual supply of heated water at preset temperature. The temperature will vary based on the consumption rate of hot water, use more and the water becomes cooler. Appliances for providing a more-or-less constant supply of hot water are variously known as water heaters, boilers, heat exchanges, and so on. According to driving energy source, water heater types include: gas or electric conventional storage tanks, solar, heat pump, and so on.

Gas-fired conventional tank heat water is shaped like an elongated torus or doughnut. The flue which runs from the top of the combustion chamber to the top of the tank forms the hole of the doughnut. This portion of the flue acts as a heat exchanger by transferring is heated by the flue as well as by the heat applied by the burner to the bottom of the tank. It is faster and has lower annual and projected lifetime costs. One reason is that on a per-Btu basis, natural gas and propane are usually much less expensive than electricity. Another reason is that tank water heaters of 100 gallons or less are mass produced and are less expensive than most other types of water heaters. In some instances, other water heater types—such as electric heaters—are a better choice. But if gas is available and the water heater is in a location where a gas vent can be installed, a gas-fired conventional tank water heater will likely be the least expensive to own and operate. However, it has no contribution to reduce CO_2 emission because it utilizes the combustion heat of gas. The thermal efficiency of a conventional gas-boiler water heater is 85% by the high-rank heating valve base, and the latent heat of the exhaust gas in the combustion process is not recovered completely, so more than energy added to the system cannot be obtained (Liu et al., 2010).

The typical electric water heater is wired to a 220v circuit. (Sowmy et al., 2008)This equipment raises the water temperature in a tank using the heat generated by electrical-resistance heating elements-usually two, one in the middle of the tank and one at the bottom. Because electric resistance heating converts nearly 100% of the energy in the electricity to heat, there are electric heat pumps on the market that use electricity to extract heat from the outside air or the ground for heating. However, most electricity is produced from oil, gas, or coal generators that convert only about 30% of the fuel's energy into electricity. Because of electricity generation and transmission losses, electric heat is often more expensive than heat produced in the home using combustion appliances, such as gas, oil, and propane furnaces, and the electricity used still incurs large CO_2 emissions at the power station. Energy conservation in household water heating is increasingly important for reducing an amount of CO_2 emission (Goto et al., 2011), however, the disadvantage of electrical water heaters is their excessive consumption of electrical energy to ensure adequate hot water temperature (Abrams, 1998; Perlman et al., 1988 and Colliver et al., 1988).

Latent heat thermal energy storage is one of the most efficient ways to store thermal energy for heating water by energy received from sun. Solar water heating system proves to be an effective technology for converting solar energy into thermal energy. The efficiency of solar thermal conversion is around 70% when compared to solar electrical direct conversion system which has an efficiency of only 17% (Jaisankar et al., 2011). Solar thermal utilization, especially the application of solar water heater technology, has developed rapidly in recent decades (Han et al., 2010 and Aguilar et al., 2005). Many researchers have focused on solar-assisted heat pump water heaters (Huang et al., 2007; Huang et al., 2005; Li et al., 2007a and 2007b). Solar water heater systems are designed to deliver the optimum amount of hot water for most of the year. However, in winter there sometimes may not be sufficient solar heat gain to deliver sufficient hot water. Because solar water heater capacity is dependent upon weather patterns and seasons some solar heaters use antifreeze in winters. In this case a gas or electric booster is normally used to heat the water. In addition, solar water heater installation and equipment costs can be higher when compared to other types, but their operating costs are lower (U.S. DOE, 1995).

Instead of creating heat directly, heat pump water heaters transfer heat. Many experimental and theoretical studies on the application of a heat pump in a water heater system have been conducted. A representative heat pump water heater operates on an electrically driven vapor-compression cycle and pumps energy from its surroundings to water in a storage tank, thus raising the temperature of the water, such as air-source heat pump water heaters, ground-source heat pump water heaters, and so on.

Air-source heat pump water heaters heat water by removing heat from ambient air. Therefore, they can offer a space cooling benefit, since as indoor air is used to heat the water, heat pump water heaters vent cool air into the space. However, it requires warm ambient temperatures and a large heat pump or storage tank to provide a constant flow of hot water (Bodzin, 1997). Most of these heaters have a back up heating elements to heat water during cold periods. They heat water more slowly than other types of heaters, and are more expensive to install, but have a shorter pay back period due to increased savings provided hot water energy use is relatively high.

Most geothermal heat pump water heaters can make hot water at any time of the year because heat is drawn from the earth, which is warmer than air temperature in winter. Even in severe weather this type of heater is about 30% more efficient than the most efficient air source heat pump (DOE, 2004). They are more efficient because they are less reliant on electric resistance heaters to supplement heating capacity (Martin and Gettings, 1998). However, due to the ground loops necessary for these types of heat pumps to function, property alterations and high initial costs have made them less practical for existing homes (Martin and Gettings, 1998 and OEE, 2003).

Comparing with gas or electric conventional storage tank water heaters and solar water heaters, adsorption heat pump water heaters have attracted considerable attention with the improvement of energy saving and environmental protection requirements. They do not emit greenhouse gases (Wang and Zhu, 2002, Wang et al., 2005a, Wang et al., 2005b); the researches on the model of adsorption heat pump were carried out, for example by Chahbani et al. (2004) and Gui et al. (2002), and the researches on the adsorbents has greatly attracted many interests (Huang et al., 2010, Okunev et al., 2008). From the practical application point of view, the major advantage of the adsorption heat pump is that it does not need maintenance for long periods since it does not contain any moving parts or only contains a few simple moving parts (Demir et al., 2008) in advanced systems.

However, the adsorption heat pump system has larger volume and weight compared with traditional mechanical heat pump system (Meunier, 2002, Wongsuwan et al., 2001). The solid adsorbent is almost multi-porous media, has large BET (Brunauer-Emmett-Teller) and low thermal conductivity. Adsorption/desorption time is long due to the low thermal conductivity, the coefficient of performance (COP) of per unit mass of adsorbent is small. Therefore, big adsorbent bed is necessary in order to obtain high output in a shorter cycle time. Eventually the size of an adsorption heat pump is large. In addition, the pipes and valves are required not only between the evaporator and the adsorber but also between the condenser and the desorber which is one of factor reasons why the volume of the conventional adsorption heat pump is large.

3 Adsorption heat pump water heaters

3.1 Adsorption heat pumps

Due to the limitation of conventional energy sources, adsorption heat pumps have considerably sparked attentions in recent years (Demir et al., 2008). A basic adsorption heat pump cycle consists of four main parts: an adsorber, which is a container filled with an adsorbent (such as zeolite, active carbon, silica gel, etc.); a condenser; an evaporator; and an expansion valve.(Figure 7) Basically, adsorption heat pump operates by cycling adsorbate between adsorber, condenser, and evaporator (Ulku, 1986; Ulku, 1987 and Meunier, 2002).

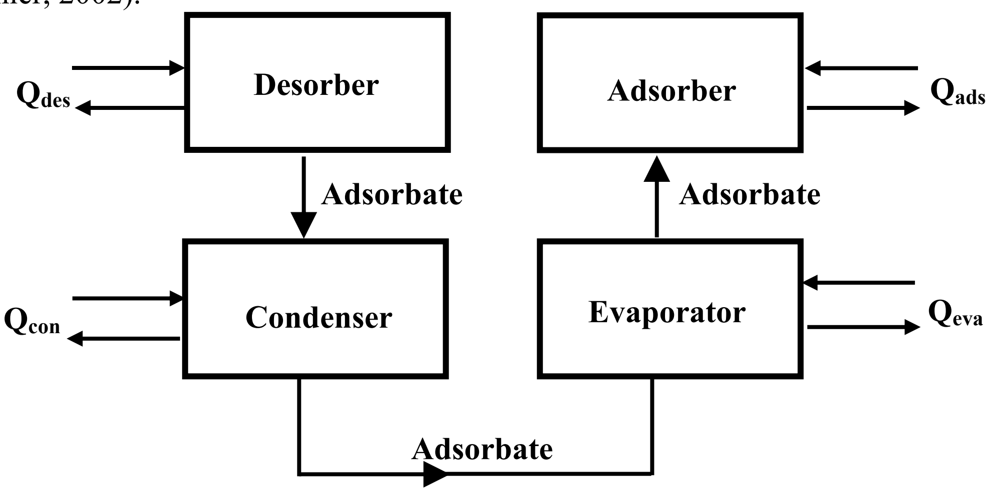


Figure 7 Structure schematic diagram of Adsorption heat pumps

In the adsorption heat pump cycle, adsorption phenomena play the same role of mechanical power, so that the working fluid can be circulated in the cycle without any mechanical power. The adsorption heat pump cycle works between three temperatures levels. The adsorption heat pump cycle can be considered as two separate cycles. The first cycle is a heat pump in which the working fluid is vaporized in evaporator by taking heat (Q_{eva}) from the low-level temperature source and releasing (Q_{ads}) heat to the first intermediate temperature source. This cycle represents adsorption process. The second cycle is a heat engine, which receives heat (Q_{des}) from the high-temperature source and releases heat (Q_{con}) to the second intermediate temperature source. The transfer of heat (Q_{con}) to the second intermediate temperature source occurs during the condensation of working fluid in condenser. This cycle represents desorption process. It is assumed that the work obtained in the heat engine is employed to run the heat pump. The temperatures of intermediate sources (T_{con} and T_{ads}) are generally close to each other. Thus, three temperature levels can be considered for an adsorption heat pump and the ideal coefficient of performance of an adsorption heat pump cycle can be obtained as follows. (Pons et al., 2000; Kodama et al., 2000 and Spinner et al., 2001)

For heating:

$$COP_{heating} = \frac{Q_{con}}{Q_{des}} = 1 + \frac{1 - T_{con}/T_{des}}{T_{con}/T_{eva} - 1} \quad (1)$$

For cooling:

$$COP_{cooling} = \frac{Q_{eva}}{Q_{des}} = \frac{1 - T_{con}/T_{des}}{T_{con}/T_{eva} - 1} \quad (2)$$

The important advantages of the adsorption heat pumps can be described as follows:

_ can operate with thermal driving energy sources such as waste heat, solar, and geothermal energies, etc.;

_ can work with low temperature driving energy sources;

_ do not require moving parts for circulation of working fluid;

_ have long life time;

_ operate without noise and vibration;

_ have simple principle of working;

_ do not require frequent maintenance;

_ are environmental friendly since do not contain any hazardous materials for environment; and

_ can be employed as thermal energy storage device.

The disadvantages of the adsorption heat pump systems are as follows:

_ have low COP values;

_ intermittently working principles;

_ require high technology and special designs to maintain high vacuum; and

_have large volume and weight relative to traditional mechanical heat pump systems (Meunier, 2002; Wongsuwan et al., 2001; Ulku et al., 1989) .

In the design of the adsorber, good heat transfer is necessary because it can assure the adsorber adsorb rapidly the desorption heat in the desorption process and discharge timely the adsorption heat in the adsorption process. Enhancement of heat transfer in the adsorber can be considered from two aspects that are enhancement of heat transfer of the adsorbent and improvement of adsorber structure (Eun et al., 2000a, 2000b). For the former, it means study of the complex adsorbents with high heat transfer performance. For the latter, it means using the heat exchanger with good heat transfer; Good mass transfer is necessary, too. If diffusion flow of the adsorbates is unblocked, it can assure the diffusion speed in the adsorption or desorption process and shorten cycle time and improve heating output of the adsorbates; the adsorber should have small specific heat and then reduce the loss of sensible heat in the heating and cooling process. Above three accepts effect each other and should be considered synthetically. But in real adsorption heat pump, the adsorbents, the adsorbates, operation process and so on are different with the ideal adsorption heat pump, and the above is target and research direction in design. The performance of the real adsorption heat pump is made be close to that of the ideal one. So in the design of adsorption heat pumps the following should be considered:

Determine the work pair according to the temperature need by the user and usable drive heat source;

Determine the cycle, the flow, and if or not use regenerative apparatus according to the temperature and flow amount need by the user.

3.2 Application of adsorption heat pumps

Heat transformation with sorption systems has received increased attention in recent years. The developments in adsorption heat pump technology have been prompted mainly in two application areas. One area of application is adsorption chiller for cooling purposes. The second area of application is adsorption heat pump for heating purposes.

Because the adsorption heat pump operates on such a simple process, the downtime is minimal and maintenance is kept to an absolute minimum too. Simplicity of operation makes the adsorption heat pump extremely reliable and safe, with low operating costs. There are no hazardous substances such as lithium bromide or ammonia within the adsorption heat pump. Instead, it uses a conventional substance, such as silica gel plus water, making the whole process highly environmentally friendly. The adsorption heat pump can operate efficiently with a lower heat source, thereby delivering cooling and heating solutions to a wider range of applications. It also has the ability to operate within a wide range of temperatures.

Adsorption chillers are driven by waste heat, and so the improvement of energy efficiency and adaptation to low temperature waste heat use attract the attention of the researchers. In order to obtain good heat and mass transfer, Glaznev and Aristov (2010) studied the effect of adsorbent grain size on the water sorption dynamics. And Gong et al. (2011) studied a new generation adsorption chiller using composite adsorbent. This paper presents a novel adsorption chiller using composite adsorbent "employing lithium chloride in silica gel" as adsorbent and water as adsorbate. A new type adsorbent bed is used to accommodate the composite adsorbent. The mass recovery between two adsorbent beds usually results in the adsorbate unbalance. However, the novel adsorption chiller designed by Gong et al. is used to solve the problem.

Compared with adsorption chillers, adsorption heat pumps for water heating have been studied by few researchers. Literature survey has shown that some studies on adsorption heat pump have been performed in order to increase the COP values and provide a continuous heating process. The continuity of heating processes is generally provided by increasing the number of adsorbers. The increase of COP is obtained by recovering and utilizing heat, which is transferred during isosteric cooling and isobaric adsorption in another adsorption cycle. This increases the COP of cycle since the amount of external heat supplied to the cycle is reduced (Meunier, 2002; Dous et al., 1989). There are the patents of adsorption heat pumps for heating, such as US2002005271 (2002) and US5518069 (1996). In these researches, the problem to be solved is to make available an adsorption device that is suitable both for the heating and, as an alternative, for the cooling especially of gas streams. An adsorption device contains an adsorbent inside an adsorbent container, a valve, and the liquid working fluid inside an evaporator. Via an adsorbent heat exchanger, heat is added to the adsorbent during the regeneration phase and removed from the adsorbent during the adsorption phase. Via a working fluid heat exchanger, heat of evaporation is added to the working fluid during the adsorption phase and heat of liquefaction is removed during the regeneration phase. Adsorption heat pump systems with large capacity are being installed every once in a while, but the small-scale domestic market is not yet really covered with appropriate technology (Ziegler, 1999).

3.3 Adsorption heat pump coupled with other equipments

Now coupling technology is gradually used in adsorption heat pump. There are adsorbent coupling and equipment coupling, and so on.

Here adsorbent coupling consists of composite adsorbent using in the same stage adsorption bed and composite adsorbent using in two or more stage adsorption beds. For the former, there are the researches such as composite adsorbent $CaCl_2$ and expanded graphite (Li et al., 2011; Li et al., 2009), Composite adsorbent $CaCl_2$/SBA-15 (Glaznev et al., 2011), and so on. For the latter, two or more different adsorption pairs are respectively used in two or more adsorption beds. Because different adsorption pairs have various adsorption capacities in their various operation temperatures, medium water can get more adsorption heat through two or more adsorption beds.

In addition, He et al. (2010) studied experimental performance of a heat pump water heater system coupled with a dehumidifier. The coupled system is operated in three modes: water heating, water heating + dehumidification and dehumidification. The trends of the parameters with time are obtained in each mode. The research indicated that the performance of the coupled system is improved. However, when the adsorption heat pump is to be used in conjunction with other equipments, it is more obvious that adsorption heat pumps have a bigger unit volume. Therefore, the downsizing design of adsorption heat pump is important after achieving a successful coupled system.

4 Summaries

In this study, from a view point of environment protection and energy efficiency, the adsorption heat pump system coupled with gas boiler is designed. Moreover, the research of adsorption heat pump system mainly focuses on its downsizing and high output.

The following is the overview of the chapters:

In Chapter 2, a hybrid heat pump water heater which consists of an adsorption heat pump and a gas boiler are proposed. While describing the principle of the hybrid heat pump water heater, with the purpose of developing the high performance adsorption heat pump, flat-tube heat exchangers with copper corrugated fins coated with functional adsorbent material-zeolite (AQSOA FAM-Z02, Mitsubishi Plastics) are adopted as the adsorbers. In addition, the performances of the adsorption heat pump and water heater are examined based on several parameters such as T_{AHP_out}, Q_{eva}, Q_{AHP}, Q_{WH}, COP and so on. And on the basis of the experimental results, a numerical analysis is presented by process simulation, and then the COP of the system is examined.

In Chapter 3, the development of an all-in-one type adsorption heat pump is based on the hybrid heat pump water heater as above. In this chapter the design goal is high performance and downsizing adsorption heat pump. Now the adsorption heat pumps in the market have big volume. For this subject, the connection parts between adsorber and evaporator/condenser are not used, that is to say, adsorber and evaporator/condenser are put into the same container, and through this method the problem of big volume is solved. A downsizing all-in-one type adsorption heat pump is designed. According to this design the energy loss caused by pressure loss should be reduced to zero because of the uniform pressure in same container, and the performance of this adsorption heat pump will be improved. In order to prove its performance, an all-in-one type adsorption heat pump sample is made and tested with the experiments under different conditions.

