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Heat transfer performance of solid sorption heat pipes with composite NaBr-NH_3 as working pair

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Abstract

Solid sorption heat pipe (SSHP) which integrates heat and mass transfer with solid-gas sorption technology is proposed in this paper. Composite sorbent with sorbate (ammonia) are chosen as the working pair to replace the capillary structure (wick) and working fluid in conventional heat pipe (HP) thus the major limits of heat transfer can be overcome. Three different amounts of ammonia (1.14 mol, 3.01 mol and 4.88 mol) filled in the SSHP are tested under different heat source temperature (from 50ºC to 90ºC) and heat sink temperature (20ºC and 25ºC) in order to investigate the overall heat transfer performance. Two modes are investigated, i.e. heating mode for which the sorbent temperature increases and cooling mode for which the sorbent temperature decreases. The test results indicate that SSHP with vertical arrangement is available and realistic for heat transfer process. The maximum heat transfer quantity in sorbent section is gotten under the condition of heating temperature of 80ºC and cooling temperature of 20ºC for cooling mode, and its value is 0.87 kW. In condenser section the heat transfer between both modes, i.e. cooling mode and heating mode, is relatively close and the maximum heat flux is 22.11 kW/m^2 and 17.61 kW/m^2 respectively. The sorbents with different sorption quantity are also studied and compared which show that the maximum heat transfer quantity per unit molar ammonia is 400.29 W/mol, corresponding to the heat flux in sorbent section 14.84 kW/m^2.

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Keywords: solid sorption heat pipe；heat transfer performance；composite sorbent；solid-gas sorption

1. Introduction

Heat pipe (HP) is well known as a conductive passive heat transfer device. Due to the excellent heat transfer capability, it has emerged as the most appropriate technology and cost effective thermal control solution in low-grade thermal energy transfer, recovery and applications[1,2]. It uses the continuous evaporation/condensation cycle and surface tension of a working fluid to attain an extremely high thermal conductivity within a small temperature drop[3]. Due to the two phase heat transfer mechanism in a completely sealed device, heat transfer capability of HP is from “one hundred to several thousand times” that of an equivalent piece of copper[4].

Over the past decades, due to the various requirements on thermal control and cooling systems, HPs have been improved significantly towards achieving higher heat flux. The performance of HP depends on several different heat transport limitations, mainly include viscous, sonic, capillary, entrainment and boiling limits[5]. Fig.1 shows that the separate performance limits define an operational range with the combination of

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temperatures and maximum transport capacities[6]. Heat transfer performance is easily dominated by sonic, viscous and entrainment limits especially when the working temperature is low. While the higher working temperature may lead to the capillary and boiling limits which result in the HP fail to operate. Within these certain limitations, the limitation caused by capillary structure is the key factor. If there is insufficient driving capillary pressure providing an adequate liquid flow from the condenser to the evaporator, dry-out phenomena will occur. Therefore, the maximum allowable heat flux of evaporator is strongly dependent on the wick structure[7].

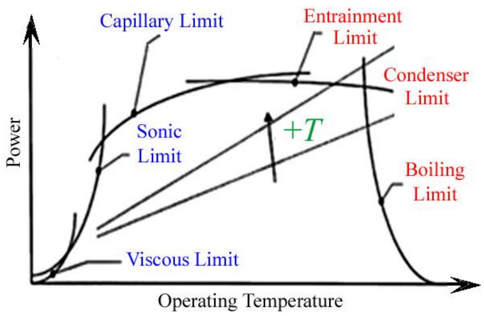


Fig.1. Typical performance map of conventional heat pipe [3]

In terms of HP's operation, the vapour flows from the evaporator (heat source) to the condenser (heat sink) is driven by the vapour pressure difference and capillary force. Meanwhile the liquid flow from the condenser (heat sink) to the evaporator (heat source) is produced by the gravitational force, electrostatic force, or other forces directly acting on it. Regardless of the orientation of the HP (such as vertical or horizontal), there is no much difference in the basic principles. A thermosyphon is a kind of wickless structure where the evaporation section must be positioned vertically below the condensation section. The condensate liquid in the thermosyphon is returned to the heated side under the effect of gravity, instead of capillary forces in wicked HPs. The major heat transfer limit of thermosyphon is known as "counter-current flow limit (CCFL) or flooding limit" [8,9].

