An Advanced Solar-Powered Rotary Solid Adsorption Refrigerator with High Performance [1]

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Abstract: In this paper, according to practical consideration, a new solar powered rotary solid adsorption refrigerator system adopting activated carbon fibre + ethanol as its adsorption pair has been designed with higher performance. Moreover, the principle of the refrigeration cycle, different components of the machine, selection of working pairs and feasible theory analysis of the refrigeration system all have been presented in detail. In addition, it shows that the new refrigerator has many great advantages including a simple structure, fast refrigeration, higher thermodynamic coefficient, friendly to the atmospheric environment, etc.

This paper explains that the refrigerating process is constant, which has a promising potential for competing the 'intermittent' cycle reported before. Through improving the refrigerant performance of heat and mass transfer in the adsorbent bed, the refrigeration cycle has been advanced from the aspect of utilization of the thermal energy from low-temperature level resources. In addition, it is shown that the commercial solar powered refrigerator will be existent in the near future.

Key words: Solar energy; Adsorption; Rotary refrigerator; Activated carbon fibre; Ethanol

Nomenclature

C_1	specific heat of activated carbon fibre（$J/kg•k$）
C_2	specific heat of ethanol（$J/kg•k$）
COP	coefficient of performance（dimensionless）
dt	variation of time (s)
dv	variation of volume (m^3)
dx	variation of mass (kg)
H	average equivalent adsorbing heat quantity(J/kg)
ΔH	adsorbing heat quantity（J）
T_0	evaporating temperature（K）
T_a	terminal point of adsorbing temperature（K）
T_k	condensing temperature（K）
T_j	terminal point of desorbing temperature（K）
x	adsorbing capacity（kg）
X_0	adsorbing rate（dimensionless）
ρ	density of activated carbon fibre（kg/m^3）
τ	time（s）
δq_x	adsorption heat quantity of unit controlling body under isotonic adsorption （J）
δq_H	absorption heat quantity of unit controlling body under isometric heating （J）
δq_0	absorption heat quantity of unit controlling body under isotonic desorption （J）
δq_T	refrigerating capacity of little unit controlling body（J）
δq_k	thermal load of condenser（J）
λ	evaporation latent heat at T_o (J/kg)

1.INTRODUCTION

Utilizing solar energy、industry heat wastes, etc as the compensation to complete the heat transfer process from low-temperature heat source to high-temperature heat source is an important way to develop more efficient utilization of energy and launch the technological transformation taking energy-saving as its key part.

As early as in the 1970s, in order to solve the problem of energy shortage, the research of solar powered solid adsorption refrigeration has been carried out in some countries including China.

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furtherit is inconvenient to operate it.

Research has shown that solar powered solid adsorption refrigeration technology has a promising potential for competing with conventional vapor compression and absorption technologies. However, because the thermodynamic coefficient of this system is relatively lower, the commercial solid adsorption refrigerators powered by solar are still non- existent.

Fortunately, with the development of science and technology, new materials、new techniques are emerging continually, such refrigeration technologies without CFCs recently have attracted extensively increasing attention from the experts all over the world because of their simple structure 、 fast refrigeration、low-level powering energy source、 without generating the greenhouse effect 、 not destroying ozone layer, etc[1].

The research contents of solid adsorption refrigeration powered by the solar energy in recent years can be summarized as the three following respects.

(1) Study on the character of refrigerant and performance of the refrigerant-adsorbent working pair and the refrigeration circulation;

(2) Research of high-efficiency heat power circulation;

(3) Research on adsorbing bed's structure and the heat transferring performance.

Among them mentioned above, the research on the adsorbing bed's structure and the heat transfer performance is exactly the hot issue in the present research. Because that is the key point of raising the refrigerating efficiency of adsorption refrigeration and making the adsorbing refrigeration machinery move towards the market in future.

Through looking over the new science and technology, according to the materials of research about adsorption refrigeration, during the last years, the results of the research on the performance of adsorbing bed's structure and heat transfer at home and abroad can be summed up as follows.