Finally, the results obtained by this research are summarized in Chapter 4.

Chapter 2 A Novel Hybrid Adsorption Heat Pump Water Heater

1 Proposals in a novel hybrid adsorption heat pump water heater

Some researchers had once studied on a hybrid water heater, which consists of a heat pump and a gas boiler, for example Atsuya (2005). They had studied this hybrid heat pump water heater with the adsorption cycle and a gas-fired water heater for commercial use. Since a hybrid heat pump water heater consists of an adsorption heat pump and a gas boiler, it combines their respective advantages. The water heater may have higher energy efficiency and COP than an adsorption heat pump itself or a gas boiler itself at low ambient temperature. Moreover, the hybrid water heater can maintain a constant output by changing the respective outputs of the adsorption heat pumps and gas boilers according to the ambient temperature, and it is necessary to ensure that the system operates economically and effectively. And then Tajima et al. have applied for two patents (P2007-92614, P2007-92632), and they have been disclosed (P2008-249274A, P2008-249276A). However, they just mention that the hybrid water heater consists of adsorption heat pump and gas boiler. We can't find any of the detailed information about adsorption heat pump, such as adsorbent and heat exchanger. And large scale and hot water demand of end users are the characteristics of the water heater for commercial use. On the contrary, the water heater for domestic use must is downsizing. So we studied a hybrid heat pump water heater for domestic use which consists of an adsorption heat pump and a gas boiler. It combines their respective advantages. In other words, a hybrid heat pump water heater can maintain a constant output by changing the respective outputs of the adsorption heat pumps and gas boilers according to ambient temperature, and it is necessary to ensure that the system operates economically and effectively.

Our proposed heater absorbs combustion heat in a gas boiler and condensation and adsorption heat in an adsorption heat pump. That is to say, in order to keep the hot water supply in constant temperature for the users, we can make the output of a gas boiler increase while adsorption heat pumps have the lower output in the coldest day of winter; and we can make the output of a gas boiler decrease while adsorption heat pumps have the higher output in the hottest day of summer. Thus, the hybrid water heater can absorb enough heat from gas boiler and adsorption heat pump, and achieve high energy efficiency. In addition, Flat-tube heat exchangers with copper corrugated fins coated with functional adsorbent material-zeolite (AQSOA FAM-Z02, Mitsubishi Plastics) are adopted as the adsorbers. FAM-02 for adsorption heat pumps is studied by Shimooka et al. (2006). AQSOA FAM-Z02 is the molecular sieve with pore size of 0.38nm, particle size of 5-2000μm. The water vapour adsorption isotherm of AQSOA FAM-Z02 is S-shaped and highly dependent on temperature (Kakiuchi et al., 2005). Adsorption heat (H_2O, 25℃) of AQSOA FAM-Z02 is 58.3kJ/mol. AQSOA FAM-Z02 can release the adsorbates when it is heated at 85°C. However, the zeolite in the zeolite heating appliance made by the Vaillant Group in Germany must be heated under higher temperature of 150°C. About this, the water heater studied in the paper is more excellent than the zeolite heating appliance of Vaillant. Furthermore, the adsorption speed of AQSOA FAM-Z02 in the relative pressure range of adsorption heat pumps is fast.(Chemicals Division et al., 2009) AQSOA FAM-Z02 is suitable for an adsorption heat pump because of its great adsorption capacity and durability in the operation range of an adsorption heat pump.

The schematic diagram of the hybrid adsorption heat pump water heater is shown in Figure 1.

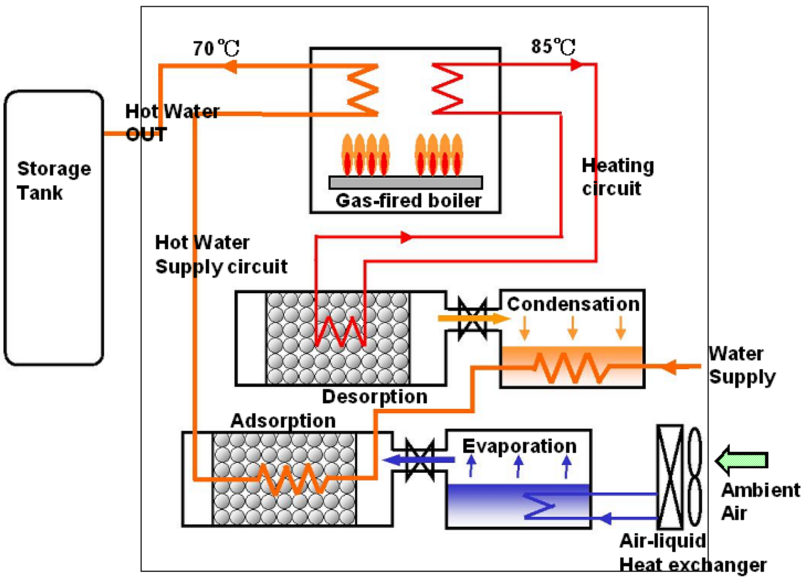


Figure 1 Schematic diagram of the hybrid adsorption heat pump water heater

Figure 1 shows that the hybrid adsorption heat pump water heater comprises an adsorption heat pump, a gas boiler, an air-liquid heat exchanger and a storage tank. The water supply will absorb the condensation heat in the condenser and the adsorption heat in the adsorber, and then will be further heated in the gas-fired boiler. Finally, the hot water of 70°C will be stored in a storage tank. At the same time, the latent heat used in the evaporation of adsorbates in an evaporator originates from the ambient air by an air-liquid heat exchanger. And the desorption heat used in the regeneration of adsorbents in a desorber originates from the high-temperature water of 85°C.

2 Basic operation of the hybrid water heater

The respective advantages of an adsorption heat pump and a gas boiler are considered, and then a hybrid water heater that combines an adsorption heat pump and gas boiler is designed.

2.1 Operation of the adsorption heat pump

The flowchart of the adsorption heat pump is shown in Figure 2 on the basis of the concept chart of the adsorption heat pump (Figure 3). The adsorption heat pump includes alternating adsorption/evaporation and desorption/condensation processes.

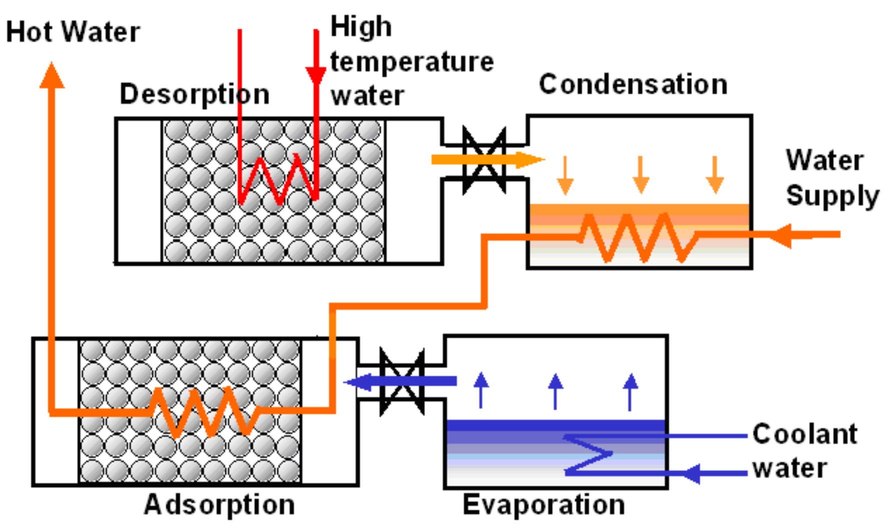


Figure 2 Flowchart of the adsorption heat pump

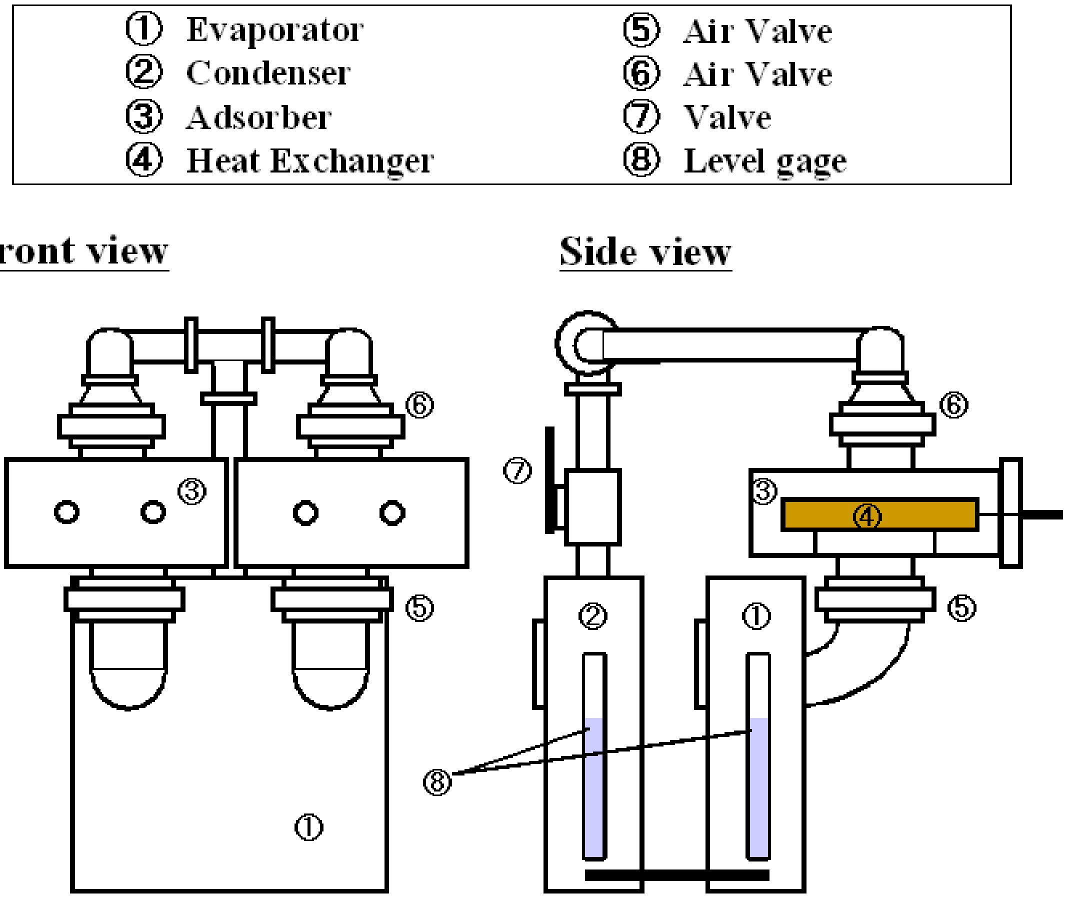


Figure 3 Concept chart of the adsorption heat pump

In the adsorption/evaporation process, the coolant water in the evaporator will absorb the heat from the ambient air through the air-liquid heat exchanger because the coolant water has a lower temperature than the ambient air. Moreover, the heat absorbed by the coolant water will cause the water in the evaporator to evaporate. An adsorbent will adsorb the water evaporated and emit adsorption heat. Therefore, the water supplied from the condenser will be heated.

In the desorption/condensation process, an adsorbent saturated with water as an adsorbate is heated by high-temperature water from a gas-fired boiler, following which, the water adsorbed on the surface of an adsorbent will be desorbed and then condensed in a condenser. Thus, the water supplied will be heated by the condensation heat.

The operation flowchart of the adsorption heat pump is shown in Figure 4. And the operation flow was described as follows.

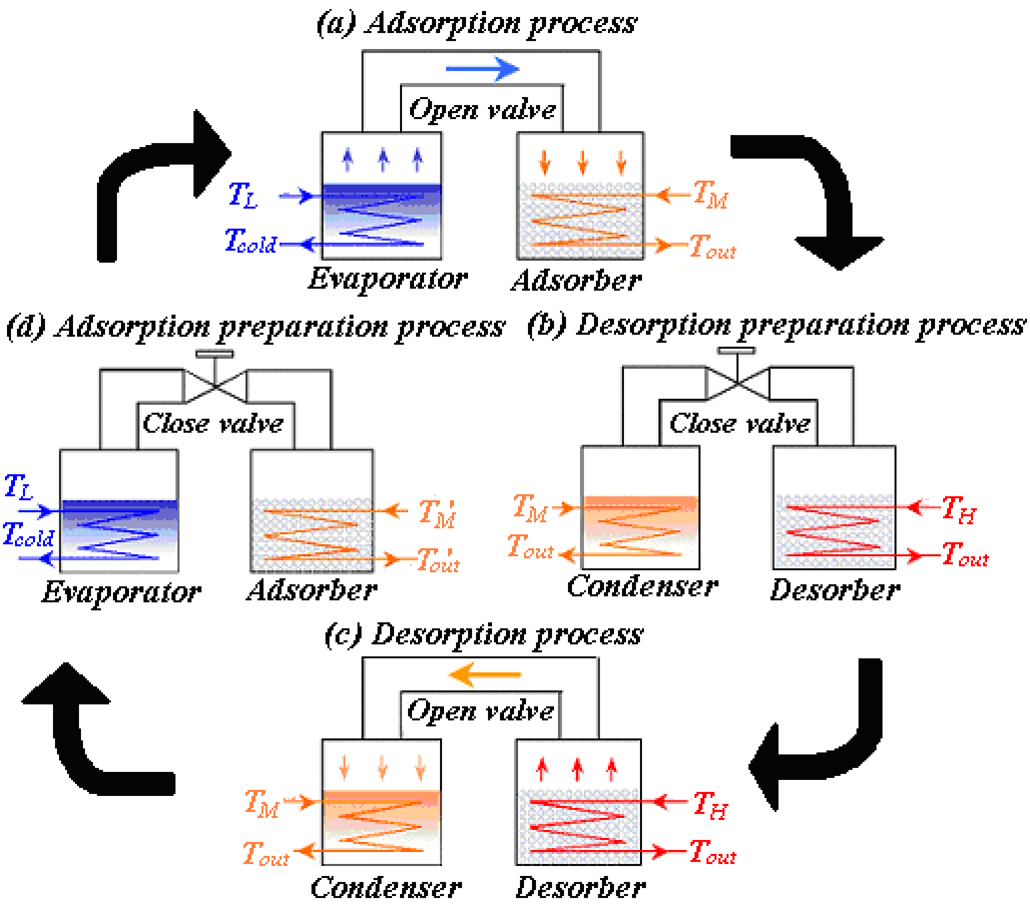


Figure 4 Operation flowchart of the adsorption heat pump

(a) Adsorption process

The connection pipe between the evaporator filled with an adsorbate and the adsorber filled with an adsorbent is reduced to a vacuum. The evaporator is filled with adsorbate steam, and the pressure in the evaporator is the saturation pressure of an adsorbate in the temperature of low-temperature heat source T_{eva}. When the valve between the evaporator and adsorber is opened, the adsorbate steam will flow from the evaporator to the adsorber by the driving force of the difference in pressure. An adsorbate obtains heat from the low-temperature heat source and evaporates in an evaporator. Along with the evaporation of an adsorbate the adsorption process starts in an adsorber.

(b) Desorption preparation process

After adsorption balance is completed, the connection pipe between the evaporator and the adsorber is switched off. The temperature in the adsorber is then equal to the temperature of the high-temperature heat source.

(c) Desorption process

When the valve between the condenser and the desorber is opened, the adsorbate steam will flow from the desorber to the condenser by the driving force of the difference in pressure. In the desorption process, the high-temperature heat source (T_{des}) will provide the heat for an adsorbate in the desorber.

(d) Adsorption preparation process

After desorption balance is over, the connection pipe between the desorber and the condenser is switched off, and the condenser attains the temperature (T_{eva}) of the low-temperature heat source; the temperature of the desorber is equal to the ambient temperature.

Like this, the adsorption and desorption cycle operate in turn from (a) to (d).

2.2 Operation of the gas boiler

In the hybrid water heater system, the gas boiler supplies hot water at two temperatures: high-temperature water at 85℃ for the adsorption heat pump and the normal hot water supply at 70℃. When the gas boiler functions as the high-temperature heat source, it will supply heat for the regeneration of an adsorbent in the adsorption heat pump. The gas boiler can then supply additional heat for the water with medium temperature from the adsorption heat pump.

3 Adsorption heat pump system design

3.1 Adsorber/Desorber

3.1.1 Heat exchanger selection

Generally, fin silica gel tube (FST) module and the plate fin tube (PFT) module are used in the adsorption heat pump. Since the PFT module is filled more easily than the FST module, the PFT module with large packing density has several applications. The PFT module stated in this paper consists mainly of plates and corrugated fins between the plates. An adsorbent is packed between the fins. The advantages of this module include not only a high heat transfer rate but also high water vapor permeability into the packed bed through the stainless steel mesh.

The PFT stainless steel heat exchanger with the volume of 1L is filled with an adsorbent and installed in an adsorber/desorber. The heat transfer area of the module in Figure 5 is 1.9m^2. The module is shown in Figure 5.

