Review and Prospect of Heat Pump Cycle Research

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Abstract: In this article, the technologies of heat pump were reviewed. First the substitute mechanisms of refrigerant were analyzed Total equivalent warming impact (TEWI) can be used to comprehensively evaluate the environmental factor of refrigerant, including the direct influence and indirect effects. Second considering the heat pump is an efficient technology to exploit new energy source, typical heat source of heat pump were analyzed. Suggest in north of China heat pump system best heat source is geothermal energy. It can be lake or river, under ground water and soil etc. Thirdly compared electrical and mechanical driven heat pump and analyzed absorption heat pump system use heat engine combined heat pump model. And then analyzed the heat pump control method. Find the variable speed control have ability to keep more precision temperature. Final the advance trend on heat pump recycle technology was proposed. It was pointed out that the regenerated energy source and natural refrigerants were promising development direction. With the wide application, the coefficient of seasonal energy efficiency will become an important index of heat pump evaluation. The capacity of heat generated by heat pump should be tunable and matches with the external load. Utilizing natural refrigerants and regenerative energy will be an eternal goal in improving heat pump technology.

Keywords: heat pump   heat source   natural refrigerant   capacity control   absorption heat pump   mechanical driven heat pump

0.Introduction

The heat pump is one of conversion technologies to improve energy source quality. Conventionally, the heat spontaneously flows from high temperature to low temperature; while by heat pump technology can the heat be transferred inversely with less high quality energy, for instance, electric power, fuel and high temperature wasted heat. The heat quality can be enhanced with heat pump to supply heat for buildings and industry. Moreover the high entropy heat is abundant in nature, for example, air, river, ocean and waste heat from industry and family. Thus this is an economical and environmental friendly technology.

Heat pump system includes a variety of cycle modes such as Stirling cycle, gaseous single phase cycle(CO_2 and inert gas), solid-steam adsorption cycle, combined cycle(the combination of steam compression and adsorption), thermal-electric effect, acoustic-thermal effect. However, to date the frequently used are steam compression and absorption cycle, which are characterized by utilizing the phase change of refrigerant.

The performance parameters of heat pump include COP, PER, Carnot-efficiency, seasonal performance coefficient (SPF), etc. The performance of heat pump can be evaluated from different aspects.

The COP of heat pump is restricted by T1, utilization temperature and T2, heat source temperature. COP decreases upon increasing T1, i.e. the lower the heat quality of system is enhanced, and the greater the high quality heat is required. COP increases with the increase of T2, i.e. a higher T2 results in a higher quality heat. The thermodynamic properties of refrigerant and the mechanical performance of cycle devices exert an effect on the performance of heat pump system due to the irreversible process in practical cycle process. The devices of heat pump system are mainly composed of water pump, fan and accessorial thermal sources, and so on, which have an important influence on SPF.

1.The development of refrigerant

Looking back on the history of refrigeration air conditioner, the refrigerants evolved from ethyl ether, dim ethyl ether in 1863, CO_2, NH_4, SO_2, CCL_4 in 1875, NH_4 in 1859, CFC（R11、R12、R22, and so on ）in 1933, to present HFC and its mixtures. The evolution of refrigerants are driven by the technology progress and an growing concern over safety, and in substitution history, the main concern is the toxicity, stability and inflammability of refrigerants; with the advancement of technology, the economy, thermodynamic properties such as heat capacity, critical point and the compatibility with device lubricant have become the conditions in selecting refrigerants. The synthetic Freon developed by Dupont Com. meets the above requirements very well, and proves to be of great success in market. Accordingly, the steam compression cycle system got a predominant position in heat pump conditioning refrigeration technology.

With the increasing awareness on the issues of greenhouse effect and ozone layer destroy, people realize that Freon only brings transient convenience, but causes long-term environmental problems, that is greenhouse effect and ozone layer destroy. The ozone depletion potential (ODP) and global warming potential (GWP) are used respectively to denote the ability of refrigerant to destroy ozone layer and cause green house effect.