In recent years, much attention has been paid to the solid-gas sorption technology. It appears to be an attractive alternative for thermal energy storage and cooling or air conditioning applications owing to the advantage of being absolutely benign for the environment (zero ODP and zero GWP)[10,11] and its high reaction heat and energy density[12,13]. Two main technologies considered in the concept of solid-gas sorption are adsorption and chemical reaction (including chemical compounds like ammonia salts). In the case of adsorption, physical adsorption on the surface occurs without modification of the solid itself. In the case of chemical reaction, reaction occur which induce modification of the solid itself.

Interesting connections can be evidenced in the literatures between HPs and thermal engineering applications[14], for instance the adsorption refrigeration systems integrated with heat pipes are reasonable for cooling and heating[15]. The research work in Shanghai Jiao Tong University have proved that heat pipes could be used as heat exchangers for adsorbers, evaporators or condensers in adsorption water chiller, adsorption room air conditioner and adsorption ice maker for fishing boats[16-19]. But all the studies above are working on the combination of heat pipes with sorption systems for heat transfer intensification of the system, not for using the sorption technology itself to serve as the heat pipe for heat transfer.

In this paper, a new concept of solid sorption heat pipe (SSHP) is proposed, and the chemisorption heat pipe is designed and tested. The composite sorbent is employed as working fluid instead of the conventional wick, and combination of solid-gas reaction and condensation process could transfer the thermal energy continuously from sorbent section to condenser section. Experiments of the vertical type SSHP with three different molar amounts of ammonia are conducted under the condition of changing heating temperature continually at a certain cooling temperature in order to gain an insight into the overall heat transfer performance.

2. Working principle of SSHP

SSHP employs the solid sorbent with sorbate as working pair to substitute the capillary structure (wick) and working fluid in HP, thus it can overcome the major limits of conventional heat pipe and achieves heat transfer continuously for long-distance and large-scales.

The structure of SSHP consists of a sorbent section (sorber/desorber and evaporator), a condenser section and an adiabatic section with the similar orientation of two-phase closed thermosyphon(seen in Fig.2).

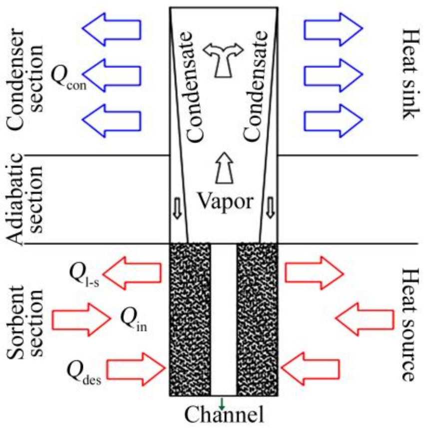


Fig.2. Structure and working principle of SSHP

The heat transfer mechanism of SSHP can be illustrated by two working phases:

(1) The heating and desorbing phase. In this phase the sorbent section is heated, which provide the desorption heat (Q_{des} in Fig.2). Then the sorbate is desorbed and the vapor flows through the vapor channel to the condenser section.

(2) The condensing and liquid reflowing phase. In this phase the vapor at the condenser section is cooled by the cooling fluid, thus the film condensation starts at the inner walls and the vapor sorbate is condensed into the liquid working fluid with the release of latent heat of vaporization to the heat sink (Q_{con} in Fig.2). After that, the condensed liquid sorbate reflows to the sorbent part along the inner wall by gravity and sorption effect to the sorbent section, and is sorbed there by solid sorbent.

The solid sorbents are filled in sorbent section of SSHP, and then the sorbate is filled inside the solid sorbents. The heating process at the sorbent part of the HP provides the desorption heat of solid sorbent. The condensing process releases the heat and the condensation liquid flows back to the sorbent part. By such a process the desorption will transfer the heat from the sorbent part to the condensation part.

In this paper, NaBr and NH_3 are chosen as the sorbent-sorbate working pair and the SSHP machine is developed with a composite sorbent of NaBr impregnated in expanded natural graphite treated with sulfuric acid (ENG-TSA). Composite sorbents could improve the heat and mass transfer performance of the original chemical sorbents effectively [20,21].