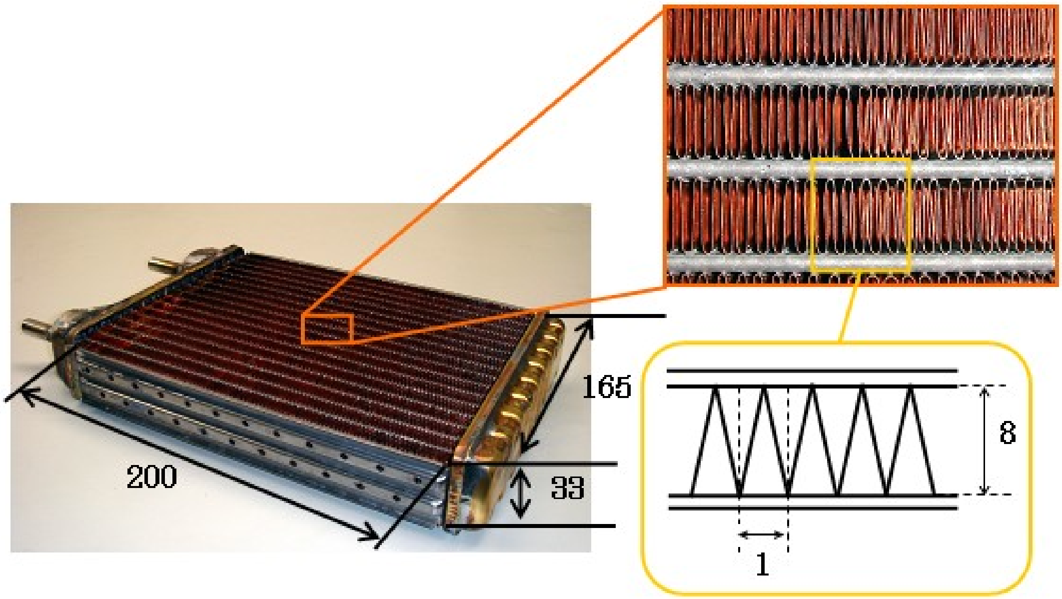


Figure 5 Photograph of plate fin tube module (units: mm)

3.1.2 Adsorbent selection

There are many pairs of adsorbate and adsorbent for an adsorption heat pump such as water/silica gel, water/zeolite, water/activated carbon and so on. Several adsorbents suited to the adsorber are studied in this paper. The steam adsorption isotherms of these pairs at 30℃ are shown in Figure 6.

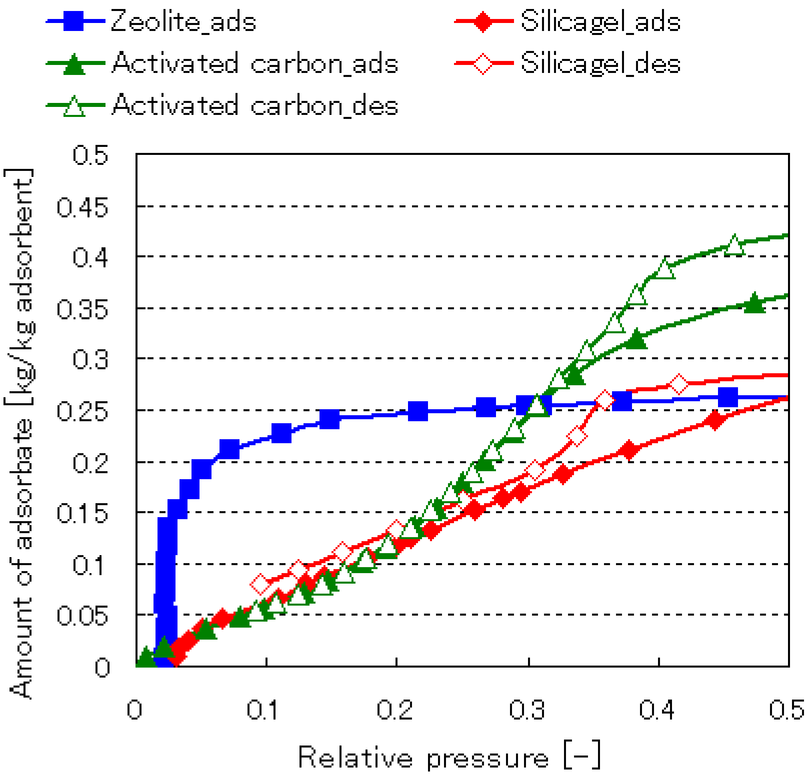


Figure 6 Adsorption isotherms for water vapor at 30℃

The elementary operation condition is T_{des} = 75℃, T_{ads} = 30℃ and T_{eva} = 14℃ for the steam adsorption heat pump; therefore, an adsorbent that have a larger adsorption capacity difference under the operation relative pressure range $\varphi_1 = 0.11 \sim \varphi_2 = 0.375$ is important. Because accompanying temperature variation the drive heat source due to seasonal variation differs largely, it is necessary for the selection of adsorbent.

From the adsorption isotherm of water and silica gel at a lower relative pressure, it can be observed that the adsorption capacity difference is smaller. The adsorption capacity increases gradually with the increase in the relative pressure, and the same adsorption capacity difference can be obtained within the same relative pressure interval. The adsorption heat of zeolite is extremely large-above 100 KJ/mol-when it adsorbs steam at a lower relative pressure. Then, the increase in the adsorption heat will decline gradually with the increase in the adsorption capacity. The operation range of the adsorption heat pump becomes very narrow because the adsorption balance can be accomplished below a relative pressure of 0.1. When activated carbon is used as an adsorbent, the adsorption capacity difference is smaller in the operation range of the adsorption heat pump because the adsorption capacity increases distinctly at a relative pressure of approximately 0.5. Recently, for activated carbon as an adsorbent, the adsorption capacity difference can increase though treating the surface of adsorbent; in particular, the activated carbon prepared with alkali gave a great adsorption capacity (Urabe et al., 2008). However, the adsorption capacity per unit filling amount of this activated carbon is about the same as that of silica because the bulk density of activated carbon is so small.

Contrasting to activated carbon and silica, great changes have been taken happen for the adsorption isotherms of AQSOA FAM-Z02 as a kind of zeolites at different temperatures. The adsorption isotherms of AQSOA FAM-Z02 at different temperatures are shown in Figure 7.

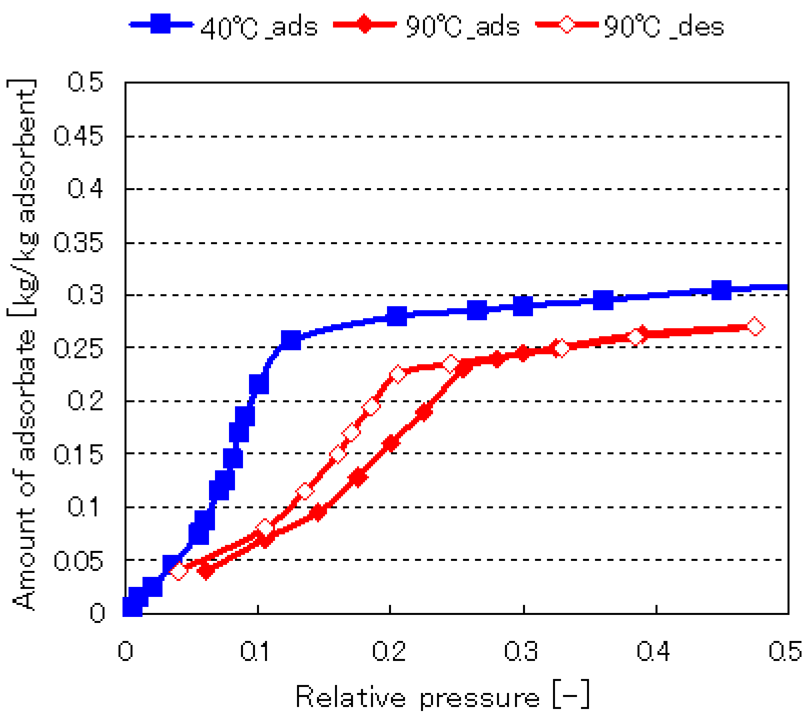


Figure 7 Adsorption isotherms for water vapor of AQSOA FAM-Z02 at different temperatures

As shown in Figure 7, the adsorption isotherm of AQSOA FAM-Z02 at 40℃ is different clearly the one at 90℃. At low relative pressures, the adsorption isotherms rise. The adsorption isotherms shift to high relative pressures with the increase in the adsorption temperature of water vapor, and the adsorption capacity decreases. According to the adsorption isotherms, the adsorption capacity is large for adsorption at low temperatures and less for desorption at a high temperature and the same relative pressure; thus, a large adsorption capacity difference can be obtained. The adsorption heat of AQSOA FAM-Z02 is 1.43 times the evaporation latent heat of water and more than the adsorption heat of other adsorbents used usually in the temperature rise cycle. And so AQSOA FAM-Z02 is suitable for adsorption heat pump.

3.1.3 Calculation condition and method of the adsorption capacity difference Δq for the adsorbents

Because the ambient temperature and the water supply temperatures will change throughout the year, the typical temperatures listed in Table1 are studied.

Table 1 Ambient temperature and water supply temperature

Ambient temperature [°C]	30	15	10	5	1
Water supply temperature [°C]	25	15	10	8	

Hot water temperature and desorption temperature are 70℃, 85℃, respectively. Relative pressure φ1, φ2 is defined as follows.

$$\varphi_1 = P_{ads} / P_{des} \tag{1}$$

$$\varphi_2 = P_{eva} / P_{ads} \tag{2}$$

The relative pressure φ1 and φ2 were calculated from formula (1) and (2) on the base of the saturated vapor pressure at different temperature, and then the adsorption capacity difference Δq of various adsorbents were obtained.

3.1.4 Calculation results

The calculation results of Δq of various adsorbents due to environmental condition are shown in Table 2.

Table 2　Calculation results of Δq of various adsorbents

<table>
<tr><th>Ambient temperature [℃]</th><th>Water supply temperature [℃]</th><th>φ_1 [-]</th><th>φ_2 [-]</th><th>$\Delta q_{FAM\text{-}Z02}$ [kg/kg]</th><th>Δq_{silica} [kg/kg]</th><th>Δq_{AC} [kg/kg]</th></tr>
<tr><td>30</td><td>25</td><td>0.066</td><td>0.605</td><td>0.26</td><td>0.29</td><td>0.35</td></tr>
<tr><td>15</td><td>15</td><td>0.036</td><td>0.398</td><td>0.30</td><td>0.23</td><td rowspan="2">0.30</td></tr>
<tr><td>10</td><td rowspan="2">10</td><td rowspan="2">0.025</td><td>0.407</td><td>0.32</td><td>0.23</td></tr>
<tr><td rowspan="2">5</td><td>0.288</td><td>0.31</td><td>0.16</td><td>0.21</td></tr>
<tr><td rowspan="2">8</td><td rowspan="2">0.022</td><td>0.325</td><td>0.32</td><td>0.16</td><td>0.23</td></tr>
<tr><td>1</td><td>0.244</td><td>0.31</td><td>0.13</td><td>0.16</td></tr>
</table>

Relative pressure φ1 and φ2 increase with the increase in the ambient temperature. Sufficient absorption capacities for three kinds of the adsorbents were obtained because the operation region of adsorption heat pump was wide in summer. Especially, Δq of activated carbon is very large because the adsorption capacity of activated carbon increases on high relative pressure. However, because the operation region of adsorption heat pump is narrow in winter, 1/2 or less of adsorption capacity in the summer for activated carbon and silica are obtained. AQSOA FAM-Z02 is stable in four seasons, and constant Δq is obtained. It can be said that AQSOA FAM-Z02 is the most excellent according to the season. And so AQSOA FAM-Z02 is selected as an adsorbent in this paper.

3.2 Connections between components

In the present study, the vacuum air-valves with inner diameters of 101mm and 51mm are used between the evaporator and adsorber and the adsorber and condenser, respectively. The flange tube (SUS304, flange size KF40) is used to connect to the rest of the apparatus. Moreover, for the movement of water between the condenser and the evaporator, a vacuum hose is used to connect the opening of the valve between the evaporator and the bottom of the condenser. Finally, the made installation is assembled with a station with four casters to make the experimental system movable. The photographs of the assembly adsorption heat pump system are shown in Figure 8.

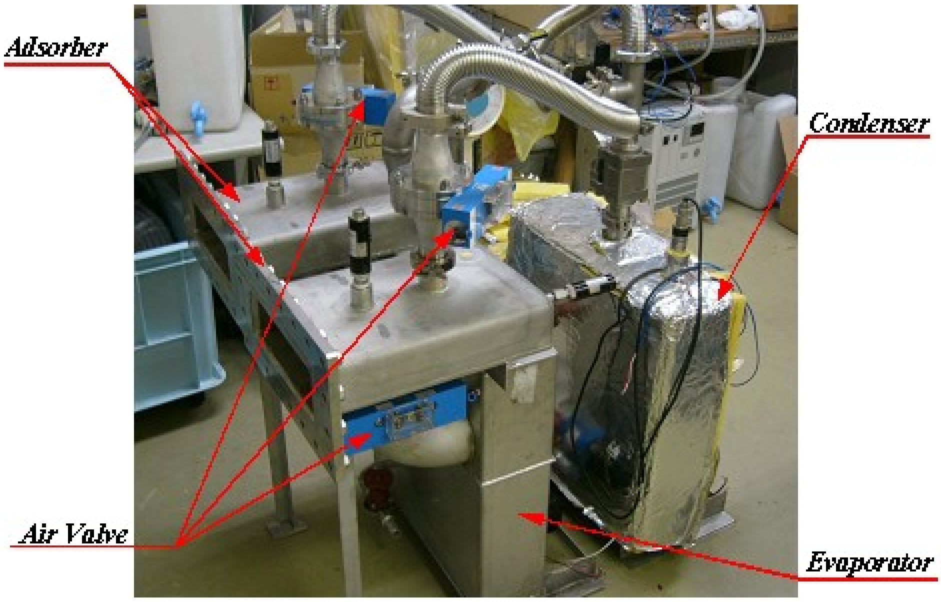


Figure 8 Photographs of the experimental apparatus

3.3 Instrumentation

A constant-temperature water circulation setup (NCC-1100, 1400, Tokyo Physics and Chemistry Instrument Company in Japan) is installed as the thermal source to maintain the adsorber and desorber, evaporator and condenser at certain fixed temperatures. An electromagnetic flow meter with a small error (MGM1090K, Tokyo Instrumentation Company) is used to measure the flow amount of the heat-exchange fluid. The temperature is determined with high accuracy using a Pt resistance bulb. Several pressure gages (VALCOM, pressure sensor) are used to measure the pressure inside the device. Moreover, measurement and data collection of the temperature is done using the Agilent BenchLink Data Logger. Electromagnetic valves are used to switch the heat-exchange fluid that is supplied respectively in turn from the high-temperature heat source and the ambient heat source to the adsorber and desorber.

4 Performance evaluations of water heater and experimental conditions

4.1 Performance evaluation of the adsorption heat pump and water heater

In this chapter, the performances of the adsorption heat pump and water heater are examined based on several parameters such as T_{AHP_out}, Q_{eva}, Q_{AHP}, Q_{WH}, COP and so on.

Moreover, Q_{eva}, Q_{AHP} and COP are defined as follows:

$$Q_{AHP\_out} = C \times \rho \times F_{con} \times \Delta T_{AHP\_ave} \tag{3}$$

$$Q_{eva} = C \times \rho \times F_{eva} \times \Delta T_{eva\_ave} \tag{4}$$

The COPs of the AHP and water heater are defined as follows:

$$COP_{AHP} = Q_{AHP\_out} / Q_{AHP\_in} = Q_{AHP\_out} / Q_{eva} \tag{5}$$

$$COP_{WH} = Q_{WH\_output} / Q_{WH\_input} \tag{6}$$

$$Q_{WH\_in} = Q_{boi} = Q_{boi1} + Q_{boi2} \tag{7}$$

$$Q_{WH\_out} = Q_{con} + Q_{ads} + Q_{sen} + Q_{boi1} \tag{8}$$

4.2 Experimental conditions

The following experimental conditions are assumed in the analysis. The values in the parentheses are considered to be the reference experimental conditions. In addition, the water supply temperature is the inlet temperature in the condenser, and the ambient temperature is that in the evaporator.

High-temperature water temperature (desorption temperature)		
	T_{des} = 75〜85°C	(85°C)
Water supply temperature	T_{AHP_in} = 5〜25°C	(15, 20°C)
Ambient temperature	T_{eva} = 5〜30°C	(15, 20°C)
Adsorption time	τ_{ads} = 90〜300 s	(120s)

Preparation time $\tau_p = 20$ s

Water supply flow amount $F_{con} = 0.5 \sim 2.0$ L/min （1.0 L/min）

High-temperature water flow amount in the desorber

$F_{des} = 1.0 \sim 4.0$ L/min（4.0 L/min）

Heat-exchanging fluid flow amount in the evaporator $F_{eva} = 4.0$ L/min

5 Results and discussion

5.1 Effects of ambient temperature T_{eva} and water supply temperature T_{con} on hot water temperature T_{AHP_out}, output and COP

On the basis of the assumed experimental conditions, we performed experiments in which the ambient temperature and water supply temperature were changed. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95 and the hot water supply temperature to be 70°C.