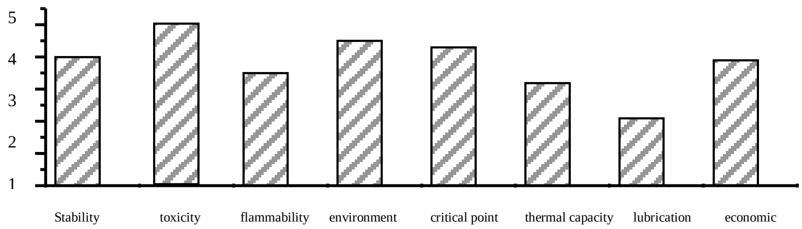

Figure 1. Major factors of refrigerant selection

From the refrigerant evolution, the importance of major factors of refrigerant selection is shown in Figure 1. Based on the importance, different factors are graded, the maximum is 5. As shown in figure, the most important is the toxicity of refrigerant. The environmental factors refer to ODP and GWP. The second important are stability and economy; in thermodynamic properties, critical point is the highest and oil compatibility is the lowest. The practical refrigerant alternatives are selected as well in terms of the figure.

In refrigerant substitution, the environmental factor should be comprehensively and systematically considered. Otherwise, the efficiency of cycle energy would be lowered and energy consumption would be increased, leading to indirect environmental problems. Total equivalent warming impact (TEWI) can be used to comprehensively evaluate the environmental factor of refrigerant, including the direct influence and indirect effects.

According to chemical component, the refrigerants can be classified as Freon series and natural work fluid.

Freon series are classified as:

(1) CFC includes R11, R12, R13, R113、R114、R115、R500、R502, etc. They have such merits such as good thermodynamic properties, low toxicity, mature manufacture technique, low price and the corresponding well-designed devices. But OPD and GWP are higher, restricting their applications.

(2) HCFCs includes R22，R401，R402，R403，R408，R409, etc. They have the same merits and demerits as CFC.

(3) HFC: According to the prohibition scheme, the short-term and medium-term alternatives are proposed, which have the similar thermodynamic properties to those of CFC and HCFCs, ensuring the little alteration of devices. HFC includes R134a, (substitution for R12), R152a(substitution for R500), R32（substitution for R22）, R125 and R143a（substitution for R502）, and so on.

(4) Mixture refrigerants: Since the alternative CFC and pristine HCFCs cause the properties of system to decrease, the mixture refrigerants are developed to sustain and enhance the property of COP. Mixture refrigerants include R410A，R407C, etc.

Freon series are synthetic products, and consumed in great amount; it is gaseous at room temperature and diffusible, and its structure is relative stable, which makes it far off mass cycle balance in nature; its regeneration rate is far below the consumption rate, resulting in a high concentration of gaseous Freon. Thus, from the viewpoint of sustainable development, Freon refrigerants should not mass-produced, and it is not an ultimate solution to replace Freon of known harm and high concentration with the one of unknown harm and low concentration.

Immoderately discharge of Freon into the air is threatening the environment. So developing recycle technology and modifying the tightness of device is a critical solution to the application of Freon refrigerants.

Natural refrigerants include ammonium, water, CO2 and carbohydrate, and so on. Nature is rich in natural refrigerants, which do not vary their contents. Therefore, they do environment no harm, and even a large amount of utilization will not cause direct environmental problems. But the COP of natural refrigerant system is lower than that of Freon system. So considering the energy consumption, the emission amount of CO2 for natural refrigerant system should be larger than that for Freon system. Increasing the COP of natural refrigerants is a key solution.

Of course, the natural refrigerants are not perfect in other properties. For instance, the toxicity of ammonium and combustibility of carbohydrate should be solved.

2.Heat source of heat pump

The COP of heat pump is closely related to the characteristics of heat source. The ideal heat source is that the system has a higher and more stable temperature in the heat supply process, i.e. the quantity of heat per joule contains low entropy, and the reservation of heat source is abundant; the heat source is non-contaminated to the environment and corrosive less to devices. In development and transformation, it needs low investment and operation expense.