(1) The finned tubes adsorbing bed. The advantages of this kind of adsorbing bed are its simple structure、the cheap cost of fabrication, but its heat exchange coefficient (about 10-20W/m^2℃) is low ,and the temperature distributing is not even ,

(2) The plate and spiral adsorbing beds. The advantages of these kinds adsorbing bed are the big heat exchanging area、little loss of heat、even temperature distributing and its better performance of the heat transfer, but the situation of pressure dropping is still a problem waiting to be studied. Its shortcoming is that the process is more complicated and the fabrication cost is higher.

(3) Constant heat recycling adsorbing refrigeration. According to the constant heat recycling circulation, this system is designed including two or more adsorbent beds、evaporator、 condenser and heat recycling devices. This system has a lot advantages too, such as its structure is very compact, heat loss is little, thermodynamic coefficient is higher, operation is more convenient [2], and it is very suitable to be used in the application of space flight undertaking. But because its pressure loss and refrigeration capacity is difficult to control and the procedure technology is very complicated, then its economy effect is relatively weaker on civil refrigeration.

As we know, the main purpose of the present study is to obtain higher performances of the refrigerator than those mentioned above. Recently, an the foundation of simulation calculation and theory analysis, the authors of the this paper have designed an experimental research system for this solar powered rotary solid adsorption refrigeration adopting activated carbon fibre + ethanol as its refrigeration working pair [3]. Using the rotary activated carbon fibre ripple board adsorbing bed as its key part, on the basis of enhancing the heat transfer and the quality of mass transferring design、 using adsorption research results of mechanism、 improving the mass transferring process during the adsorption and desorption course, this system can make the refrigerator have many advantages, such as its simple structure、no noise、 fast refrigeration、 higher thermodynamic coefficient of realizing constant refrigerating、without polluting atmospheric environment、no harm to human body and so on, these requirements are crucial to the design of the 'advanced' machine, and then it will improve the performance of the refrigerator consequently.

2. DESCRIPTION OF THE 'ADVANCED' SOLID ADSORPTION REFRIGERATOR DESIGN

The process of solid adsorbing refrigeration is realized through the adsorption- desorption circulation of the micro porous solid adsorbent adsorbing refrigerant at lower temperature and desorbing refrigerant at higher temperature. As to the absorption refrigeration also driven by heat energy, under the condition of heat source temperature being lower or condensation temperature being higher, if adopting a suitable refrigeration working pair, the adsorbing refrigeration has higher efficiency. Thus the adsorbing refrigeration has much superiority in the utilization of low-level heat source [4].

Because the adsorbent bed needs being heated and cooled repeatedly, then it can cause some energy lost by the way of apparent heat. If the energy released at the cooling stage can be retrieved at the heating stage, there will be no doubt that the ratio of the energy efficiency will be improved. Adopting the rotary adsorbing bed, it not only can retrieve the heat released from the cooling stage and fully utilize the adsorbing heat of the adsorbing bed, but also it can realize the goal of refrigerating in succession and reducing the temperature fluctuating degree of the evaporator, moreover it will improve the systematic efficiency.

The rotary solid adsorbing refrigeration machine powered by the solar energy consists mainly of adsorbent bed, the condenser, the evaporator, a throttling valve, the solar energy heater, see Fig.1.