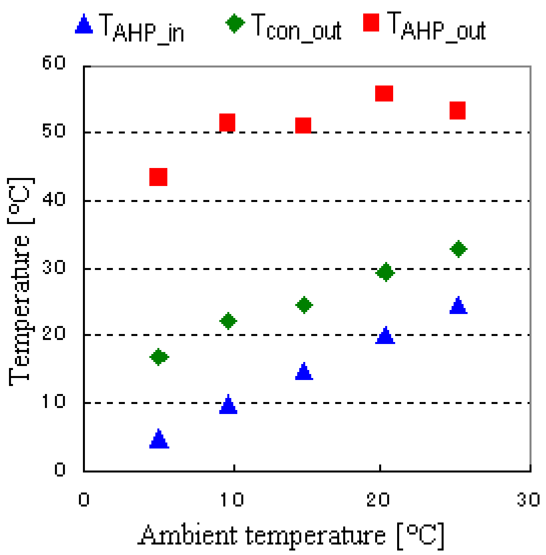


Figure 9-1 Variation of T_{AHP_in}, T_{con_out} and T_{AHP_out} with different ambient temperatures

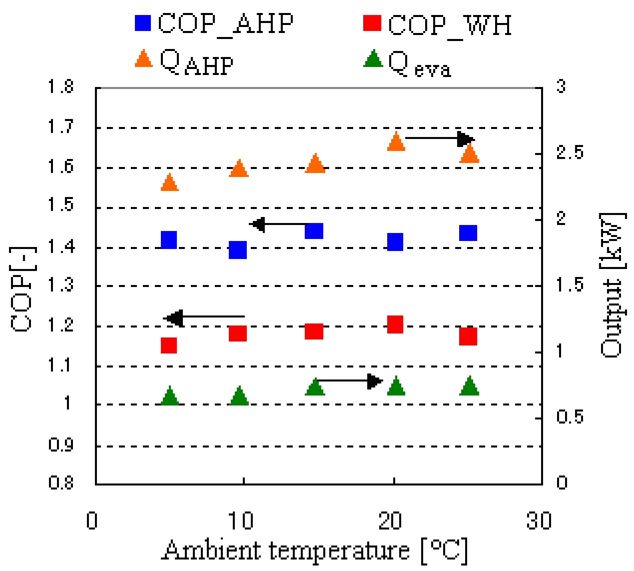


Figure 9-2 Variation of the COP and output of the adsorption heat pump with different ambient and water supply temperatures

Figures 9-1 and 9-2 show the effects of the ambient temperature and water supply temperature in the range from 5 to 25°C on the output and COP. Figure 9-2 shows that the outlet temperature of the adsorption heat pump almost increases with the ambient temperature and water supply temperature. The outlet temperature of the adsorption heat pump reaches a maximum of 55.7°C at $T_{eva} = T_{con} = 20$°C. The COP of the adsorption heat pump remains almost constant because the output of the evaporator is constant when varying the ambient temperature and water supply temperature. The COP of the water heater increases with the ambient temperature, and it is 1.2 at an ambient temperature of 20°C. This is because the output of the adsorption heat pump has a maximum at an ambient temperature of 20°C.

5.2 Effects of cycle time on hot water temperature T_{AHP_out}, output and COP under the conditions of constant ambient and water supply temperatures

When the effects of the cycle time on the hot water temperature T_{AHP_out}, output and COP are studied, four conditions, $T_{eva} = T_{con} = 5$°C, $T_{eva} = T_{con} = 15$°C, $T_{eva} = T_{con} = 20$°C and $T_{eva} = T_{con} = 25$°C, are assumed. The experiments are performed for each condition.

5.2.1 Effects of cycle time on hot water temperature T_{AHP_out}, output and COP at $T_{eva} = T_{con} = 5°C$

On the basis of the assumed experimental conditions, we performed experiments in which the cycle time was changed. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95 and the hot water supply temperature to be 70°C.

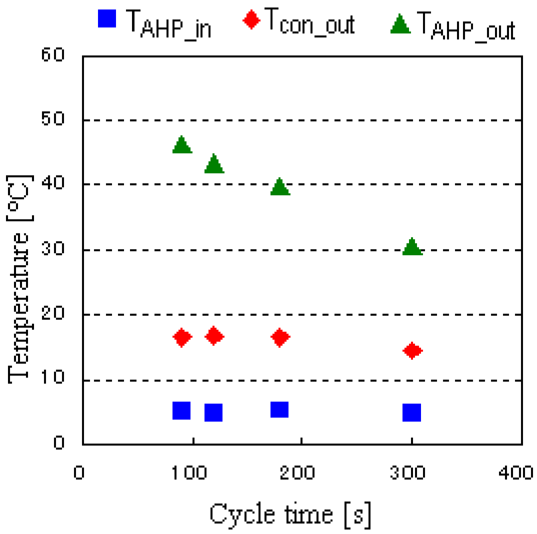


Figure 10-1 Variation of the temperature with cycle times at $T_{eva} = T_{con} = 5°C$

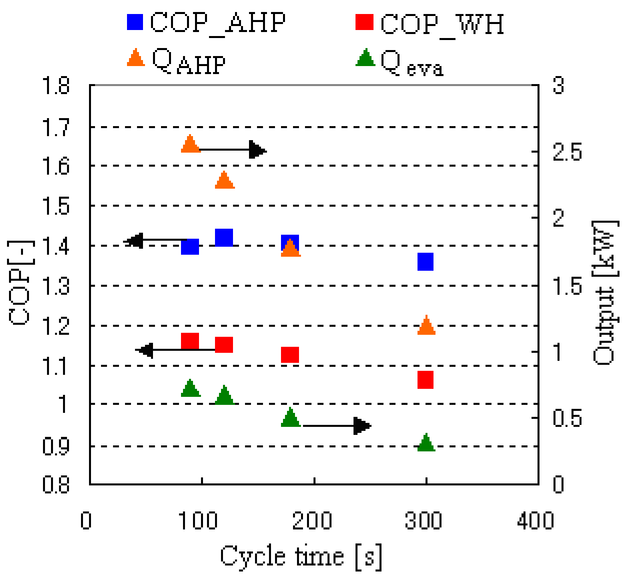


Figure 10-2 Variations of COP and output with cycle times at T_{eva} = T_{con} = 5°C

Figures 10-1 and 10-2 show the effects of the cycle time on the outlet temperature of the adsorption heat pump, output and COP at T_{eva} = T_{con} = 5°C. Figure 10-1 shows that the outlet temperatures of the condenser and adsorption heat pump decrease with an increase in the cycle time. The adsorbent AQSOA FAM-Z02, having a high adsorption speed, can achieve adsorption balance in 60 s, and thus the outlet temperature of the adsorption heat pump decreases with increasing cycle time. The emitted heat in the adsorber decreases with an increase in the cycle time; the temperature difference between the outlet and inlet of the adsorber decreases, and thus the outlet temperature decreases in one cycle time. The COP of the adsorption heat pump decreases with an increase in the cycle time. Generally, the COP of the adsorption heat pump increases with the adsorption amount difference and cycle time; however, the heat added in the desorption process is so much that the COP decreases due to the large temperature difference between the ambient temperature and desorption temperature. Further, the COP has a maximum in a shorter cycle time. Further, the maximum COP of the water heater is 1.16 at a cycle time of 90 s at T_{eva} = T_{con} = 5°C. At the same time, the average outlet temperature of the adsorption heat pump is 46°C.

5.2.2 Effects of cycle time on hot water temperature T_{AHP_out}, output and COP at $T_{eva} = T_{con} = 15°C$

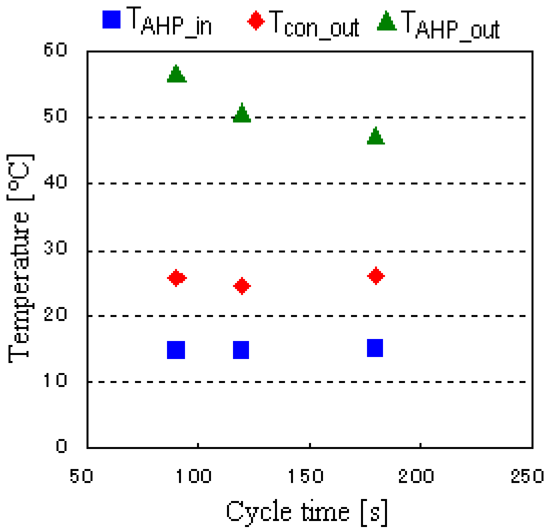


Figure 11-1 Variation of the temperature with cycle times at $T_{eva} = T_{con} = 15°C$

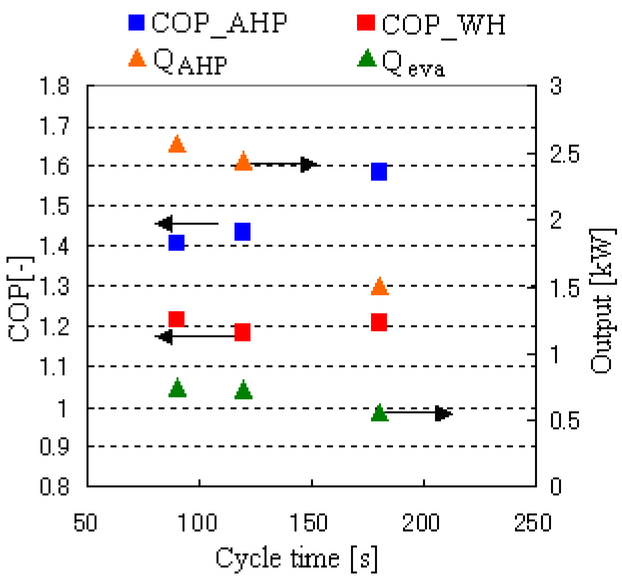


Figure 11-2 Variation of COP and output with cycle times at $T_{eva} = T_{con} = 15°C$

Figures 11-1 and 11-2 show the effects of the cycle time on the outlet temperature of the adsorption heat pump, output and COP at $T_{eva} = T_{con} = 15°C$. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95 and the hot water supply temperature to be 70°C. Figure 11-1 shows that the outlet temperature of the condenser is constant. The outlet temperature of the adsorption heat pump decreases with an increase in the cycle time. Since the cycle time increases, the adsorption process approaches a balanced state and the adsorption amount begins to decrease; finally, the adsorption heat is so little that the water supply cannot be heated sufficiently. Figure 11-2 shows that the COP of the adsorption heat pump increases with the cycle time, but the COP of the water heater, AHP output and evaporator decrease. The outlet temperature of the adsorption heat pump is the maximum at 57°C when the cycle time is 90 s. Moreover, the maximum COP of the water heater is 1.22.

5.2.3 Effects of cycle time on hot water temperature T_{AHP_out}, output and COP at $T_{eva} = T_{con} = 20°C$

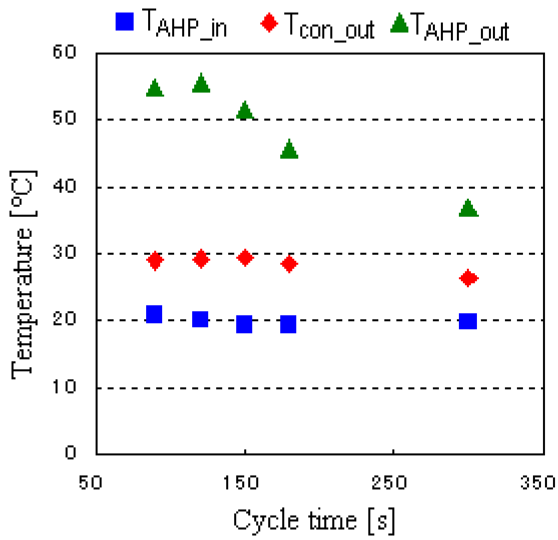


Figure 12-1 Variation of the temperature with cycle times at $T_{eva} = T_{con} = 20°C$

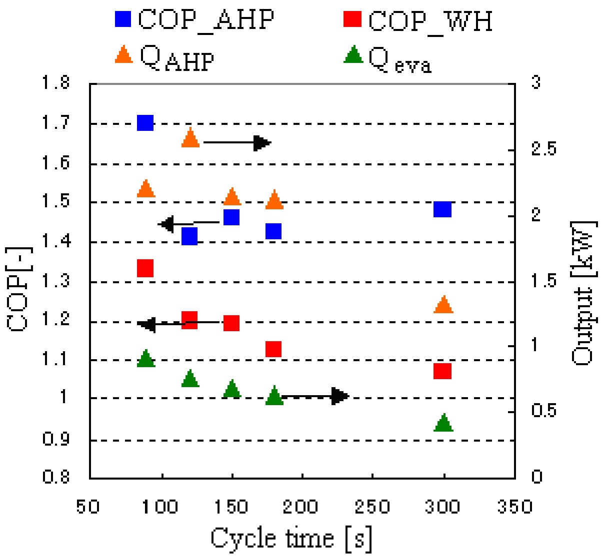


Figure 12-2 Variation of COP and output with cycle times at T_{eva} = T_{con} = 20°C

Figures 12-1 and 12-2 show the effects of the cycle time on the outlet temperature of the adsorption heat pump, output and COP at T_{eva} = T_{con} = 20°C. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95 and the hot water supply temperature to be 70°C. Figure 12-1 shows that the outlet temperatures of the condenser and adsorption heat pump decrease with an increase in the cycle time. Since the cycle time increases, the adsorption process approaches a balanced state and the adsorption amount decreases; finally, the adsorption heat becomes so less that the water supply cannot be sufficiently heated. Figure 12-2 shows that the COP of the adsorption heat pump attains a minimum and the output of the adsorption heat pump attains a maximum with an increase in the cycle time. Further, the COP of the water heater and the output of the evaporator decrease with an increase in the cycle time. Moreover, the outlet temperature of the adsorption heat pump reaches a maximum of 57°C when the cycle time is 90 s. Moreover, the COP of the water heater reaches a maximum of 1.22. The outlet temperature of the adsorption heat pump is the same as that at T_{eva} = T_{con} = 15°C. With an increase in the adsorption temperature, the adsorption amount of AQSOA FAM-Z02 decreases and it is almost constant at a relative pressure > 0.2. It cannot increase even if the range between relative pressures φ_1 andφ_2 is sufficiently broad.

5.2.4 Effects of cycle time on hot water temperature T_{AHP_out}, output and COP at $T_{eva} = T_{con} = 25°C$

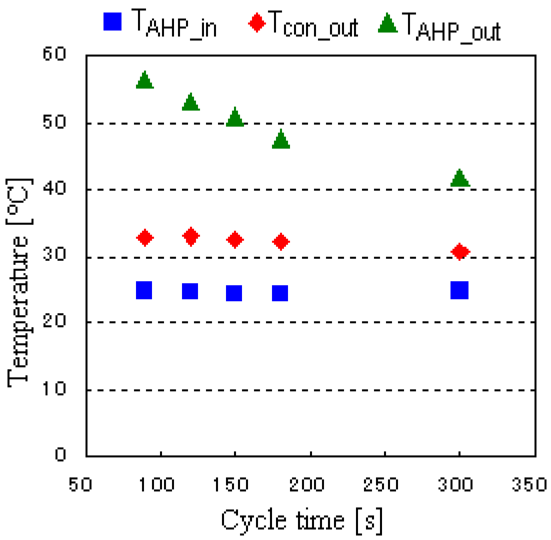


Figure 13-1 Variation of the temperature with cycle times at $T_{eva} = T_{con} = 25°C$

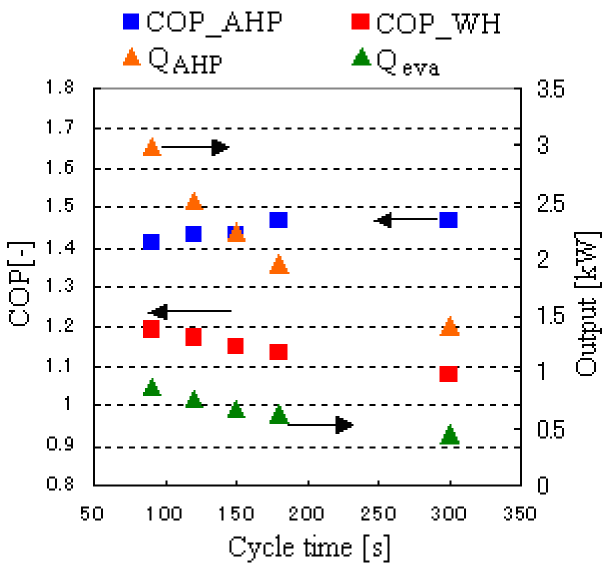


Figure 13-2 Variation of COP and output with cycle times at $T_{eva} = T_{con} = 25°C$

Figures 13-1 and 13-2 show the effects of the cycle time on the outlet temperature of the adsorption heat pump, output and COP at $T_{eva} = T_{con} = 25°C$. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95 and the hot water supply temperature to be 70°C. Figure 13-1 shows that the outlet temperatures of the condenser and adsorption heat pump decrease with an increase in the cycle time. Because the cycle time increases, the adsorption process approaches a balanced state and the adsorption amount decreases; finally, the adsorption heat is so less that the water supply cannot be sufficiently heated. Figure 13-2 shows that the COP of the adsorption heat pump increases with the cycle time. Further, the output of the adsorption heat pump and evaporator and the COP of the water heater decrease with an increase in the cycle time. With an increase in the cycle time, the outlet temperature of the adsorption heat pump decreases, and thus an increasing amount of heat is obtained from the gas boiler in order to continually heat the water supply. Finally, the COP of the water heater decreases. Moreover, the outlet temperature of the adsorption heat pump reaches a maximum of 56°C when the cycle time is 90 s. The COP of the water heater reaches a maximum of 1.19.

From the above experiments, we observe that COP of the water heater has a maximum during the shortest cycle time for constant values of T_{eva} and T_{con}. However, if the cycle time decreases, the adsorbent deteriorates easily.