The decomposition (desorption) and synthesis (adsorption) processes of the NaBr-NH_3 solid-gas chemical reaction is shown in Eq. (1).

$$\mathrm{NaBr}+5.25\mathrm{NH}_3 \leftrightarrow \mathrm{NaBr}\cdot 5.25\mathrm{NH}_3+\Delta H_{\mathrm{NaBr}} \quad (1)$$

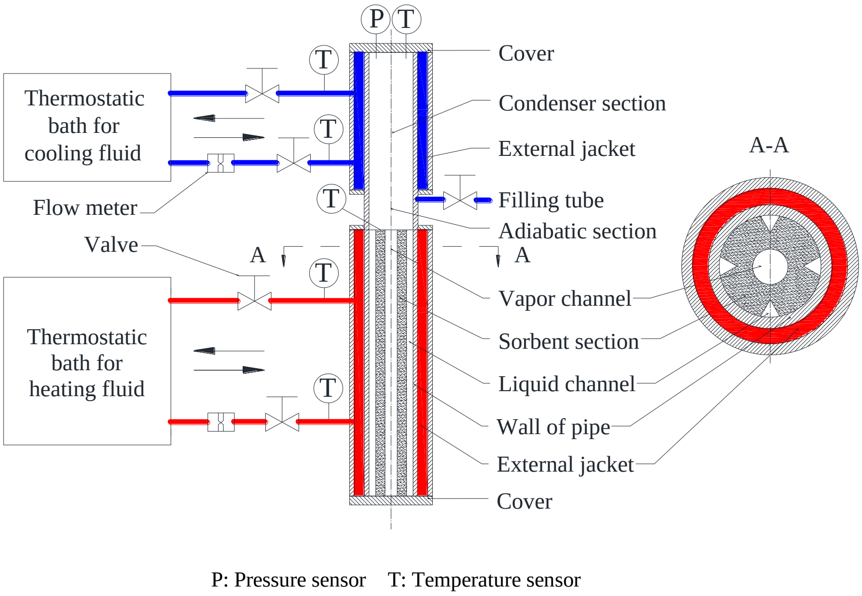
where ΔH_{NaBr} is reaction enthalpy of NaBr (kJ mol^{-1}).

3. Test unit and analysis methods

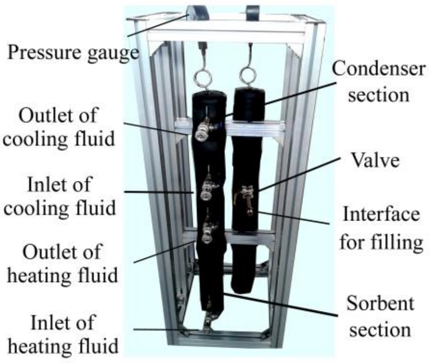
The test unit (Fig.3a) mainly includes one SSHP, two thermostatic baths, two flow meters, six platinum resistance thermometers, one pressure transmitter and valves. The prepared composite (NaBr and ENG-TSA) is filled inside the space of sorbent section and then compressed to form consolidated blocks. After that, the sorbent section is connected with adiabatic and condenser sections thus composing the SSHP machine totally. Before the experiments, the SSHP is maintained at a vacuum state and then a certain amount of NH_3 is charged into the SSHP through the bypass in the adiabatic section.

The sorbent blocks exchange heat with the heat transfer fluid (heating fluid) through SSHP outer jacket in sorbent section, whereas the sorbate vapor desorbs from the sorbent blocks via the vapor channel in the middle of the block. In condenser section, sorbate vapor transfers the heat to the heat transfer fluid (cooling fluid) through SSHP outer jacket and meanwhile the cooling sorbate liquid returns to the sorbent through the inner wall surface, thus the low-grade heat transfer is achieved by desorption and condensation processes from sorbent section to condenser section.

The measuring instruments include flow meters, temperature sensors and pressure sensors. The data from the sensors is acquired every 6 s and stores in an Agilent 34970 data logger. The temperature sensors are platinum resistance type PT100, which are installed within the sorbent section, condenser section and the heat transfer fluid paths. The sensors are embedded into 3 mm diameter stainless steel tubes and silicone heat transfer compound is used to enhance the heat transfer between the tubes and the sensors. The uncertainty of temperature measurement is 0.15ºC. The pressure in the SSHP is measured with a pressure sensor with uncertainty of ± 2.5 mbar. The volumetric flow rate of the heat transfer fluid is measured with positive displacement flow meters.