The low-pressure refrigerant vapor with low temperature from evaporator is introduced to the 3/5 area of the nether part of the rotary adsorbent bed by the gas circulation pump. It will make the adsorbent bed temperature drop first and then it will be adsorbed by the activated carbon fibre, adsorption heat released from the adsorbing course will be taken away by the refrigerant vapor not adsorbed and then it will go through the ripple board path and enter the solar energy heater orderly. The solar energy heater is composed of vacuum pipe heat collector and auxiliary heating devices, etc. The refrigerant vapor not adsorbed by the adsorbent bed will be heated by the solar energy heater and then it will adsorb heat and its temperature will rise gradually, and it will enter the 2/5 area of the upper part of the rotary adsorbent bed after its pressure rising enough, then it will meet the adsorbent bed layer rotating up which has adsorbed fully refrigerant. Because the refrigerant adsorbed by the adsorbent bed will be heated by the high-temperature refrigerant vapor, then it will be desorbed from the activated carbon fibre, afterwards, it enters the condenser and then it will be cooled by the cooled water and it will be condensed into liquid refrigerant. After being throttled and its pressure being reduced, the liquid refrigerant will enter the evaporator. In the evaporator, the low-pressure refrigerant liquid will adsorb the heat from the cooled medium, and then it will be gasified into refrigerant vapor. Because the cooled medium has lost heat, it will generate the refrigeration effect after its temperature decreasing. Then the low-pressure refrigerant vapor of low temperature will be channeled into the 3/5 area of the under part of the rotary adsorbing bed by the gas pump again, and then the next adsorption-desorption refrigeration course will begin, such circulation will go on and on, thus the goal of refrigerating in succession will be achieved finally.

Because it is the high-pressure refrigerant vapor with high temperature that flows through the 2/5 areas of the upper part of the rotary adsorbent bed and it is the low-pressure refrigerant vapor with low temperature that flows through the 3/5 area of the nether part of the adsorbing bed, in order to improve the adsorbing efficiency, it should make the refrigerant from the 3/5 area of the nether part of the adsorbing bed lie in the extrusion section of the gas circulation pump, see Fig. 1.

The rotary adsorbing bed is the key device of the components of the refrigerator. And it consists of rotary activated carbon fibre、outer cover、transmission device, etc, see Fig. 2. The activated carbon fibre wheel is made by the metal net boards knotted by the activated carbon fibre felt(pocket-type pocket-type , 4mm thickness) and arranged in the center of the wheel with radiation form. The wheel is rotated at a slow speed, the low-pressure refrigerant vapor with low temperature coming from evaporator

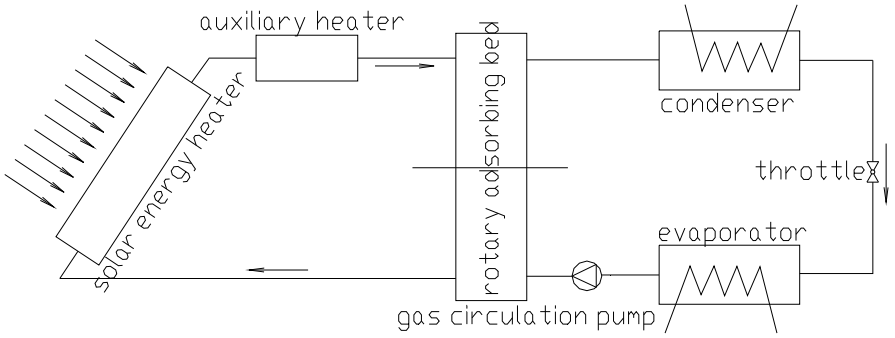

Fig.1. Operation principle of rotary solid adsorption refrigerator

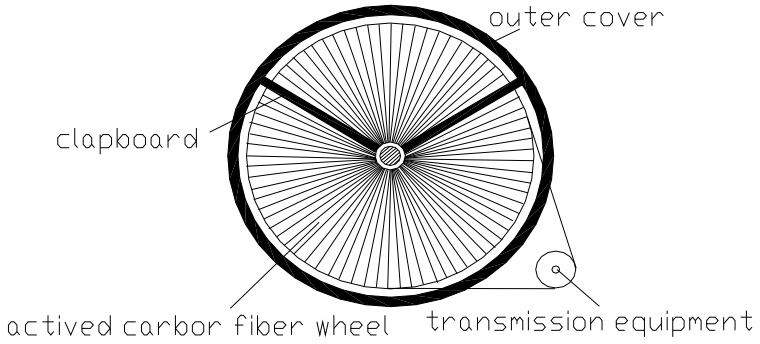

Fig.2. Rotary activated carbon fibre adsorbing bed

Tab. 1 Working Performances of the refrigeration working pairs

COP=λ/H (where, λ is the evaporation latent heat under To, J/kg; H is average equivalent adsorbing heat, J/kg)