Table 1 lists the typical heat source of heat pump. The common temperature is below 25 ℃。Although theoretically the higher temperature of heat source, the better the performance of system, but the operation temperature is higher as well. For the steam compression heat pump currently used, the medium and high temperature system(≥60℃) tends to cause lubrication and mechanical problems due to incomplete technology. Therefore, for the heat source with temperature greater than 25℃, the direct heat exchange mode is frequently used.

Table 1 typical heat source of heat pump

Heat source		Temperature range（℃）	Entropy per joule （10^{-3}J/K）
Natural	Air	-10~15	3.80~3.47
	Sea	3~8	3.64~3.56
	Lake, river	0~10	3.68~3.55
	Ground water	4~10	3.61~3.55
	Shallow soil	0~7	3.68~3.57
	Deep soil	7~15	3.57~3.47
	Solar energy collector	0~20	3.68~3.42
Waster heat	Waste gas	15~25	3.47~3.36
	Waste heat flow	＞10	3.53

The natural heat source is mainly originated from solar energy and radiation heat of the earth. The radiation heat is reserved in environment or collected by mankind in medium. The heat source is characterized by the intermission and decentralization. The temperature of heat source varies with the intensity of sun radiation, and changes obviously with season, day and night. Another heat stems from geothermal energy. Some heat source is influenced both by geothermal energy and solar energy, and the temperature of heat source is relatively stable.

(1) Air

Air is the most extensive and most frequently used heat source for free. However, the temperature of air fluctuates greatly owing to the evident effect exerted by weather variations. What’s more, the production characteristics of heat pump for heat supply vary inversely with the demand.

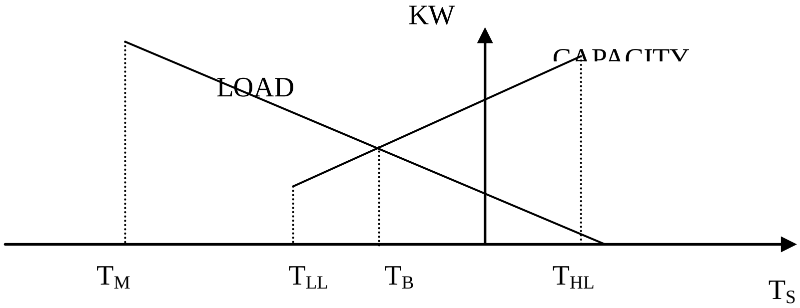

Figure 2. The heat capacity and load of building versus environmental temperature

As shown in the figure 2, with the decrease of T_s, the load of building is increased, and the capacity of heat pump decreases. T_m corresponds to the maximum of load. At T_{LL}, the heat pump system is invalid, cannot work. T_{LH} is the upper limit work temperature of heat pump. T_B is the equilibrium point. When the environmental temperature is below T_B, the heat pump system cannot satisfy the load of building. Thus, the heat pump system with air as heat source is restrained by region. Typically, at south of Yangtze River the heat pump based on system air heat source is widely employed; whereas at north of Yangtze River, the heat pump system is merely an accessorial heat supply mode.

(2) Seawater, lake water, river water and groundwater

Since water is a heat source medium, water at sea, lake, river and underground is markedly characterized by its more stable temperature relative to air source, and the load of water system is not much influenced by the variation of environmental temperature. The heat resource of seawater, lake water, river water and groundwater should be exploited to its full. In Figure 2, the slope of capacity of heat source heat pump decreases, and T_{LL} is decreased. A reasonable design can make T_{LL}equal to T_M, that is heat pump becomes dominant in heat supply.

The system can also be classified as open and closed one. Open system requires that water be of high quality, no corrosive, and groundwater be released without toxic gas emission or influencing water level.