5.3 Effects of ambient temperature on hot water temperature T_{AHP_out}, output and COP at constant water supply temperature

5.3.1 Effects of ambient temperature on hot water temperature T_{AHP_out}, output and COP at water supply temperature $T_{con} = 15°C$

On the basis of the assumed experimental conditions, we performed experiments in which the ambient temperature was changed. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95 and the hot water supply temperature to be 70°C.

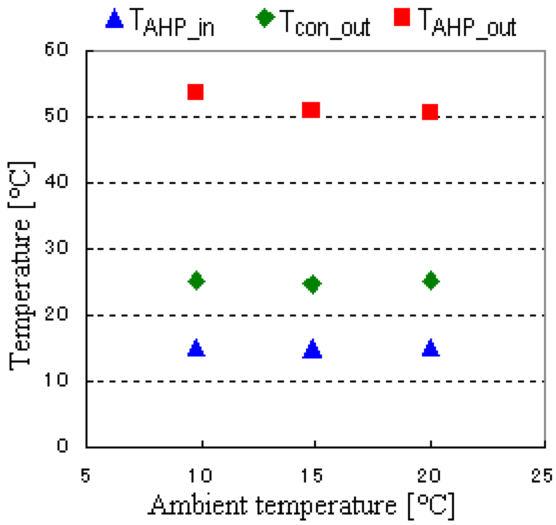


Figure 14-1 Variation of the temperature with different ambient temperatures at a water supply temperature of 15°C

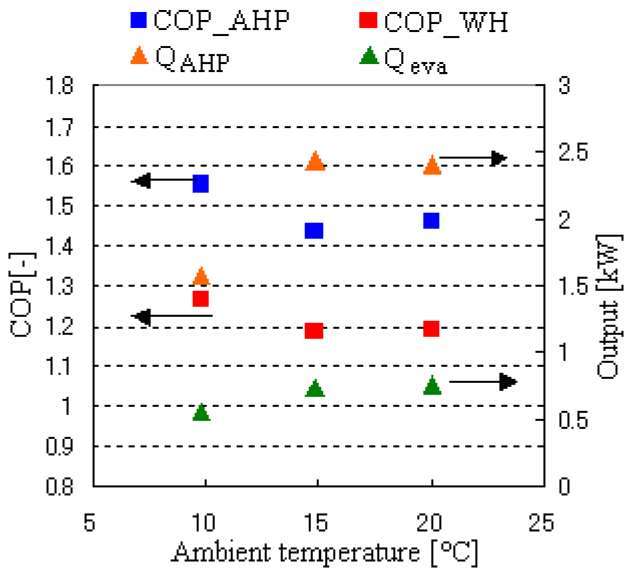


Figure 14-2 Variation of COP and output with different ambient temperatures at a water supply temperature of 15°C

Figures 14-1 and 14-2 show the effects of the ambient temperature on the outlet temperature of the adsorption heat pump, output and COP at T_{con} = 15°C. Figure 14-1 shows that the outlet temperature of the condenser remains constant with an increase in the ambient temperature. The outlet temperature of the adsorption heat pump decreases. Figure 14-2 shows that the COPs of the adsorption heat pump and water heater decrease with an increase in the ambient temperature. The outputs of the adsorption heat pump and evaporator increase with the ambient temperature. The relative pressure φ_2 shifts to a high relative pressure and then the adsorption amount $\triangle q$ increases because the outlet temperature of the adsorption heat pump remains constant for an increase in the ambient temperature and the adsorption isotherm of vapour does not change. However, a low COP does not result from an increase in the adsorption amount but from the condensation of vapour in the adsorber.

5.3.2 Effects of ambient temperature on hot water temperature T_{AHP_out}, output and COP at a water supply temperature of T_{con} = 20°C

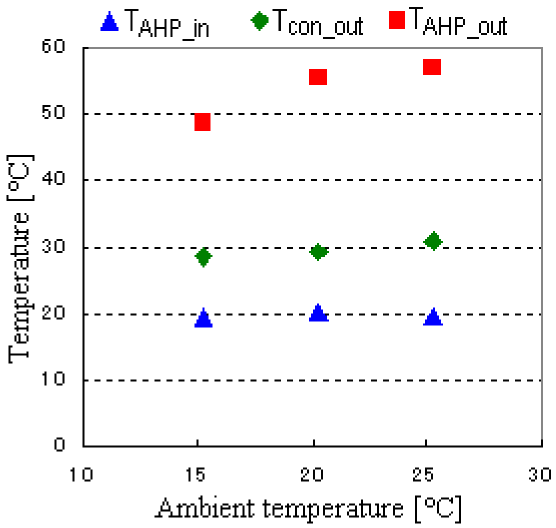


Figure 15-1 Variation of the temperature with different ambient temperatures at a water supply temperature of 20°C

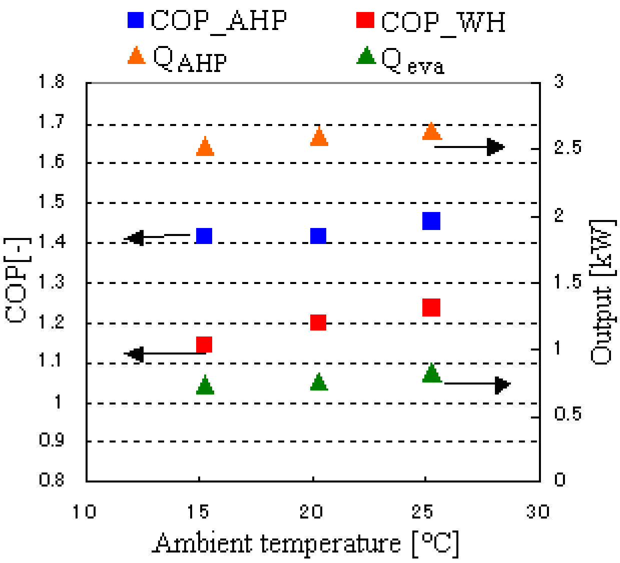


Figure 15-2 Variation of COP and output with different ambient temperatures at a water supply temperature of 20°C

Figures 15-1 and 15-2 show the effects of the ambient temperature on the outlet temperature of the adsorption heat pump, output and COP at T_{con} =20°C. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95 and the hot water supply temperature to be 70°C. Figure15-1 shows that the outputs of the adsorption heat pump and the condenser increase with the ambient temperature. The relative pressure φ_2 shifts to a high relative pressure with an increase in the ambient temperature, and thus the adsorption amount increases. Figure 15-2 shows that the COP of the adsorption heat pump and water heater and the outputs of the adsorption heat pump and evaporator increase with the ambient temperature.

5.3.3 Effects of ambient temperature on hot water temperature T_{AHP_out}, output and COP at a water supply temperature of T_{con} = 25°C

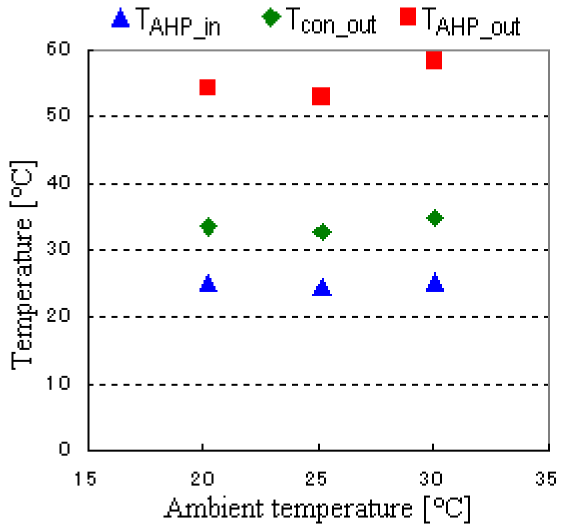


Figure 16-1 Variation of the temperature with different ambient temperatures at a water supply temperature of 25°C

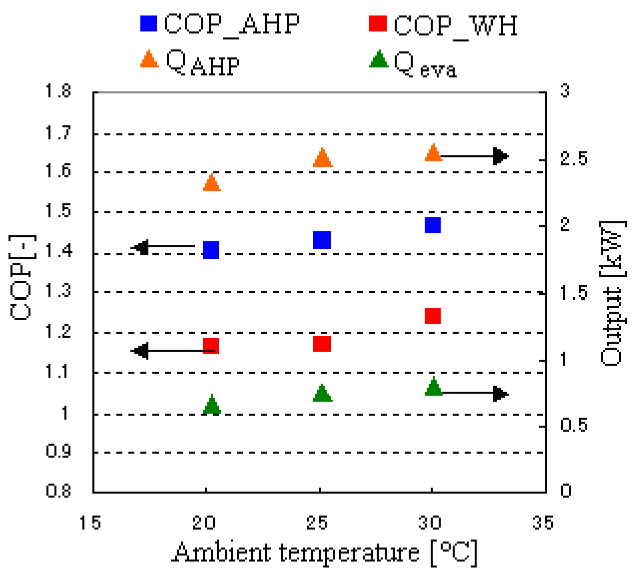


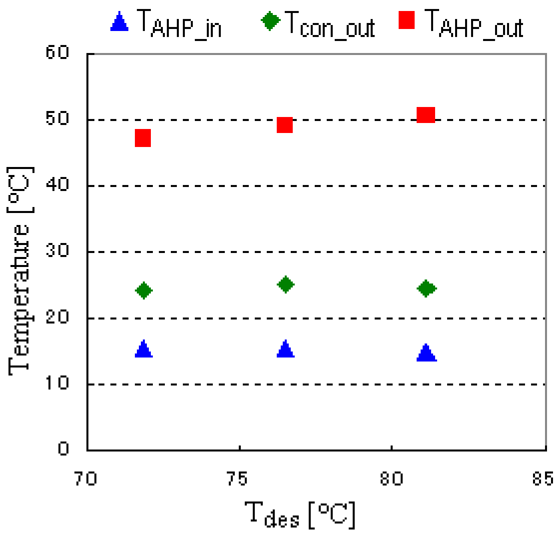
Figure16-2 Variation of COP and output with different ambient temperatures at a water supply temperature of 25°C

Figures 16-1 and 16-2 show the effects of the ambient temperature on the outlet temperature of the adsorption heat pump, output and COP at T_{con} = 25°C. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95 and the hot water supply temperature to be 70°C. Figure 16-1 shows that the outlet temperatures of the condenser and adsorption heat pump increase with the ambient temperature. This is because the temperature in the evaporator increases and the relative pressure φ_2 shifts to a higher relative pressure, and then the adsorption amount difference increases. Figure 16-2 shows that the COP of the adsorption heat pump and water heater and the outputs of the adsorption heat pump and evaporator increase with the ambient temperature. The additional heat that increases the hot water temperature from the outlet temperature of the adsorption heat pump to a hot water supply temperature of 70°C is less than the heat used to increase the temperature of the adsorption heat pump. Moreover, the COP of the water heater is a maximum of 1.24 at an ambient temperature of 30°C, and the average temperature of the hot water supply is 58°C at a water supply temperature of 25°C.

From the above results, under the condition of a water supply temperature greater than 20°C, the outlet temperature of the condenser increases with the ambient temperature, and the COP of the water heater and adsorption heat pump increase gradually as well. If the ambient temperature is higher than the water supply temperature, the COP of the water heater increases.

5.4 Effects of desorption temperature on hot water temperature T_{AHP_out}, output and COP at T_{eva} = T_{con} = 15°C

On the basis of the assumed experimental conditions, we performed experiments in which desorption temperature were changed.



Figures 17-1 Variation of the temperature with different desorption temperatures at $T_{eva} = T_{con} = 15°C$

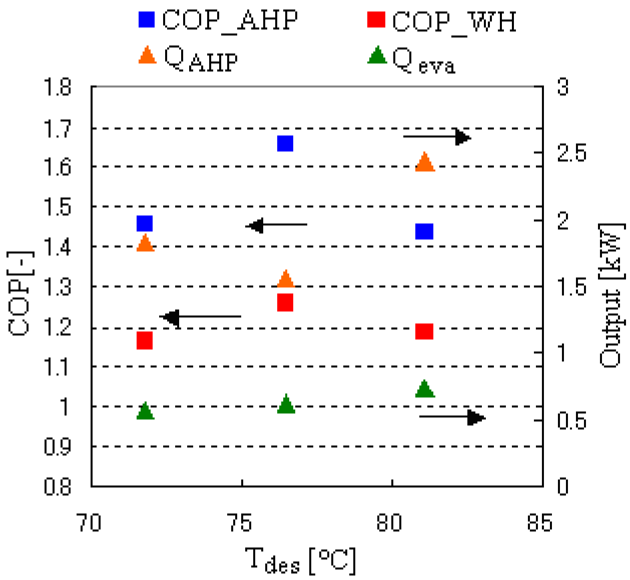


Figure 17-2 Variation of the COP and output with different desorption temperatures at $T_{eva} = T_{con} = 15°C$

Figures 17-1 and 17-2 show the effects of the desorption temperature on the outlet temperature of the adsorption heat pump, output and COP at $T_{eva} = T_{con} = 15°C$. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95. In the experiments, desorption temperature is assumed to be 75, 80, and 85°C; however, the desorption temperature shown in Figures 17-1 and 17-2 is lower than the assumed temperature because it is the average temperature of the inlet and outlet temperature of the desorber. Figure 17-1 shows that the outlet temperature of the adsorption heat pump increases with the desorption temperature. Due to the faster adsorption speed of the adsorbent AQSOA FAM-Z02 and the lower relative pressure φ_1, the desorption process operates smoothly. Figure 17-2 shows that the output of adsorption heat pump is minimum at a desorption temperature of 80°C; this is the result of the condensation phenomena that exists in the adsorber.

5.5 Effects of high-temperature water flow amount on hot water temperature T_{AHP_out}, output and COP at $T_{eva} = T_{con} = 20°C$ for a water supply flow amount of 1 L/min

On the basis of the assumed experimental conditions, we performed experiments in which the high-temperature water flow amounts were changed.

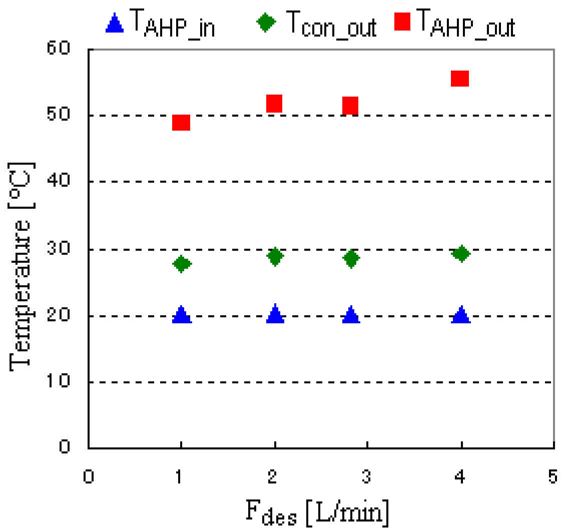


Figure 18-1 Variation of the temperature with different high-temperature water flow amounts at $T_{eva} = T_{con} = 20°C$

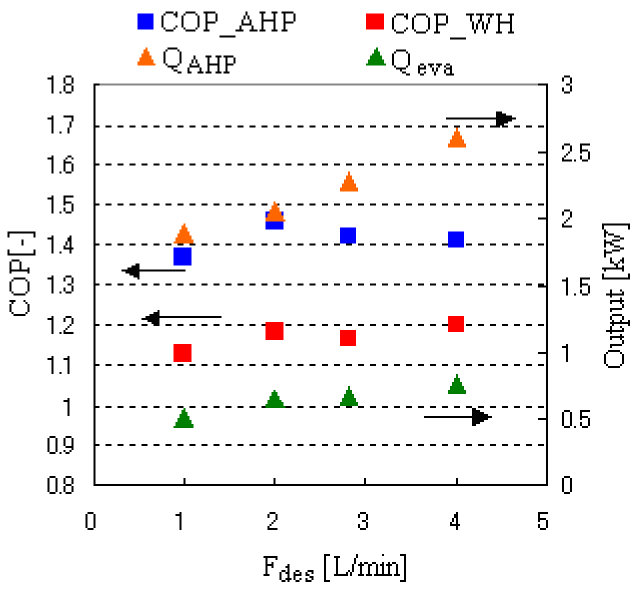


Figure 18-2 Variation of COP and output with different high-temperature water flow amounts at $T_{eva} = T_{con} = 20°C$

Figures 18-1 and 18-2 show the effects of the high-temperature water flow amount on the outlet temperature of the adsorption heat pump, output and COP at $T_{eva} = T_{con} = 20°C$. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95. Figure 18-1 shows that the outlet temperature of the adsorption heat pump increases with the high-temperature water flow amount. This is because the supply heat increases proportionally with the high-temperature water flow amount during desorption cycle time. In addition, Figure 18-2 shows that the COP of the water heater increases with the high-temperature water flow amount, and the COP of the adsorption heat pump is maximum at 2 L/min, before beginning to decrease. From the above results, when the high-temperature water flow amount is twice the water supply flow amount, desorption process can operate adequately in an experiment.

5.6 Effects of water supply flow amount on hot water temperature T_{AHP_out}, output and COP at $T_{eva} = T_{con} = 15°C$

On the basis of the assumed experimental conditions, we performed experiments in which the water supply flow amount was changed.