working pair	T_0 (K)	T_k (K)	T_a (K)	T_j (K)	x_0 (kg/kg)	COP	Vacuum Degree	Resisting Pressure	poisonous?
silica gel-water	278	308	303	373	0.07	0.87	high	low	no
activated carbon - ammonia gas	268	303	303	363	0.15	0.86	high	high	yes
activated carbon -methanol	268	303	303	383	0.171	0.84	high	moderate	yes
activated carbon -ethanol	268	303	303	373	0.145	0.85	moderate	moderate	no

enters each channel of the nether 3/5 area part of the wheel through the right end of the gas circulation pump. Some refrigerant vapor is adsorbed by the activated carbon fibre and the refrigerant vapor not adsorbed brings the adsorption heat into the solar energy heater from the left end of the wheel. After being heated, the hot air current will enter every channel of the 2/5 upper area of the wheel from the left end, then it will take the refrigerant adsorbed by the activated carbon fibre away and then enter the condenser together.

The outer cover of rotary adsorbing is made of steel sheet. Two clapboards are welded respectively on the inboard of both the wheel ends in order to separate the low-pressure refrigerant vapor of low temperature from high-pressure refrigerant vapor of high temperature. There is a pipe sect set up on each area of the outside closed head of the two ends and on the upside and downside parts corresponding to the clapboard. The pipe sects can make themselves link to the vapor pipes. The outer cover demands to be airproofed strictly, it does not allow the gas to leak.

The automatic adjusting speed device and the transmission device can regulate the rotating speed automatically to receive different adsorbing efficiency, which will consequently control the amount of the vapor heated and regulate the balance of adsorbing-desorbing.

In the constantly refrigerating circulation, while

utilizing every half of circulation to finish, the adsorbing bed being on the state of desorbing with high pressure and high temperature, the adsorbing bed being on the state of adsorbing with low pressure and low temperature, as the adsorbing bed rotating , the rotary adsorbing bed will make some of the former refrigerant vapor desorbed spread rapidly to the latter and then it will be adsorbed, which will achieve the goal that it can make the temperature and pressure of the former part decreasing but make the latter's increasing partly. During the course of the inner vapor being recycled, because the two parts of the adsorbing bed being in an adiabatic state, only the mass being transferred, the course of the inner vapor being reclaimed working so fast, thus the adsorbing bed's performance of heat and mass transfer will have been made improve greatly [5].

3. CHOICE OF THE REFRIGERATION WORKING PAIR

Studies have shown, as evaporating temperature T_O=273~263K, condensing temperature T_k =298~313K, adsorbing temperature of terminal point T_a=298~303K, desorbing temperature of the terminal point T_j=343~383K, we can use the working pair's characteristics of the solid adsorbing refrigeration driven by solar energy are given in Table 1 [6]

The activated carbon is a kind of organic matter with a lot of extremely tiny holes inside, each liter activated carbon has about 485g weight, effective contact area of 1g (about 2cm^3) activated carbon is close to 1000m^2, in normal situation, the quality adsorbed is 15%~20% to its own mass, it has good adsorbing performance, and it can adsorb many kinds of refrigerant vapor (such as water、ammonia、methanol 、ethanol 、Freon etc.). Activated carbon-water is a very good kind of refrigeration working pair, the evaporating pressure of the fresh water is very low near 0□, and then it will be frozen, so under 0□ it is very difficult to use it. The solidifying point of methanol is lower (- 980□), the systematic pressure is relatively higher under low temperature, furthermore it is relatively smaller in diameter of the molecule, besides, it is easy to be absorbed, the evaporating latent heat is bigger too, thus people have paid much more attention to studying this working pair-activated carbon-methanol. But the methanol is virulent, it can result in losing one's sight, and its desorbing temperature can't exceed 150□ either, otherwise the activated carbon can promote methyl alcohol to decompose. The evaporating latent heat of ethanol is lower than the methanol, but the maximal adsorbing amount and the the adsorbing characteristic of ethanol similar to the methanol in the activated carbon [8].