(a)



(b)

Fig. 3. Experimental test system of SSHP. (a) Schematic diagram; (b) Photo

Experiments are conducted under different operation conditions to investigate the influence of parameters on the overall performance of the SSHP machine. The controlled conditions in the tests are the inlet hot water temperature of heat source ($T_{H,\ in}$) and the inlet cold water temperature of heat sink ($T_{C,\ in}$). The heat transfer quantity and heat flux in sorbent and condenser sections can be obtained by Eq. (2) and Eq. (3) respectively.

$$Q_{sor} = Q_{in} = C_{p,H}\rho q_{V,H}(T_{H,in} - T_{H,out}); \quad q_{sor} = Q_{sor}/A_{sor} \tag{2}$$

$$Q_{con} = Q_{out} = C_{p,C}\rho q_{V,C}(T_{C,out} - T_{C,in}); \quad q_{con} = Q_{con}/A_{con} \tag{3}$$

4. Results and discussions

Three different amounts of ammonia (1.14mol，3.01mol and 4.88mol) filled in the sorbent part are tested under different heat source (from 50ºC to 90ºC) and heat sink (20ºC and 25ºC) conditions. Firstly, No.2 SSHP with 3.01mol is taken as example to investigate the variation of inner temperature and pressure in the machine. Then the experimental process is conducted under the conditions of heating mode (heating temperature increases) and cooling mode (heating temperature decreases) respectively at a certain cooling temperature in order to calculate the heat transfer quantity in sorbent and condenser sections. Moreover the overall heat transfer performance of No.1, No.2 and No.3 are studied by comparing the heat transfer per unit molar of ammonia and the heat flux in sorbent section.

4.1. Operation characteristics of the SSHP

Fig.4 (a) shows the change of temperature of SSHP for heating mode when the condensing part isn't cooled by the cooling fluid. The inlet temperature range of sorbent section is set from 50ºC to 80ºC with an interval of 10ºC. At the initial phase, the temperature of different positions has the similar trends. The temperature increases simultaneously with the heat transfer fluid temperature. When the heating temperature reaches up to 60ºC or above, it can be seen that the inner temperature of evaporator section appears continuously fluctuation, which indicates the occurrence of desorption of solid-gas reaction.

Besides temperature, the value of pressure inside the machine is another significant parameter for the solid chemisorption cycle. The inner pressure of condenser section with the augmentation of heating temperature over time is plotted in Fig.4 (b). Compared with the curve of T_c in Fig.4 (a), the p_c shows the same trend with T_c. Moreover, the duration of desorption process under a certain condition can be estimated via temperature by calculating the time required from transient state to steady state, as shown in Fig.4 (a).

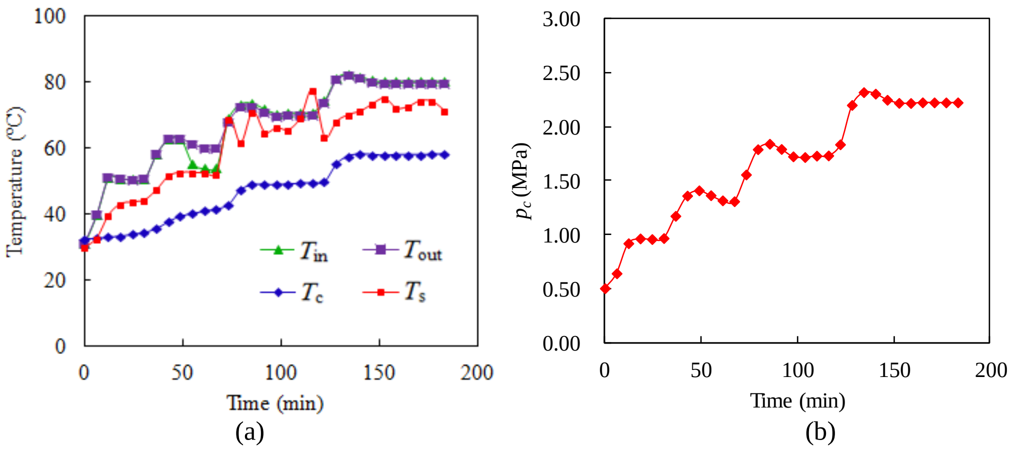
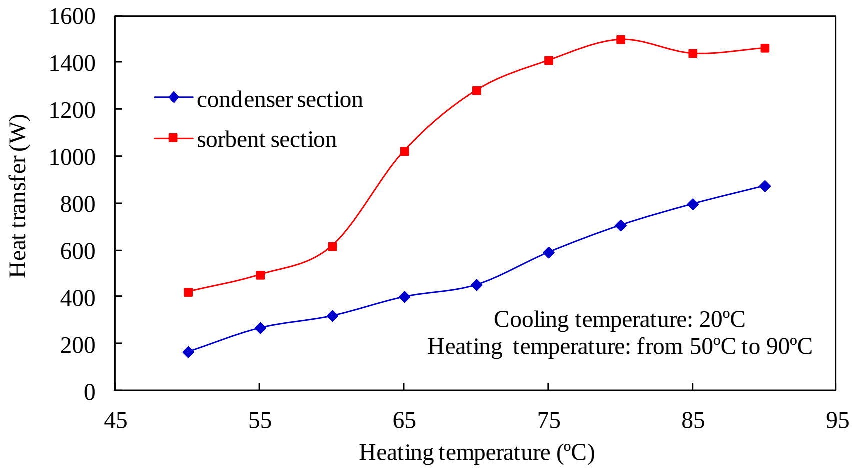