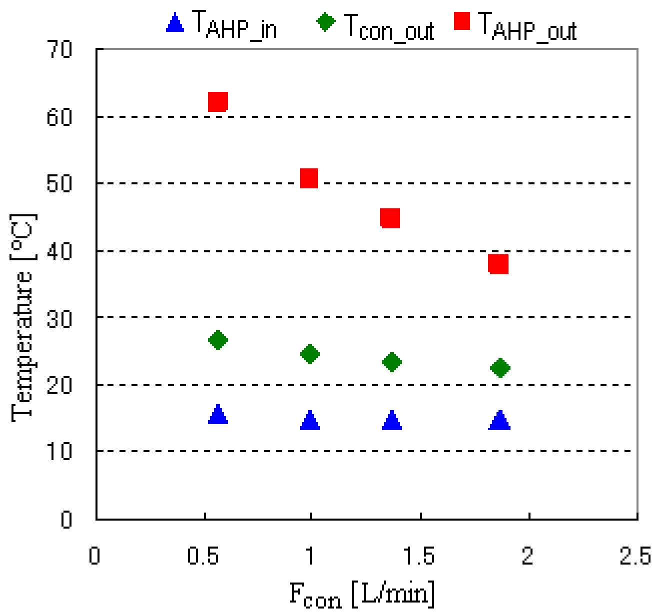


Figure19-1 Variation of the temperature with different water supply flow amounts at $T_{eva} = T_{con} = 15°C$

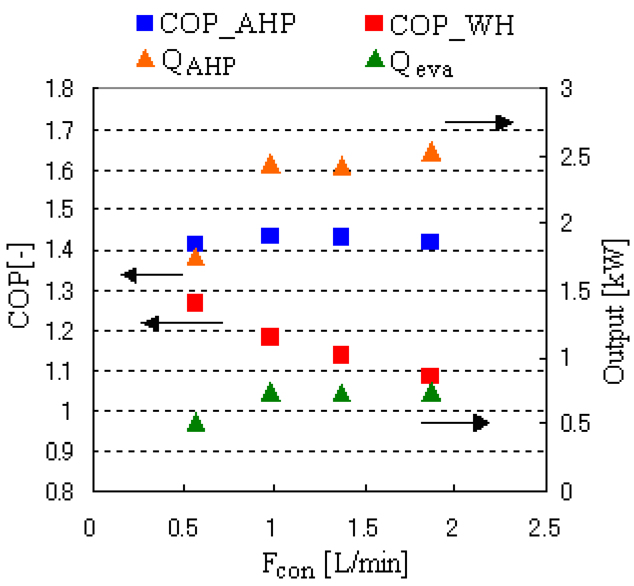


Figure 19-2 Variation of COP and output with different water supply flow amounts at $T_{eva} = T_{con} = 15°$

Figures 19-1 and 19-2 show the effects of the water supply flow amount on the outlet temperature of the adsorption heat pump, output and COP at $T_{eva} = T_{con} = 15°$. The experimental COP of the adsorption heat pump is obtained by assuming the heat efficiency of the gas boiler to be 0.95. Figure 19-1 shows that the outlet temperature of the adsorption heat pump decreases with an increase in the water supply flow amount. The heat used for heating the water supply mainly originates from the condensation heat in the condenser and the adsorption heat in the adsorber, and when the water supply flow amount increases, the heat is constant and the outlet temperature of the adsorption heat pump decreases. Figure19-2 shows that the output of the adsorption heat pump increases with the water supply flow amount, while the COP of the water heater decreases. This is because a greater amount of heat is obtained from the boiler because of the low outlet temperature of the adsorption heat pump.

6 Numerical analysis by process simulation

6.1 Conditions and formulas for numerical analysis

On the basis of the experimental results, a numerical analysis is presented by process simulation with HYSYS, and then the COP of the system is examined.

The conditions of the numerical analysis and experiment are as follows:

Heat capacity of AQSOA FAM-Z02, copper and water is 0.88, 0.386, and 4.18 kJ/kg·℃, respectively.

Adsorption and desorption time: $\tau_{ads} = 120$ s

Preparation time: $\tau_p = 20$ s

High-temperature water temperature: $T_{des} = 85°C$

Heat-exchange efficiency of the evaporator: 75%

Adsorption efficiency of the adsorbent: 95%

Further, the defined COP is the same as the formula (6), and Q_{sen} in the formula (8) is defined as follows:

$$Q_{sen} = Q_{sen\_H_2O} + Q_{sen\_FAM} + Q_{sen\_Cu} \tag{9}$$

6.2 Results of numerical analysis

Based on the accuracy of the above numerical analysis method, the COP of a hybrid water heater for a one-year period is calculated. As the results of numerical analysis, the COP of a hybrid water heater over the course of one year is shown in Figure 20.

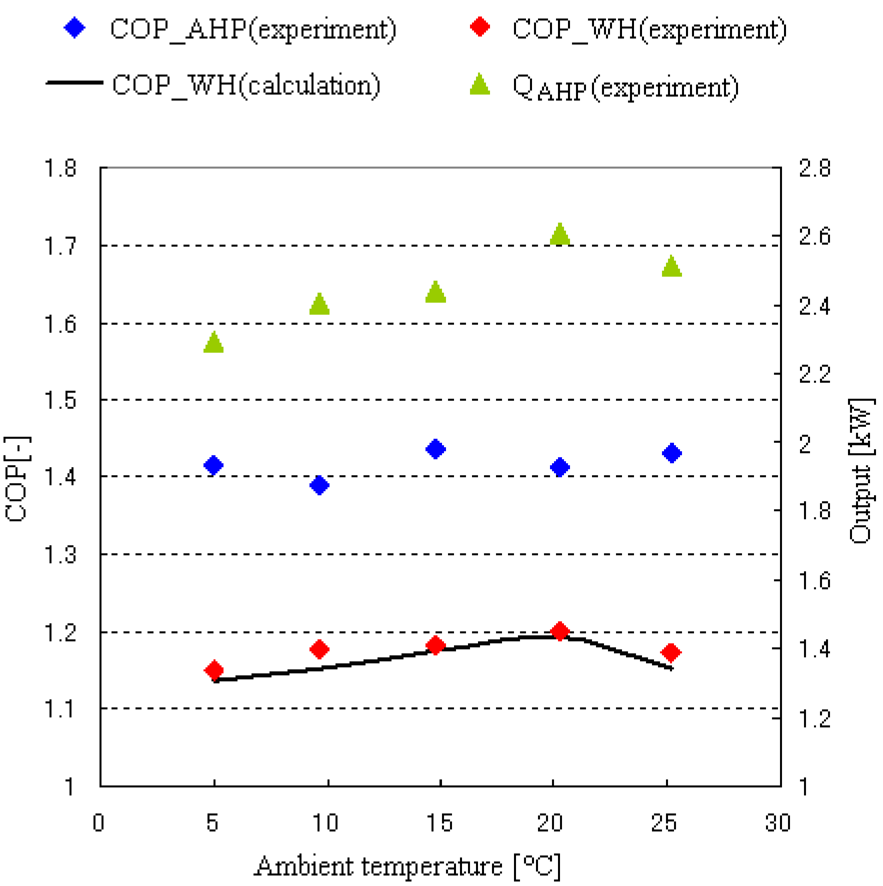


Figure 20 Comparison of calculated and experimental COPs

The results of the numerical analysis are generally the same as the experimental ones; moreover, the COP has a maximum of 1.2 in October. Further, the COP of the hybrid water heater is generally constant throughout the year since AQSOA FAM-Z02 as the adsorbent has sufficient adsorption capacity in the low relative pressure conditions in winter. From the above results, we conclude that the performance of the hybrid adsorption heat pump water heater is better than that of conventional gas boiler water heaters even at the lowest ambient temperatures.

7 Conclusions

In this study, the adsorption heat pump cycle is examined based on the experimental output and COP. Moreover, a numerical analysis of a process simulation for a hybrid water heater system is presented, and the COP of the system is predicted.

The following conclusions can be drawn from this experimental study:

1. When the water supply temperature and ambient temperature are both 5°C in winter, the outlet hot water temperature of the adsorption heat pump is highest, and is a maximum of 46.3°C under an inlet water supply temperature of 5°C. Further, it is predicted that the hybrid water heater can operate normally without any operational problems even if the ambient temperature is very low.

2. The COP of the water heater decreases with an increase in the cycle time; moreover, the water heater has an outlet hot water temperature of 57°C and COP of 1.22 when the cycle time is 90 s.

3. When the ambient temperature is changed and it is higher than the water supply temperature under the condition of constant water supply temperature, the COP of the water heater increases.

4. When the flow amount of the heat-exchange fluid in the desorber is more than twice that of the water supply, the COP of the water heater increases.

5. The COP of the water heater increases with a decrease in the water supply flow amount.

On the basis of the experimental results, the COP of the hybrid water heater during a one-year period is calculated by simulating the process. As the results of numerical analysis, the COP has a maximum of 1.2 in October. We conclude that the hybrid water heater has a better performance even at low ambient temperatures.

Chapter 3　Development Of An All-in-one Type Adsorption Heat Pump

1 All-in-one type adsorption heat pump system

1.1 Design concept of all-in-one type adsorption heat pump system

In this research, we proposed all-in-one type adsorption heat pump and tried to produce a sample adsorption heat pump. The performance of adsorption heat pump prototype was evaluated with experiments under different conditions, for example, time, temperature and volume flow and so on.

In view of the aim for the development of the adsorption heat pump, the concept diagram of an all-in-one type adsorption heat pump system is presented in Figure 1.

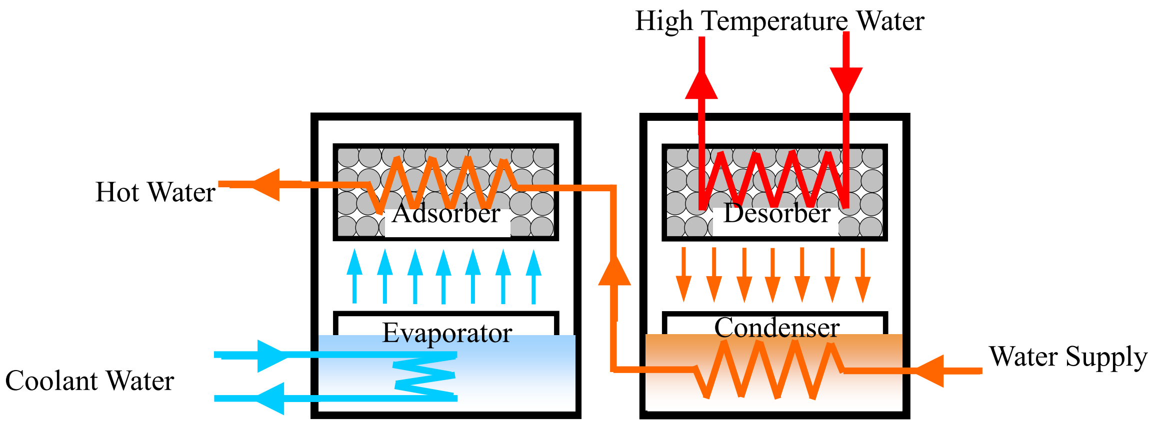


Figure 1 Concept diagram of all-in-one type adsorption heat pump system

In Figure 1, in order to obtain continuous heat, two all-in-one type adsorption heat pump prototypes can be operated in a periodic and phase-shifted mode. While one prototype is in an adsorption phase, the other prototype is in an evaporation phase. While one prototype is in desorption phase, the other prototype is in condensation phase.

The conventional adsorption heat pump consists of four independent containers: an evaporator, a condenser, an adsorber, and a desorber. The pipes for cycling the adsorbate and the valves are required not only between the evaporator and the adsorber but also between the condenser and the desorber. Each container contains a heat exchanger for the heat and mass transfer of the fluids. Compare with the conventional adsorption heat pump, in this design, two heat exchangers which are the core parts are put into a container and the adsorption heat pump is downsized. Accordingly, the adsorbate can move freely and smoothly without going through the pipe in the container. The energy loss caused by the pressure loss is reduced to zero because of the uniform pressure in one container. The operation principle of designed all-in-one type adsorption heat pump is expressed as follows:

In the evaporation/adsorption process, the water used as the adsorbate absorbs the heat from the water supply of the evaporator and evaporates in the vacuum. The evaporated water flow directly upward to the upper heat exchanger and is adsorbed by the adsorbent. And then the adsorbent emits adsorption heat. Therefore, the water supply of the adsorber is heated.

In the condensation/desorption process, the adsorbent saturated with water vapor is heated by high-temperature water, following which, the water adsorbed on the surface of an adsorbent will be desorbed, and then the desorbed vapor fill the container and is condensed by the water supply of the condenser. Thus, the water supply will be heated because of absorbing condensation heat.

1.2 All-in-one type adsorption heat pump prototypes

All-in-one type adsorption heat pump prototype is actually a container in which two heat exchangers are installed. The dimension of the container is 412mm×203mm×193mm. The designing volume of this all-in-one type adsorption heat pump prototype is 16.1L.

The container made of resin material consists of two parts. Two parts are assembled to form a sealed unit and in vacuum. It is only connected to the surroundings only by hydraulic piping. In addition, because the water lever in the container cannot be observed directly, a transparent plastic tube used as a water level gauge is installed in the container wall, as in Figure 2.

Figure 2 All-in-one type adsorption heat pump prototypes

In order to improve the heat transfer of water vapour heat exchangers are both placed up and down and assembled into such a container. These two heat exchangers are identical. Adopting the structure of corrugate copper fins and flat iron tubes can improve the heat and mass transfer effectively, Figure 3 depicts this structure. The dimension of each heat exchanger is 277mm×133mm×54mm. One heat exchanger is used as an adsorber/desorber and the other as an evaporator/condenser. The surface of the heat exchanger used as an adsorber/desorber is coated with the adsorbent. The coating thickness is 162μm.

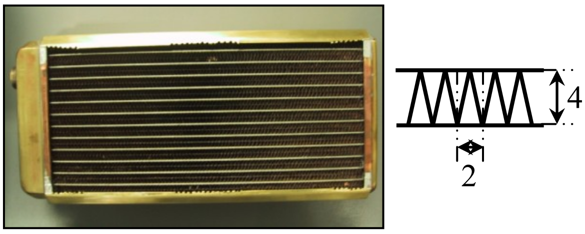


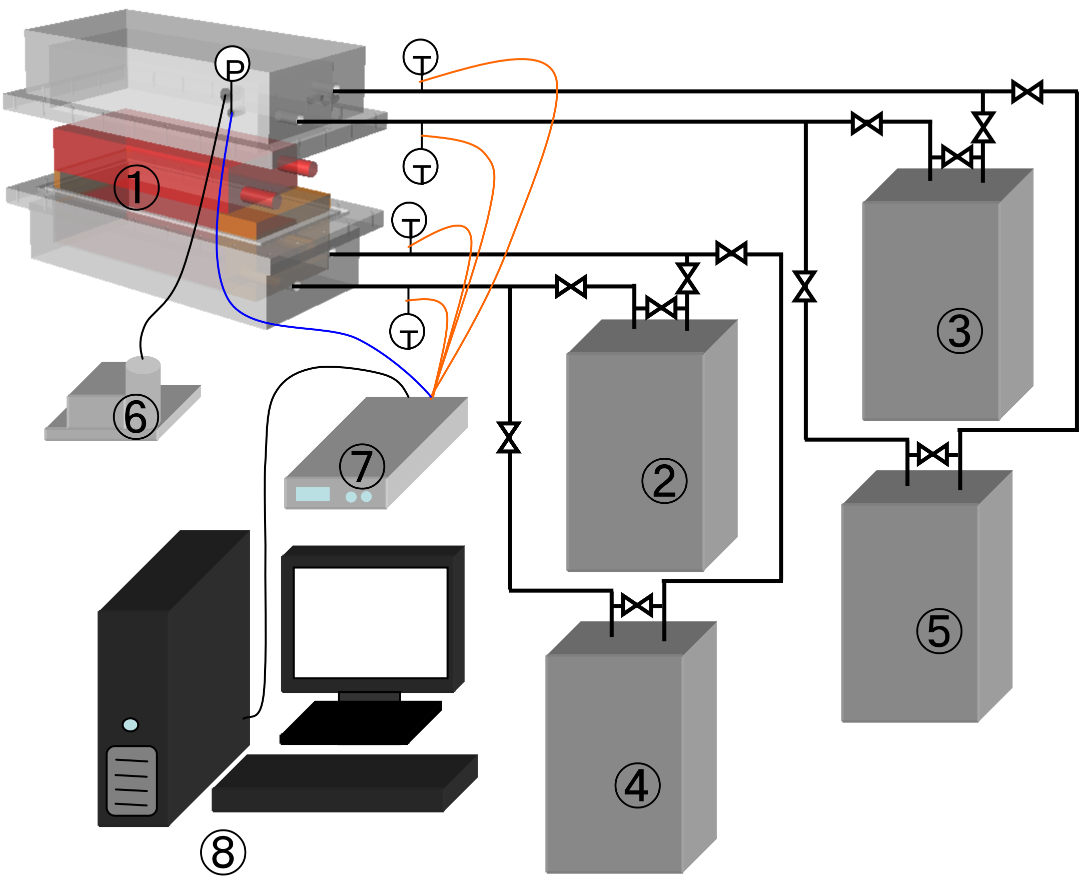
Figure 3 Heat exchanger (Unit: mm)

Moreover, the adsorbent is AQSOA FAM-Z02 (Mitsubishi Plastics) which can be regenerated by utilizing the low-temperature heat energy between 75 °C and 100°C.