The utilization of seawater is closed system. The depth ranges from 25 to 50 meters. In winter, the water temperature of river and lake is lower; so avoiding freezing is the critical to heat pump system.

According to the heat exchange between refrigerant and heat source, heat pump system can be categorized into direct and indirect evaporation systems. In direct evaporation system, refrigerant directly exchanges heat with heat source, and is more efficient than indirect system, but is hard to maintain.

(3) Soil heat source

Soil and groundwater heat sources share the identical characteristic, i.e. temperature is constant and not sensitive to the variation of environmental temperature. As a kind of regenerative energy, the heat released by soil heat source in winter can be compensated in summer. The heat pump system of soil source includes direct and indirect evaporation modes.

The tubes underground can be aligned horizontally and vertically.

Shallow soil refers to underground 30M to 100M; deep soil refers to 100M to 200M. The temperature distribution of soil source is related to underground depth. Temperature rises about 2 to 5℃ every 100 meters downwards.

The soil heat source is abundant in nature and not limited by region. The terrestrial heat that can be directly utilized (temperature is above 40℃) is circumscribed by geographical location and underground depth. This is not the soil heat source of interest.

(4) Solar energy collector

Solar energy collector can transform the solar radiation energy to heat energy stored in medium to be used. Due to the limited capacity of medium, this kind of energy is unstable in storage, and varies day and night. Moreover, the energy collection is discontinuous, and cloudy and foggy weather affects its collection. So it is vital for solar energy collector to increase the stability of supply. It is required that the storage devices are equipped and more stable heat source be ready. So the solar energy collector can be combined with other heat sources.

(5) Waste heat

The waste heat emitted by ventilation system and waste heat emitted in the production process can be recycled. A large amount of heat is produced in the process of sewage disposal; whereas, the large amount of heat consumed in the operation process can be completely provided by heat pump system. Heat pump technique can play an important role in recycling waste heat.

3.High quality energy of heat pump and driving mode

Two kinds of heat pump systems currently in operation are steam compression and absorption heat pump. Other heat pump systems will not be introduced.

Table 2. The utilization mode of high quality energy by heat pump system

Heat pump mode	Energy form	Manner of energy conversion	Resource	Conversion device
Compression mode	Mechanical work	Electric energy	Coal, gas, oil, Solar, wind, hydrodynamic nuclear energy	Generator
		Chemical energy	Gasoline, natural gas, methanol, DME	Internal-combustion engine, external-combustion engine, gas turbine
Absorption mode	Heat energy	热能	Industrial waste heat	Heat exchanger
		化学能	Fossil fuel	Boiler
		Radiation energy	Solar energy	Solar energy collector

(1) Electric power-driven heat pump

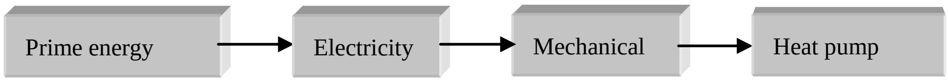

Figure 3 Energy conversions driven by electric power

From Figure 3, prime energy efficiency for electric heat pump system

$$PEER = \frac{Q}{H} = \frac{Q}{W} \times \eta_1 \times \eta_2 = COP \times \eta_1 \times \eta_2$$

Where η_1 and η_2 is the efficiency of electric generation and mechanical efficiency, respectively. The COP of heat pump currently used is up to 2.5 to 5; η_1 is 25%~30%; η_2 is 70%~85%, PEER is 0.44~1.28.

Since the operation of heat pump is heavily dependent upon the seasonal variations, electrically conditioned heat pump system can lead to the imbalance of electric load whether for winter heating or for summer refrigeration, which caused a sort of burden to both the safety of installed capacity of electric power generation and operation maintenance.

In spite of the above-mentioned shortcomings, the supply of electric power is widely utilized. What's more, electric power is the most convenient energy; so the electric heat pump conditioning system holds a big market share.