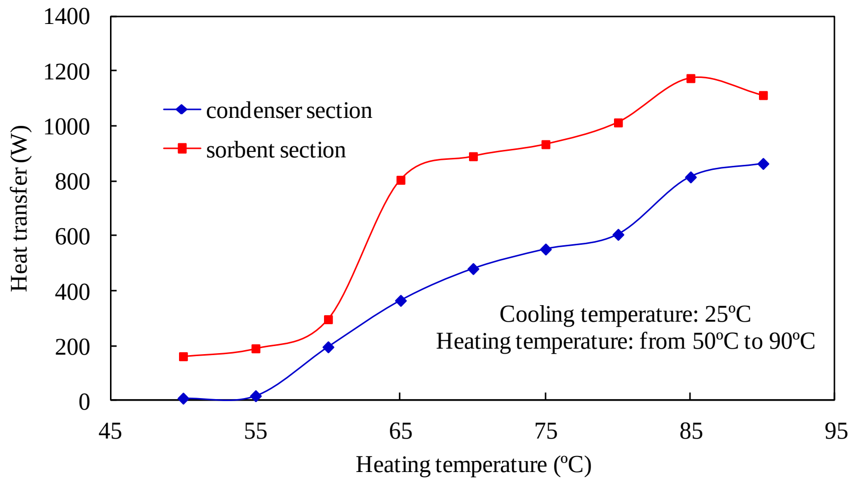
Fig.4. Operation characteristics of the No.2 SSHP. (a) Temperature; (b) Pressure

4.2. Heat transfer performance of No.2 SSHP

Fig.5 shows the heat transfer in sorbent section and condenser section in heating mode under the certain condensing temperature. It can be observed that the heat exchange between the unit and heat source/sink increases gradually with the rise of heating temperature. In the range of 60-80ºC, the augmentation of heat transfer rate is significantly larger than others because the desorption process to be achieved requires large amount of heat which accounts for the major part of the energy for charging phase provided by heating fluid. The more low-grade heat input corresponds the larger capacity of heat of condensation to be output. Under the condition of heating temperature of 80ºC and cooling temperature of 20ºC, heat transfer quantity reaches up to the maximum value of 1.50 kW.



(a)



(b)

Fig.5. Heat transfer under the heating mode. (a) Cooling temperature: 20ºC; (b) Cooling temperature: 25ºC

Furthermore, the heat transfer difference between sorbent section and condenser section is significantly large when the heating temperature is up to 60ºC and above. The reason may be the absence of the liquid and solid sorbent reaction and the accumulation of sensible heat in the process supposed that the heat loss isn't negligible.