2 Performance evaluation of all-in-one type adsorption heat pump system

2.1 Experimental system

A flow diagram of the all-in-one adsorption heat pump system for heating application is shown in Figure 4. The system mainly consists of an all-in-one type adsorption heat pump prototype, four constant-temperature water circulation setups (NCC-1100, 1400, Tokyo Physics and Chemistry Instrument Company, Tokyo, Japan), an oil-sealed rotary vacuum pump (USW-150, PHIL SATO Vacuum Incorporated Company, Osaka, Japan), and a device for data measurement, acquisition and process.



①All-in-one type adsorption heat pump prototype ②~⑤Constant-temperature water circulation setup ⑥Vacuum pump ⑦Data logger ⑧Computer (Ⓣ: Temperature measure point, Ⓟ: Pressure measure point)

Figure 4 All-in-one type adsorption heat pump systems

In addition, the temperature is determined with high accuracy by using a Pt resistance bulb. The vacuum gauge (Tokyo Physics and Chemistry Instrument Company, Tokyo, Japan) is used to measure the pressure in the container in leak detection test and preparation of experiment. In leak detection test we can know whether the container is sealed or unsealed. And in preparation of experiment the container is evacuated until a stable vacuum. Four electromagnetic flow meters (MGM1090K, Tokyo Instrument Company, Tokyo, Japan) are used to measure the volume flow for four heat-exchange fluids. Electromagnetic valves are used to switch the heat-exchange fluid that is supplied respectively in turn from different heat sources to the adsorber/desorber or the evaporator/condenser. Moreover, measurement and data collection is done by using the Agilent Bench-link Data Logger.

In this research, the discontinuous heat is obtained because only one prototype is used. Therefore, the experimental results are presented on the basis of one prototype.

2.2 Experimental conditions

Performance of adsorption heat pump depends on many parameters, such as temperature, cycle time and volume flow. Some parameters are assumed in the experiments.

Firstly, for the temperature, the evaporation temperature and the condensation temperature are determined by the real corresponding temperature in whole year. The changes take place in ambient and water temperature of whole year. Take the water temperature for example; it changes from 10°C to 25°C in the city of Kumamoto, Japan. The water is used as low-temperature hydraulic circuit and supplied to all-in-one type adsorption heat pump. Therefore the effects of the temperature should be considered. Moreover the adsorption temperature and desorption temperature depend on the adsorption pair used. Here the adsorbent of AQSOA FAM-Z02 has a low regeneration temperature of 75°C ~100°C, therefore desorption temperature is set as 80°C. And adsorption temperature is changed between 25°C and 40°C according to the adsorption isotherms of AQSOA FAM-Z02. Secondly, cycle time is set between 300s and 480s. Finally, the volume flow of the fluid is changed between 2.0 L/min and 5.0 L/min.

In addition, the value which is showed in the parentheses is used as experimental reference. The detailed experimental conditions are used as follows:

Desorption temperature T_{des} = 80°C

Adsorption temperature T_{ads} = 25~40°C (25°C)

Condensation temperature T_{con} = 10~25°C (15°C)

Evaporation temperature T_{eva} = 10~25°C (15°C)

Cycle time τ_{cycle} = 300~480 s (300s)

Heat-exchanging fluid volume flow in an evaporator F_{eva} = 2.0L/min

Water supply volume flow F_{con} =2.0~5.0 L/min (2.0 L/min)

Intermediate-temperature water volume flow in an adsorber F_{ads} = 2.0 L/min

High-temperature water volume flow in a desorber

F_{des} = 2.0~5.0 L/min (5.0 L/min)

2.3 Evaluation methods

Different from the evaluation methods in the previous chapter, the heating power density and the COP, two important performance evaluation parameters for the adsorption heat pump, are used to evaluate the all-in-one type adsorption heat pump in this chapter. In the previous chapter, because conventional adsorption heat pump cycle operates, outlet temperature of adsorption heat pump as a practicability standard is used. However, for advanced miniaturized adsorption heat pump in this chapter, it is focusing considerable attention on small volume and high power.

During one cycle the instant temperature differences of heat exchangers are not constant; this can be depicted by the temperature curves shown in Figure 5. In Figure 5, Ads/Des in is the inlet temperature of the adsorber or desorber. Ads/Des out is the outlet temperature of the adsorber or desorber. Similarly, Eva/Con in is the inlet temperature of the evaporator or condenser. Eva/Con out is the outlet temperature of the evaporator or condenser. Figure 5 shows the temperature changes in inlets and outlets of four heat exchangers with the time. With the time changing, the outlet temperatures change due to the changes of the heat exchange. Accordingly, inlet and outlet temperature differences of heat exchangers which consist of the condenser, adsorber and desorber are measured in the experiments. The average outputs of the condenser, adsorber and desorber are calculated according to obtained inlet and outlet temperature differences. The heating power density and the COP of the all-in-one type adsorption heat pump are also calculated.

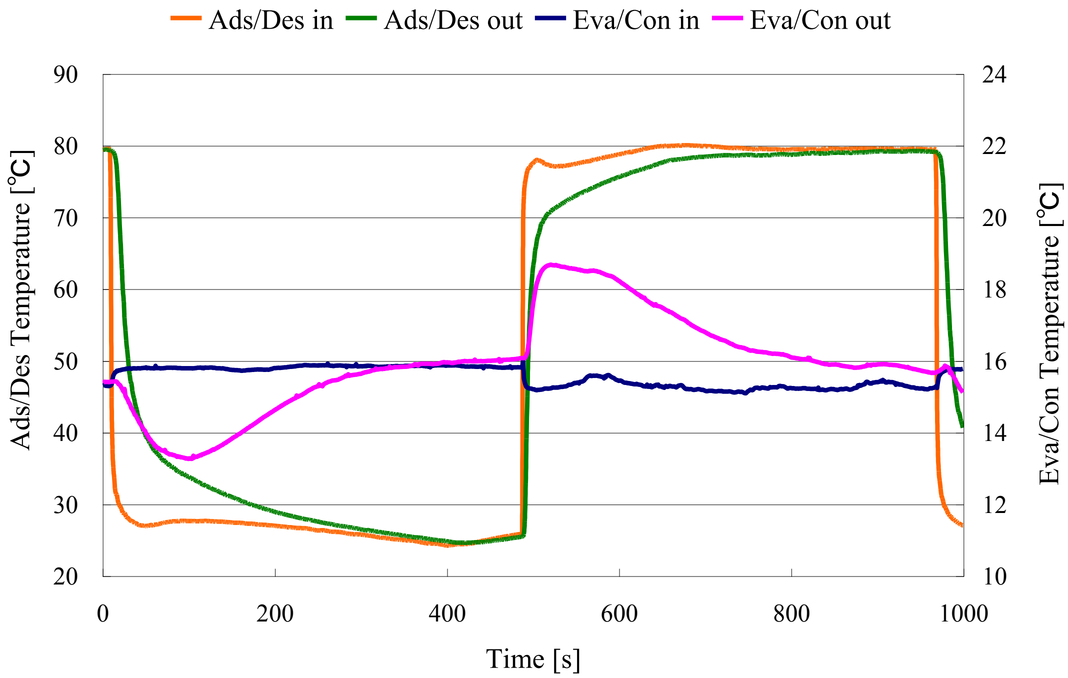


Figure 5 Diagram of the inlet and outlet temperatures in one cycle

Therefore the average output over the whole cycle is calculated after obtaining the instant output. The instant output of each heat exchanger is calculated according to the following equations:

$$Q_{ads} = CF_{ads}\rho\Delta T_{ads\_ave} \quad (1)$$

$$Q_{con} = CF_{con}\rho\Delta T_{con\_ave} \quad (2)$$

$$Q_{des} = CF_{des}\rho\Delta T_{des\_ave} \quad (3)$$

And then the heating power density of each heat exchanger is the total heating power of the adsorber and condenser per volume. Here, the volume of all-in-one type adsorption heat pump in this chapter is 16.1L.

And the COP is determined by the average heat output and heat input over the whole cycle as follows:

$$COP = \frac{Q_{ads} + Q_{con}}{Q_{des}} \tag{4}$$

3 Experimental results and discussions

3.1 Effects of evaporation and condensation temperature on heating power and COP

Ambient and water temperature vary with the seasons in whole year. In the experiments four representative water temperatures which are 10°C, 15°C, 20°C and 25°C are preferred. On the basis of the above mentioned reference experimental values except evaporation and condensation temperatures, we have carried on the experiments by changing the evaporation and condensation temperatures. Changes in the inlet and outlet temperatures of evaporator and condenser are shown in Figure 6.

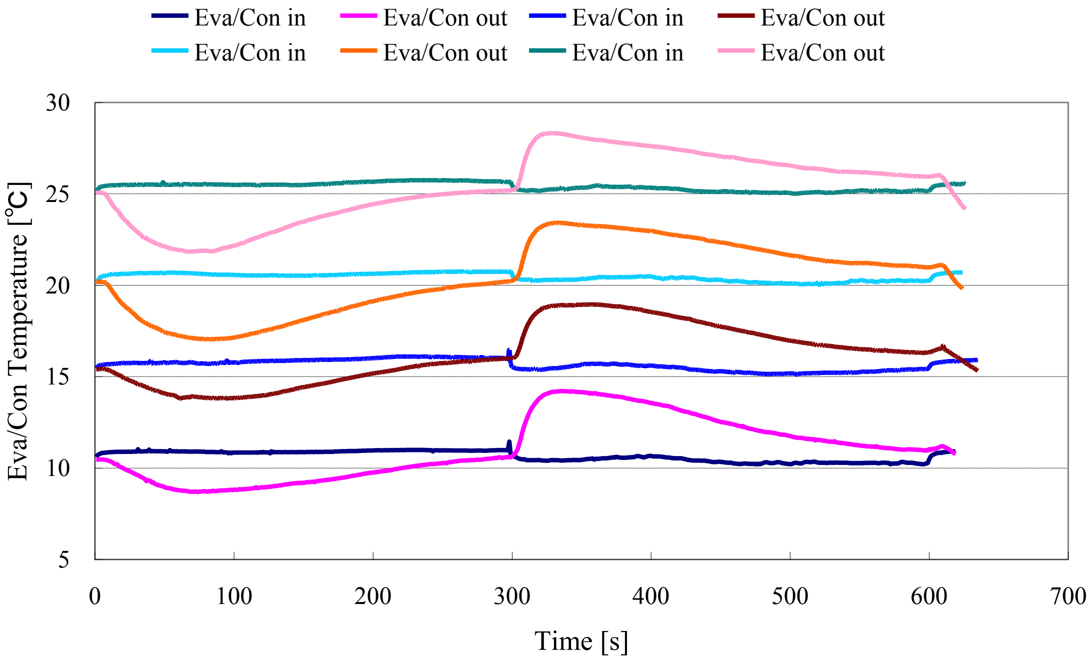


Figure 6 Changes in inlet and outlet temperatures of evaporator and condenser

From Figure 6, since inlet temperatures of evaporator and condenser change during adsorption and desorption process, the instant temperature difference between inlet and outlet of evaporator and condenser change under the corresponding operation condition. The temperature difference affects heating output of each module, which consists of evaporator, condenser and desorber, as shown in Figure 7.

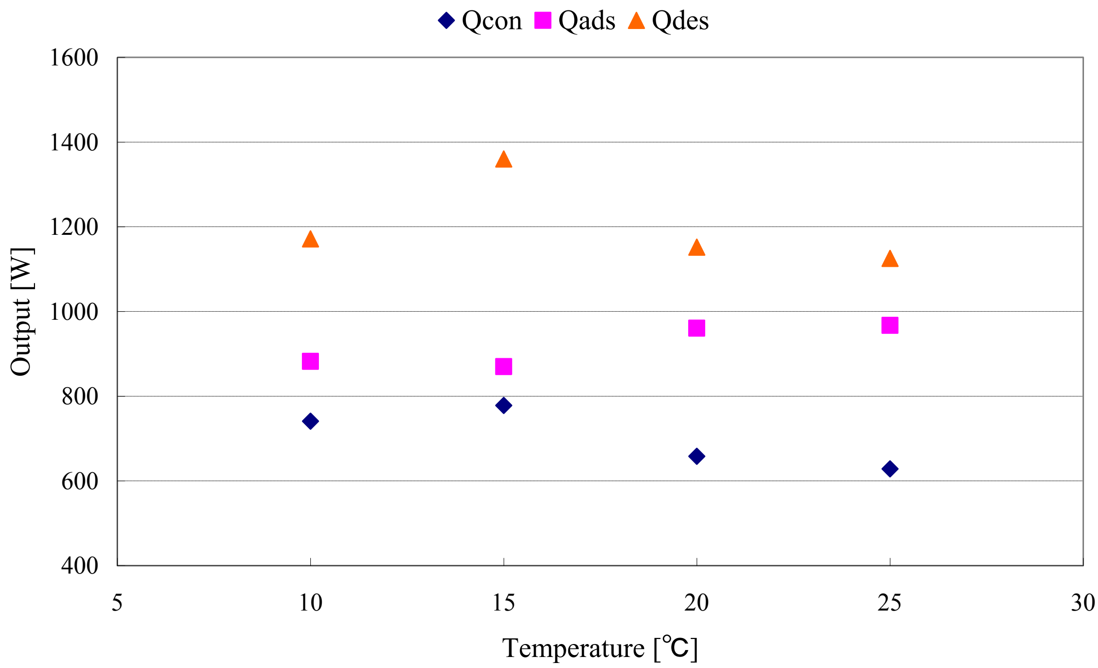


Figure 7 Variations of output with evaporation and condensation temperatures

In Figure 7, it can be seen that the average output of the condenser and desorber decrease with the increase of evaporation and condensation temperature during one cycle. For the condenser, the lower the condensation temperature is, the higher the heat exchange efficiency is. The water vapor condenses quickly when the water vapor is desorbed from the heated adsorbent during the desorption process. In other words, a low condensation temperature is helpful to the adsorbent desorption at a constant desorption temperature. And the output power has a maximum of 1359.86W at an inlet temperature of 15°C for the condenser. Moreover, the output of the adsorber increases with the increase of evaporation and condensation temperature. For the adsorber, the higher the evaporation temperature is, the easier the water evaporates used as the adsorbate because the adsorbate can obtain enough latent heat of evaporation. Accordingly, the adsorber has higher heat output at 20°C and 25°C. In addition, the heating power density and the COP are calculated and shown in Figure 8.

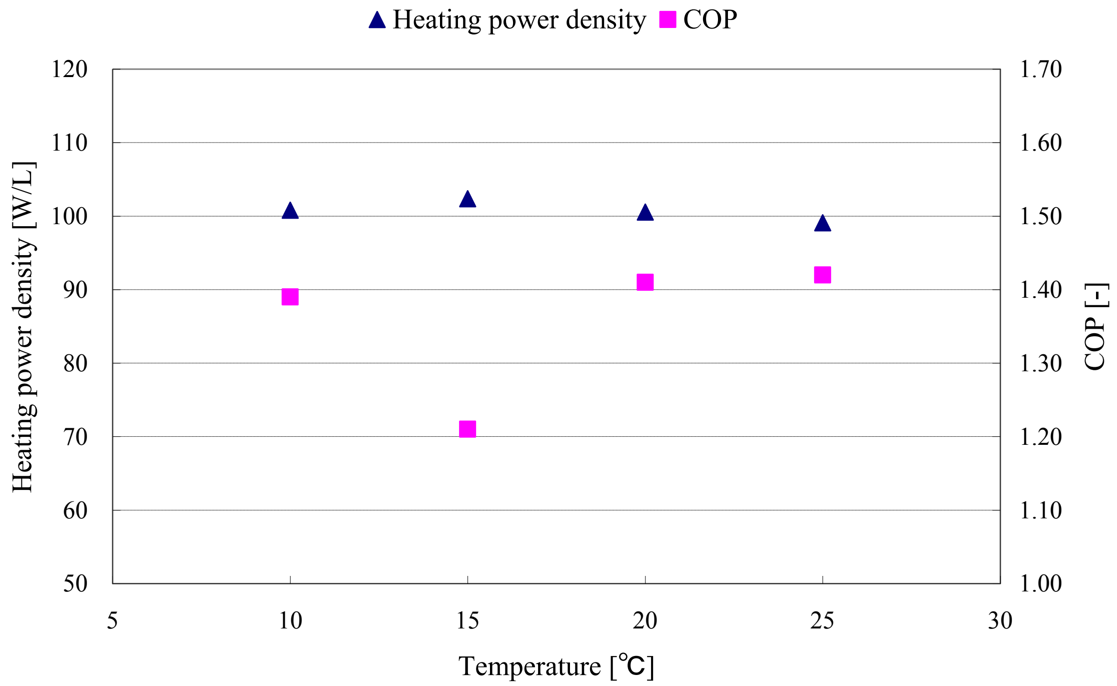


Figure 8 Variations of heating power and COP with evaporation and condensation temperatures

In Figure 8, the heating power density of all-in-one adsorption heat pump is almost constant and about 100W/L. In other words, all-in-one type adsorption heat pump has a stable heating output even if the temperature changes in a whole year. However, the COP has a minimum of 1.2 at evaporation/condensation temperature 15°C. During desorption process the good condensate effect in the condenser makes lots of water vapor condensate at the same cycle time. The operation relative pressure range of all-in-one type adsorption heat pump changes with the change of evaporation condensation temperature. At the same time, according to the adsorption isotherms of AQSOA FAM-Z02 for water vapor the adsorption capacity is higher at the relative pressure of 0.54 when the condensation temperature is 15°C. More desorption heat is required in order to make more adsorbed water evaporate. Therefore, the COP is low under the condition of the constant output of all-in-one type adsorption heat pump. The COP has a minimum of 1.2 at the evaporation/condensation temperature of 15°C.