Activated carbon fibre is a kind of adsorbent after the activated carbon having been materialized, it has very high specific surface area, generally it can reach 1000~3000m^2/g, and it has abundant tiny and even apertures, the aperture rate is up to more than 90%, it also has many other advantages, such as its adsorbing capacity is big, its adsorbing and desorbing speed is fast and so on. Studies have shown, compared with the activated carbon- methanol as working pair, activated carbon fibre- methanol can make the COP of the refrigeration system rise about 15%, the refrigeration quantity of each unit of the activated carbon fibre can reach 2~3 times of activated carbon, and it can make the time of adsorbing-desorbing reduce 1/10, the unit quality refrigeration capacity of activated carbon fiber-methanol system can reach 20~30times of the activated carbon-methanol refrigeration system[4].

Therefore, considering the aspects of the system vacuum degree、the demands of resisting pressure、ecurity and utilization, it is thought that the activated carbon fibre-ethanol is more suitable as a refrigeration working pair in application of the low-level heat energy.

4.PERFORMANCE ANALISIS OF THE SOLID ADSORBING REFRIGERATION MACHINE

Assume the specific heat of the ethanol equals to the specific heat of the saturated liquid under the same temperature, and both the evaporating temperature t_0 and the condensing temperature t_k of the system are constant, if the adsorbent bed temperature is t at the time of τ, and the adsorbing capacity is x, after $d\tau$ passing by, the temperature changed is dt, the adsorbing capacity changed is dx, the controlling body's volume is dv, the dynamic energy change relation of the course can be expressed

as follows.

①. Adsorption course under even pressure

Not until the pressure of adsorbing part of the bed drops to the evaporating pressure, dose the adsorbing bed begin to adsorb the refrigerant vapor from the evaporator, if it doesn't consider the flow loss and heat loss, in the adsorption course under even pressure, the quantity of the adsorbed heat of little unit controlling body can be calculated by

$$\delta q_x = \rho(C_1 + xC_2)dtdv + \rho\Delta H dxdv + \rho\int_{t_0}^{t} C_2(t)dtdxdv$$

Where, the first item, $\rho(C_1 + xC_2)dtdv$ is the apparent heat caused by the variation of temperature; the second item, $\rho\Delta H dxdv$ is the adsorbed heat released by the variation of the adsorbing capacity; the last one is the variation of the apparent heat of the refrigerant vapor that is heated to the temperature of the adsorbent at the evaporating temperature. The letter ρ and C_1 are the density and specific heat of the activated carbon fiber respectively, C_2 is the specific heat of the ethanol, ΔH is the absorbing heat.

②. Course of heating under even volume

The ethanol vapor that has not been adsorbed by the adsorbing part of the adsorbent bed absorbs the energy from the solar energy heater, and then both its temperature and pressure will increase, the adsorbed heat of the little unit body is calculated by

$$\delta q_H = \int_{t_0}^{t_k} (1 - x)C_2(t)dtdxdv$$

③. Desorption course under even pressure

When its pressure rises to the condensing pressure in the adsorbing part of the bed, the refrigerant vapor desorbed from the adsorbent will flow into the condenser and then it will condense, the adsorbed heat of the little unit body can be calculated by

$$\delta q_T = \rho(C_1 + xC_2)dtdv + \rho\Delta H dxd \quad (3)$$

④. Hot load of the condenser

The hot load of the condenser is:

$$\delta q_k = \rho\left[\lambda(t_k) + \int_{t}^{t_k} C_2(t)dt\right]dxdv \quad (4)$$

⑤. Refrigeration amount of little unit body

The amount of refrigeration of little unit body is:

$$\delta q_0 = \rho\left[\lambda(t_0)dxdv + \int_{t_0}^{t} C_2(t)dt\right]dxdv \quad (5)$$

⑥.Coefficient of the Performance (COP) of the refrigeration

The systematic refrigeration coefficient can be defined by

$$COP = \delta q_0 / \delta q_H \quad (6)$$

Setting up an even pressure field, the mathematical model can calculate the dynamic heat and mass transferring course of the adsorbing bed in the adsorbing refrigeration process.