The thermal energy input from heat source divides into three different parts: heat required for desorption, sensible heat and heat loss. In the course of experiments, the heating temperature is gradually increased while the cooling temperature is controlled to be constant, therefore the augmentation of sensible heat with heating temperature occupies a considerable part of the heat input in the dynamic equilibrium process. Considering the influence of sensible heat on heat transfer, the radial heat transfer quantity and heat flux in sorbent and condenser sections can be obtained by Eq. (4) ~Eq. (8) respectively.

$$Q_{\text{in}} = Q_{\text{des}} + Q_{\text{sens}} - Q_{\text{l-s}} \tag{4}$$

Where $Q_{\text{l-s}}$ can be neglected because $Q_{\text{l-s}}$ is much smaller than Q_{des}.

$$Q_{\rm des} = Q_{\rm in} - Q_{\rm sens} = C_p \rho \dot{V}(T_{\rm hw,in} - T_{\rm hw,out}) - (Q_{\rm sens,cs} + Q_{\rm sens,s} + Q_{\rm sens,ss}) \\ = C_p \rho \dot{V}(T_{\rm hw,in} - T_{\rm hw,out}) - (C_{p,\rm cs} m_{\rm cs} + C_{p,\rm s} m_{\rm s} + C_{p,\rm ss} m_{\rm ss}) \frac{{\rm d}T_{\rm sor}}{{\rm d}t} \quad (5)$$

$$Q_{\rm con} = C_p \rho \dot{V}(T_{\rm cw,out} - T_{\rm cw,in}) - (C_{p,\rm s} m_{\rm s} + C_{p,\rm ss} m_{\rm ss}) \frac{{\rm d}T_{\rm con}}{{\rm d}t} \quad (6)$$

$$q_{\rm sor} = Q_{\rm des} / A_{\rm sor} \quad (7)$$

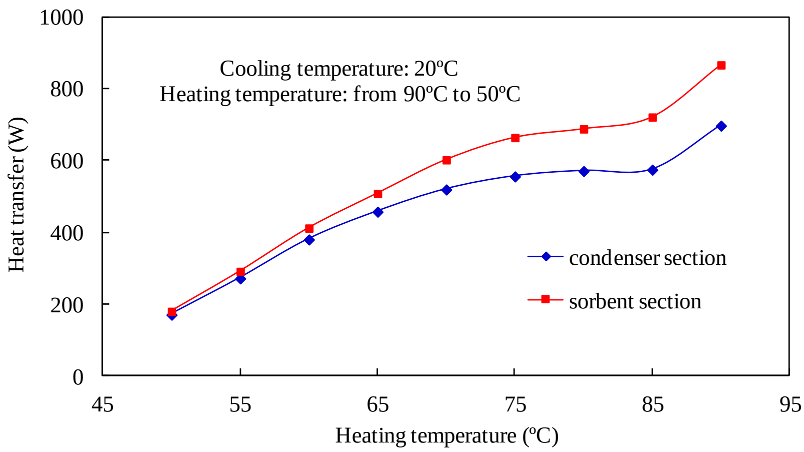
$$q_{\rm con} = Q_{\rm con} / A_{\rm con} \quad (8)$$

where $Q_{\rm sens}$ is the total sensible heat (kW), C_p is the specific heat of water (kJ kg^{-1} K^{-1}), ρ is the density of water (kg m^{-3}), $\dot{V}$ is the volumetric flow rate of water (m^3 s^{-1}), m is the mass (kg), $T_{\rm in}$ and $T_{\rm out}$ are the inlet temperature of water and the outlet temperature of water respectively (ºC), t is time (s), q is the radial heat flux (kW m^{-2}) and A is the heat transfer area (m^2). The subscripts of hw, cw, cs, s, ss, sor and con are representative for hot water, cold water, composite sorbent, sorbate, stainless steel, sorbent section and condenser section respectively.