3.2 Effects of adsorption temperature on heating power and COP

According to the adsorption isotherms of AQSOA FAM-Z02, the adsorption capacity becomes weak with the increase of the adsorption temperature of water vapor. The adsorption capacity directly affects the output of each heat exchanger. Moreover, the COP changes with the change of output of each heat exchanger. The effects of adsorption temperature on the heating power density and the COP of all-in-one type adsorption heat pump are shown in Figure 9.

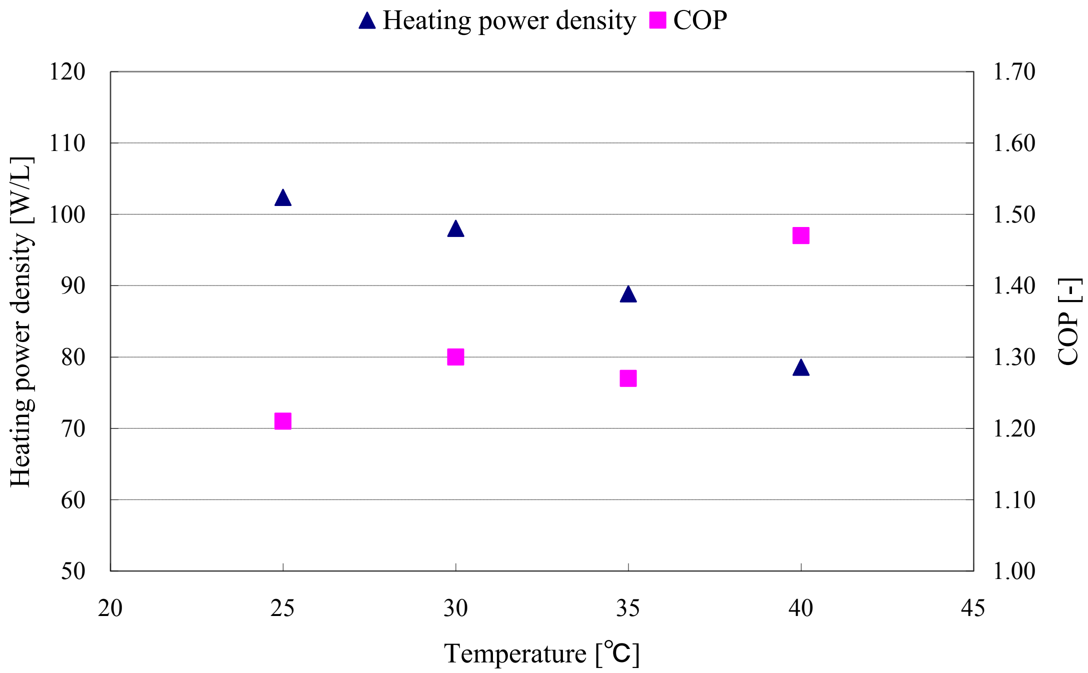


Figure 9 Variations of heating power and COP with adsorption temperature

As we can see from Figure 9, the COP increases with the increase of adsorption temperature, which makes the heating power density decreases. In the experiments the operation relative pressure range becomes narrow with the increase of the adsorption temperature due to the constant evaporation temperature and condensation temperature. It makes the adsorption capacity decrease and affects the heating power density. Accordingly, it is different from the heating power density, the COP increases with the increase of adsorption temperature because it is the ratio between the total heating output and desorber output.

3.3 Effects of cycle time on heating power and COP

Adsorption process and desorption process are periodically switched in order to continuously obtain the heat for adsorption heat pump. Greatly improved heat transfer is required to reduce the cycle time and thereby increase the power density. The evaluation experiment is required in order to optimize the cycle time and obtain the maximum amount of heating power from the adsorption heat pump. And the minimum cycle time is decided by the time required to achieve the adsorption process on the condition of the experimental reference value in the parentheses. On the basis of the above mentioned reference experimental values except cycle time, we have carried on the experiments by changing cycle time, as shown in Figure 10.

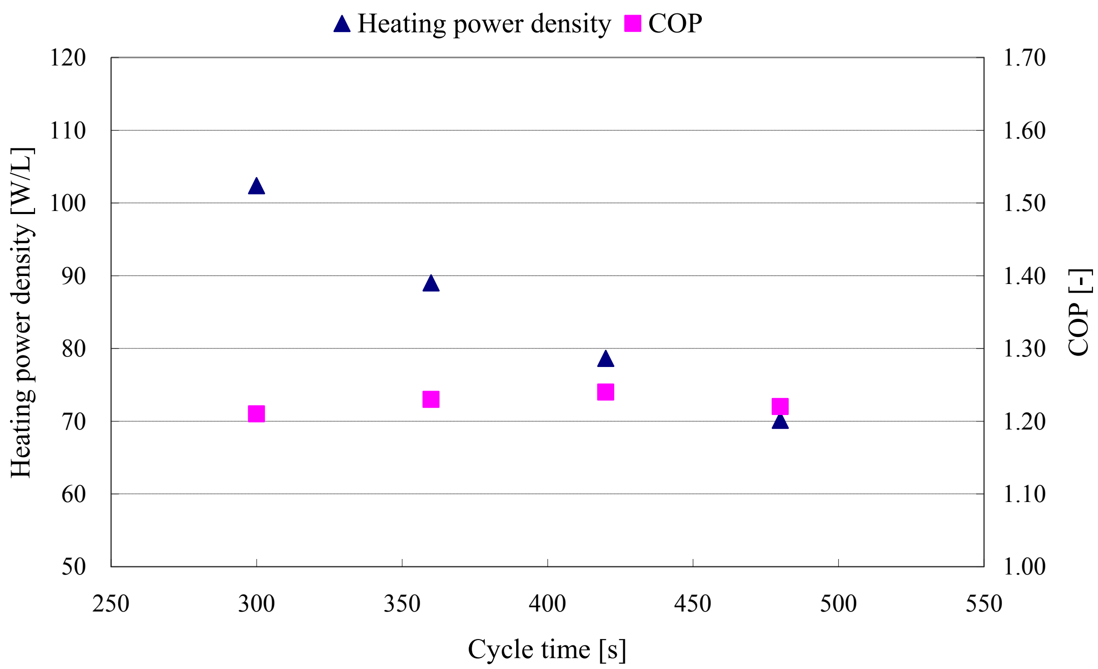


Figure 10 Variations of heating power and COP with cycle time

In Figure 10, as we expected, the heating power density of all-in-one adsorption heat pump decreases with the increase of the cycle time. The adsorbent AQSOA

FAM-Z02, with a higher adsorption speed, can reach adsorption balance within 300s. The longer the cycle time is, the smaller the temperature difference between the outlet and inlet of the adsorber in adsorption process is. The heat emitted in the adsorber decreases. Similar to the heat emitted in the adsorber, the heat emitted in the condenser also decreases with the increase of cycle time. Therefore, the heat power density of such an adsorption heat pump decreases with the increase of cycle time. The COP is almost constant even if the cycle time increases. This is because desorption heat decreases with the increase of cycle time and the COP is the ratio between the total heating output and desorption heat.

3.4 Effects of volume flow on heating power and COP

The effect of the heat source on adsorption heat pumps is an unavoidable problem. The volume flow in the condenser and desorber are changed from 2.0 L/min to 5.0 L/min due to the heat exchanger and heat source apparatus. The experiments are carried on under the conditions of the above mentioned experimental reference values except the volume flow in the condenser and desorber.

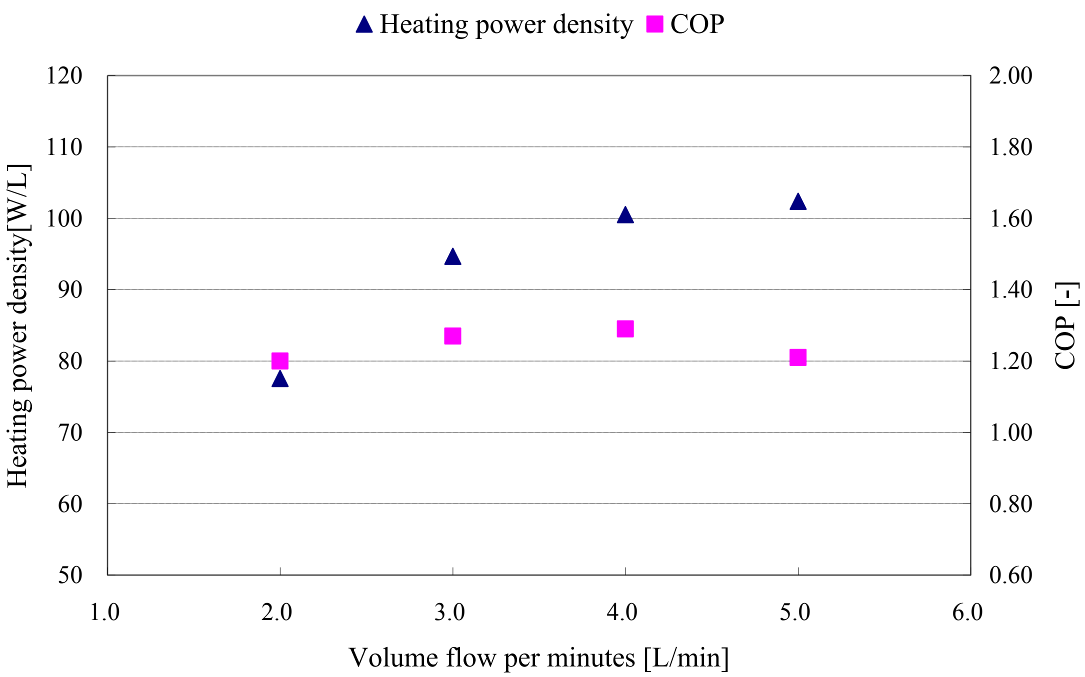


Figure 11 Variations of heating power and COP with volume flow

Figure 11 shows that the heating power density of all-in-one type adsorption heat pump increases linearly on the whole with the increase of the volume flow. In the desorption process of one cycle, lots of desorption heat make the regeneration of the adsorbent better, and then more water vapor from the adsorbent condenses because of lots of exchange heat. In the adsorption process, the complete condensation and desorption improve the adsorption of the water vapor. The factors contribute synthetically to the increase of the heating power density.

3.5 Comparison of heating power density

Nunez et al. (2007) proposed a similar all-in-one type adsorption heat pump system, but there is no detailed information about the heat exchanger, we only know that the adsorbent is silica gel from the paper. The dimensions of both modules together are 355mm×520mm×1360mm. From this dimensions, it is calculated that the volume of the adsorption heat pump is 251L. Also, the heating power from 8000 to 22000 W are achieved, in other words, the heating power density is from 32W/L to 88W/L.

A comparison of the heating power density with the data presented by Nunez et al. is conducted. From the above mentioned results in this research, the heating power density is from 58W/L to 110W/L. The comparisons between two adsorption heat pumps are shown in Table 1.

Table 1 Comparisons of two adsorption heat pumps

	Volume [L]	Minimum heating power density [W/L]	Maximum heating power density [W/L]
Adsorption heat pump designed by Nunez et al.	251	32	88
All-in-one type adsorption heat pump	16.1	58	110

Compared to the heating power density of the adsorption heat pump designed by Nunez et al., the adsorption heat pump designed in this paper only has a volume of 16.1L, but its heating power density is 1.25~1.8 times of the adsorption heat pump designed by Nunez et al.. Therefore, we can conclude that the all-in-one type adsorption heat pump designed in this research has the advantages of downsizing and high output.

4 Conclusions

An all-in-one type adsorption heat pump has been designed for heating application. The use of the corrugated-fin heat exchanger and the new functional adsorption material reduce the size of the adsorption heat pump.

Tested by the evaluation experiments, the all-in-one type adsorption heat pump can be operated normally. In addition, compared with the adsorption heat pump designed by Nunez et al., the all-in-one type adsorption heat pump in this paper has the advantages of downsizing and high output.

Nomenclatures

C	Specific heat [kJ/kg·℃]
COP	Coefficient of Performance [-]
COP_{AHP}	COP of adsorption heat pump [-]
COP_{WH}	COP of water heater [-]
F	Volume flow per minutes [L/min]
P	Saturated vapor pressure [Pa]
P_{TL}	Saturated vapor pressure of the adsorbate at low temperature [Pa]
P_{TM}	Saturated vapor pressure of the adsorbate at middle temperature [Pa]
P_{TH}	Saturated vapor pressure of the adsorbate at high temperature [Pa]
Q_{ads}	Adsorption heat [kW]
Q_{AHP_in}	Input heat for adsorption heat pumps [kW]
Q_{AHP_out}	Output heat for adsorption heat pumps [kW]
Q_{boi}	Total combustion heat from the gas boiler [kW]
Q_{boi1}	Gas boiler's combustion heat used in heating water supply [kW]
Q_{boi2}	Gas boiler's combustion heat used in desorption process [kW]
Q_{con}	Condensation heat [kW]
Q_{des}	Desorption heat (Q_{des}=Q_{boi2}) [kW]
Q_{eva}	Evaporation heat [kW]
Q_{sh}	Sensible heat [kW]
Q_{WH_in}	Input heat for the hybrid water heater [kW]
Q_{WH_out}	Output heat for the hybrid water heater [kW]
T_{ads}	Adsorption temperature [°C]
T_{con}	Condensation temperature [°C]
T_{des}	Desorption temperature [°C]
T_{eva}	Evaporation temperature [℃]
ΔT_{AHP_ave}	Average temperature difference between the inlet and the outlet of AHP in one cycle time [°C]
ΔT_{eva_ave}	Average temperature difference between the inlet and the outlet of an

	evaporator in one cycle time [°C]
Δq	Adsorption capacity difference between φ1 and φ2 [kg-H_2O/kg-adsorbent]
$\Delta q_{FAM-Z02}$	Adsorption capacity difference for AQSOA FAM-Z02 [kg-H_2O/kg-AQSOA FAM-Z02]
Δq_{silica}	Adsorption capacity difference for silica [kg-H_2O/kg- silica]
Δq_{AC}	Adsorption capacity difference for activated carbon [kg-H_2O/kg- activated carbon]
τ_{ads}	Adsorption time or desorption time [s]
τ_{cycle}	Cycle time [s]
τ_p	Preparation time [s]
φ1(φ2)	Relative pressure during the desorption (adsorption) process in the adsorption heat pump [-]
ρ	Density of the fluids [g/L]

Achievements

Nowadays, energy consumption has increased enormously with rapid population and economic growth. The rapid growth of the total energy consumption will cause serious environmental problems. Therefore, further improvement in energy efficiency is an urgent requirement in order to resolve these problems. The use of more energy-efficient appliances can be preferred to save energy and reduce environmental pollution. Therefore, a hybrid heat pump water heater consists of an adsorption heat pump and a gas boiler has been studied. It can effectively utilize waste heat between 75 and 100°C. And then an all-in-one type adsorption heat pump has been also studied. A sample adsorption heat pump with downsizing and high output is produced. Detailed descriptions are expressed as follows:

A novel hybrid adsorption heat pump water heater has been studied for domestic use. It is a water heater with dual heat sources, and it combines the performance of adsorption heat pumps and conventional gas boilers. On the basis of the assumed experimental conditions, we performed a series of the experiments on the output and coefficient of performance of the system. Some important conclusions and suggestions that improved the hybrid water heater system are presented. In addition, a numerical analysis for experimental results was presented by process simulation, and then the coefficient of performance of the system was examined. Moreover the water heater can make year-round high heat efficiency operation.

The following conclusions can be drawn from this experimental study:

1. When the water supply temperature and ambient temperature are both 5°C in the coldest day of winter, the outlet hot water temperature of the adsorption heat pump is a maximum of 46°C. Further, it is predicted that the hybrid water heater can operate normally without any operational problems even if the ambient temperature is very low.

2. The COP of the water heater decreases with an increase of cycle time; moreover, the water heater has an outlet hot water temperature of 57°C and COP of 1.22 when the cycle time is 90 s.

3. When the flow amount of the heat-exchange fluid in the desorber is more than

twice that of the water supply, the COP of the water heater increases.

4. The COP of the water heater increases with a decrease in the water supply flow amount.

On the basis of the experimental results, the COP of the hybrid water heater during a one-year period is calculated by simulating the process. As the results of numerical analysis, the COP has a maximum of 1.2 in October. We conclude that the hybrid water heater has a better performance even at low ambient temperatures.

In addition, a miniature all-in-one type adsorption heat pump with high heat output is designed. In this design, a heat exchanger coated with adsorption material is used as an adsorber or desorber, and another heat exchanger is used as an evaporator or condenser. A seal unit is formed by assembling two heat exchangers into a vacuum tight container and is connected to the surroundings only by hydraulic piping. Moreover, the adsorbent is AQSOA FAM-Z02 which can be regenerated by utilizing the low-temperature heat energy between 75 and 100°C. Tested by the evaluation experiments, the all-in-one type adsorption heat pump can be operated normally. In addition, compared with the adsorption heat pump designed by Nunez et al., its heating power density is 1.25~1.8 times of the adsorption heat pump designed by Nunez et al.. The adsorption heat pump only has a volume of 16.1L. Therefore, the all-in-one type adsorption heat pump in this paper has the advantages of downsizing and high output.

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