5.CONCLUSIONS

Adopting activated carbon fiber-ethanol as its working pair, the rotary solid absorbing refrigeration machine driven by solar energy has its innovation lying in following.

5.1 Constantly Refrigerating Course has been Realized

Usually the adsorbing refrigeration system includes two adsorbent beds, because the adsorbent bed needs to be heated and cooled repeatedly, some energy will be lost by the way of apparent heat, and furthermore, because of the shift loss it will generate the intermittence refrigeration course. Adopting the rotary adsorbing bed, however, it may not only retrieve the heat released from the cooling stage and fully utilize the adsorbed heat, but also can realize the refrigerating course in succession.

5.2 Having Improved the Heat and Mass Transferring Performance of Refrigerant in the Adsorbing Bed and the Speed of Adsorbing and Desorbing

This subject adopts the kind of shaped adsorbent technology of ripple board of activated carbon fibre, which not only has fundamentally solved the problem of particle adsorbent touching thermal resistance, but also it has reduced the thickness of the adsorbing bed and increased the exchanging heat area of the adsorbing bed according to the activated carbon fibre board arranged radiantly, and while the structure has left such gas paths that are convenient for the vapor to spread、permeate and to produce convection. Consequently, it has enhanced the heat and mass

transferring ability and improved the adsorbing and desorbing speed.

5.3 Comprehensive Utilization of the Advanced Refrigeration Circulation

This kind of rotary adsorbent bed fixed with activated carbon fibre board arranged as radiation form, which can be regarded as a series of small adsorbing bed with heat exchanging independently. In the slow rotary course, each small adsorbent bed has great temperature gradient along the fluid procedure. The upper and nether parts of the adsorbent bed are working on the opposite direction. With the wheel rotating, the returning mass and heat processes are working on the boundary between the adsorption and desorption rapidly, it has utilized the heat released from the adsorbing course to the maximum extent and it has realized the course of recycling the gas at the end of the adsorption. The application of the gas circulation pump has increased the adsorbing pressure of the adsorbing bed, and it has realized the forced convection course too, moreover it has improved the performance of the heat and mass transfer of the adsorbent bed. So it can be said that the rotary adsorbent bed formed by activated carbon fibre board arranged as radiation form has comprehensively utilized the advanced refrigeration circulation, such as the constant heat recycling, the thermal wave regeneration [9], the thermal wave convection circulation [10], the mass recycling circulation [11] and so on, and then it will improve the circulation efficiency greatly.

5.4 Have Ameliorated the Systematic Circulation Way

Ameliorating the systematic circulation way is a greatly potential method of improving the adsorbing refrigeration efficiency. This system designed by regarding the refrigerant itself as the heating medium, it not only can avoid the exchanging heat loss, but also it can retrieve the adsorbing heat to the maximum extent, and then it will improve the systematic circulation efficiency.

Adopting activated carbon fibre+ ethanol as its working pair, powered by solar, using rotary adsorbent bed made by the activated carbon fibre board arranged like the radiation form as the key part, on the basis of strengthening the heat transfer, the rotary solid adsorption refrigeration machine can improve the spreading mass quality. By using the research results of the adsorbing mechanism, it has strengthened the mass transfer course of adsorption and desorption in the adsorbent bed. Thus it will make the refrigerator have the advantages including simple structure, fast refrigerating, higher thermodynamic coefficient, not polluting the atmospheric environment, no harm to human body and so on.

In the research field of using solar energy to refrigerate, it is hopeful to fill in some blanks of coupling theoretical research about heat and mass transferring process and make a breakthrough at the aspects of strengthening the transferring quality and improving heating power coefficient.

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