(2)Mechanically driven-heat pump：

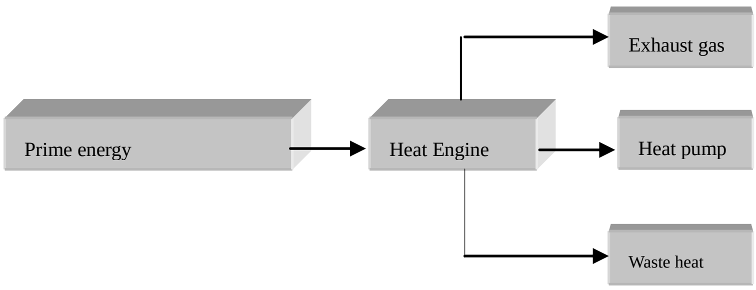

Figure 4 Diagram of energy conversion for mechanically driven-heat pump

As shown in Figure 4, commercial energy transforms from the fossil energy to mechanical one, which drives heat pump system, and meanwhile, the wast heat from gnerator and the exhaust gas can be recycled.

Prime energy efficiency:

$$PEER = \frac{Q_1 + Q_2 + Q_3}{H} = COP\eta_E + \eta_R$$

Where Q_1、Q_2、Q_3 is the heat produced by heat pump, waste heat from generator and exhaust gas, respectively. $\eta_R = \frac{Q_3 + Q_2}{H}$ is the united efficiency of excess heat recycle. η_E, the efficiency of generator ranges from 23% to 40%. It varies with the cycle mode, rotation speed and load of generator. The generator includes internal-combustion engine, external-combustion engine.

The COP of mechanically driven heat pump is identical to that of electric one, which ranges from 2.5 to 5. If the utilization of excess heat is taken into account, the PEER is 0.8 to 2.

(3) Absorption heat pump

The compression heat pump is driven by mechanical work, while the absorption heat pump is driven by heat energy. From the definition of prime energy efficiency, we have,

$$PEER = \frac{Q}{H} \qquad \text{The value varies from 1 to 1.8.}$$

From the point of energy consumption, the energy consumed by absorption heat pump is high entropy heat energy, which can be easily supplied not only by commercial energy but also by solar energy of waste heat produced in life. By this way can H be obtained without charge. So if T, the compensation time coefficient of energy investment for device operation, is greater than 1, it is economically competitive. In addition, the operation noise for absorption heat pump is far lower than for the mechanically driven compression system. Furthermore, the maintenance cost of absorption heat pump is lower as well. But if the high quality commercial energy is used to drive heat pump, the operation expense will be raised owing to lower efficiency relative to compression system.

Absorption heat pump is essentially composed of two cycles; one is normal heat pump cycle. The other is heat engine cycle. Figure 5 describes the cycle mechanism of absorption heat pump. In general, there is a relation between T1, temperature of high temperature heat source, and T2, application temperature of heat energy, and T3, temperature of low temperature heat source.

$$T_1 > T_2 > T_3$$

In heat engine cycle the efficiency of Cornot cycle is: $\eta = \frac{T_1 - T_3}{T_1}$

In heat pump the COP of Cornot cycle is： $COP = \frac{T_2}{T_2 - T_3}$

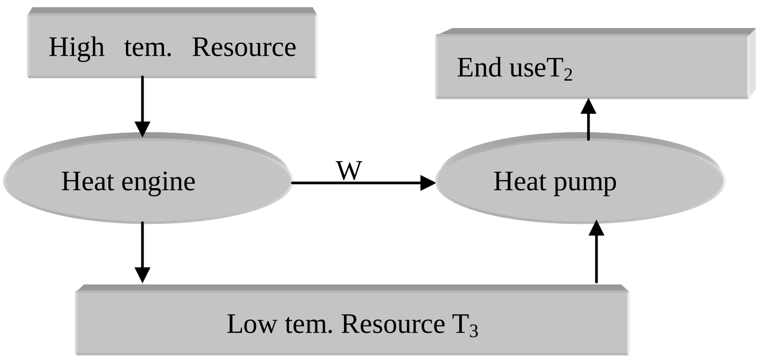

Figure 5 Analysis of the cycle mechanism of absorption heat pump

The PEER of heat pump system is: $PEER = \frac{Q}{H} = COP \times \eta$

Compared to the mechanically driven heat pump system, for the cycle efficiency of ideal adsorption, the COP, η and PEER are all restricted by temperature of heat source.

The practical cycle is also affected by the physical properties of refrigerants. In absorption cycle, the commonly used refrigerants are mixtures of lithium bromide and water or ammonium compounds. In heat engine cycle, to guarantee the normal operation of generator and absorber, T1, cannot be too high, and T3 cannot be too low either. Therefore, η of system is far below that of normal heat engine cycle.

If the mixture of lithium bromide and water is used as refrigerant, the refrigerant is water for heat pump cycle of absorption heat pump. In normal operation condition, the pressure ratio π of water is greater than Freon, Too much work is consumed. The COP of system decreases compared to other refrigerants.

Consequently, whether for heat engine or heat pump cycles, the characteristics of refrigerants results in the decrease of efficiency. But since the absorption system is composed of the perfect combination of two cycles, there is no intermediate loss in the process of separation and mixing of mixture refrigerants. Hence, the transfer loss is decreased compared to the energy conversion of mechanical system with independent completion of normal and reversible cycles.

From the analysis of three kinds of driving cycle, a conclusion can be drawn that a system cannot be evaluated in general way; the factors such as practical energy condition and application background should be considered in selecting a system.

4.The control of heat pump system

There are two purposes for the control and adjustment of heat pump; one is to guarantee the safety of system. Due to the device technology, the device must be operated in safe condition, for instance, ensure that device operates in the range of bearable pressure, operates without freezing, and compressor operates without liquid hammering. In designing a system, many factors should be comprehensively taken into account to ensure the safe operation of system.

The other purpose is to guarantee that the heat generated meets the demand of consumer load. If the heat generated exceeds the demand of consumers, the excess heat is wasted. On contrary, the system cannot satisfy the demand of consumers. This type of adjustment is called capacity control adjustment.

In practice, the operation of heat pump system is limited by many conditions. So in the first the control adjustment must guarantee the safe operation of system. The COP should be maximized when the heat is adjusted to meet the demand of consumers, which minimizes the consumption of commercial energy.

Q_1, the quantity of heat can be determined as follows:

$$Q_1 = G \times (h_5 - h_2)$$

W, the input work is:

$$W = \frac{G \times (h_2 - h_1)}{\eta_m \times \eta_s}$$

G, the mass flow rate of refrigerant for positive-displacement compression heat pump is:

$$G = \frac{\eta_v \times V \times n}{v_1}$$

Where η_s is the absolute efficiency, η_G is mechanical efficiency, η_v is volume efficiency, n is rotation speed(RPM), V is the effective volume, and v_1 specific volume of refrigerant.

The COP of system is:

$$COP = \frac{Q_1}{W} = \frac{h_5 - h_2}{h_2 - h_1} \times \eta_s \times \eta_m$$

The quantity of heat is controlled by adjusting G and enthalpy difference (h_2-h_5). The h_2-h_5 is adjusted by changing the temperature of high and low temperature heat source, i.e. varying the operation condition, which can be realized by varying the throttle device. However, in the case of fixed devices, this kind of adjustment is limited considering the safety of system operation. For the mixture refrigerants, the adjustment is realized by varying the component of refrigerants. The main method of volume adjustment of steam compression heat pump is control adjustment compressor, of which included are on-off adjustment and shift gear adjustment of compressor.

(1) On-off model control

From formula above, it can be seen that when the rotation speed is set 0-1 control modes, the input amount of gas is adjusted by 0-1 modes, by which the amount of heat generated changes based on 0-1.

The advantage of on-off control is that the control structure is simple, and the response is quick, but the disadvantage is that the amount of super adjustment is great, control precision is poor and output is step change. To circumvent these shortcomings, multi-cylinder unload can be used in the systems. Adjusting the effective volume, V. In consequence, the precision can be improved by varying step length of adjustment.

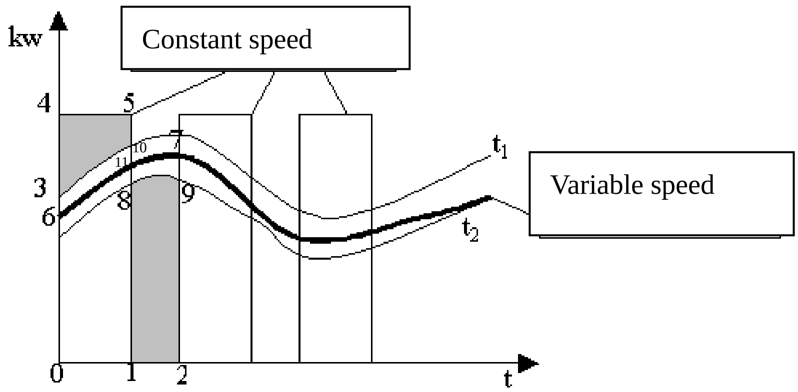

Figure 6 Diagram of heat pump control principle

(2) Variable speed control

Based on formula above, the variation of n also changes the G. So Volume adjustment with variable rotation speed is an effective method of volume adjustment. For mechanically driven heat pump system, adjusting the amount of fuel supply of engine can change the rotation speed; whereas for electric heat pump, it can be adjusted by line frequency.

Figure 6 displays the diagram of heat pump control principle. On-off modulation is schematically drawn. It’s assumed that the quantity of heat generated is merely affected by on-off adjustment. The curve of t1 is the heat capacity stop temperature corresponds to; the curve of t2 is the heat capacity startup temperature corresponds to. The heat pump with variable speed is characterized by stable operation, exact temperature adjustment, small over-adjustment, and quick response. But due to continuous operation, its economized energy depends on practical situation compared to the on-off modulation.

When the on-off adjustment is closed (time 1-2), the area 1289 corresponds to the practical load. Hence, over the range of time 0-2, the enclosed area of 0-3-10-8-9-2-0 determines the load. At stop time (1-2), the heat is transferred from the enclosed area of 3-4-5-10 to the area of 1-2-9-8. The enclosed area of 0-1-5-4 determines the generated heat. The heat generated by heat pump with variable speed corresponds to the enclosed area of 0-2-7-6. Thereby, when the area of 1-2-7-11 is larger than that of 6-11-4-5, a larger amount of heat can be produced by on off than variable speed continuous tuning.

Nevertheless, the more stable temperature can be maintained by variable speed continuous tuning.

From the above analyses, we can get a deep insight into the various modulation methods of heat pump systems, especially for on-off and variable speed adjustment whose advantages vary with the situation. Therefore, their merits and demerits cannot evaluate without knowing real background.

5. Prospect of cycle technology

Natural refrigerants are the preferred in the future. Looking back on the development of refrigerants, we find that the natural refrigerants are being optimized in many aspects such as environmental factor, toxicity and economy. But for 600a、R290, etc. The prevention of combustibility needs further investigation.

Natural refrigerants are not well developed due to their poor thermal properties. So it is the future direction to develop heat pump cycle technology suitable for natural refrigerants. The thanscritical CO2 cycle will become an important technology.

With the wide application, the coefficient of seasonal energy efficiency will become an important index of heat pump evaluation. The capacity of heat generated by heat pump should be tunable and matches with the external load.

6. Conclusion

The heat pump technology is worthwhile to be popularized. It is an effective way to exploit new energy. This technology needs further investigation. Heat pump technology can reduce discharge considering environmental factor, but we must pay attention to the application of refrigerants. Utilizing natural refrigerants and regenerative energy will be an eternal goal in improving heat pump technology.

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