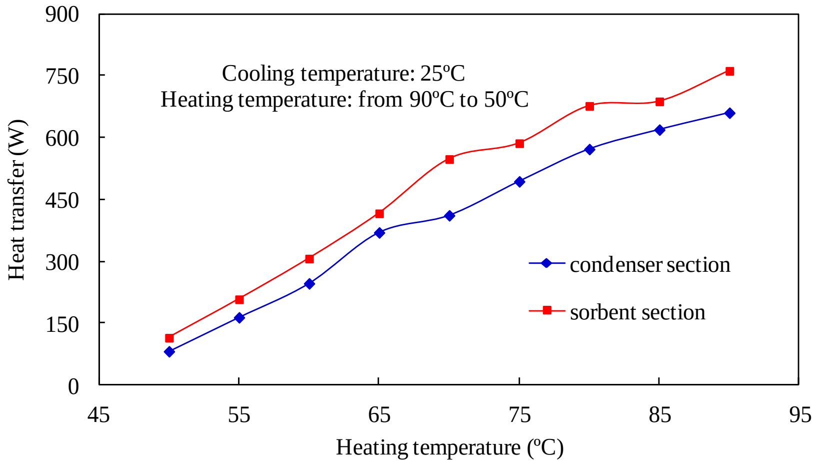
The variation of heat transfer in sorbent section and condenser section for cooling mode is plotted in Fig.6. It can be seen that the heat transfer difference between sorbent section and condenser section under the same condition is much smaller than that of heating mode. The maximum heat transfer quantity of cooling mode in sorbent section occurs under the condition of heating temperature of 80ºC and cooling temperature of 20ºC, respectively, and its value is 0.87 kW.

In condenser section, the SSHP exchanges thermal energy with heat sink mainly by the way of gas sorbate to be condensed. Comparison of heat transfer in condenser section in Fig.5 and Fig.6, it can be found that the difference between two modes is relatively close and the heat transfer changes approximately linear with the heating temperature.

Besides the maximum heat transfer, heat flux is also an important parameter to analyze and evaluate the overall heat transfer performance. Fig.7 shows the heat flux of condenser section in the two modes at certain cooling temperature. The maximum heat flux is 22.11 kW/m^2 and 17.61 kW/m^2 under the process of temperature increase and temperature decrease respectively.

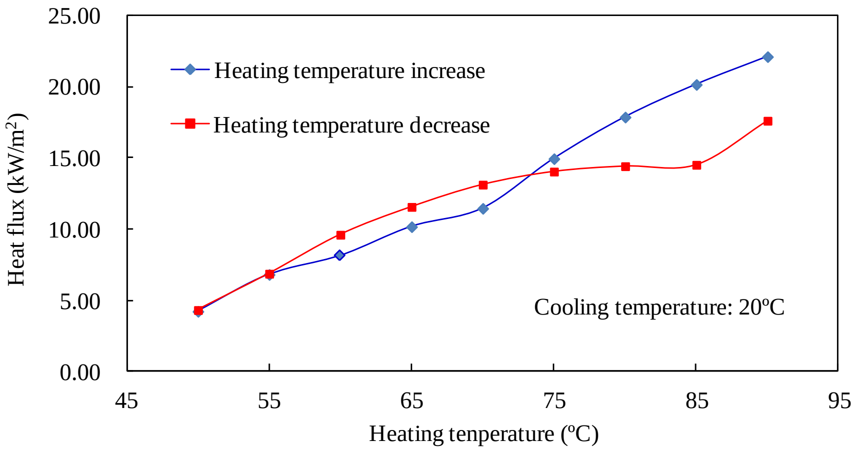


(a)

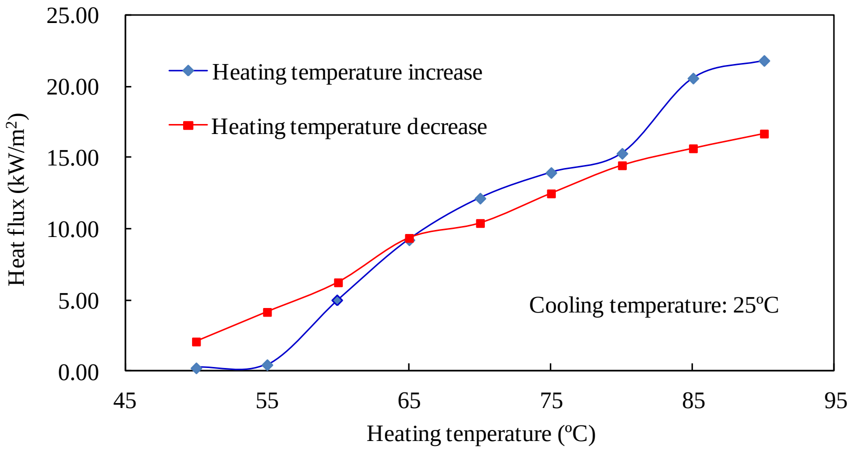


(b)

Fig.6. Heat transfer under the cooling mode. (a) Cooling temperature: 20ºC; (b) Cooling temperature: 25ºC



(a)



(b)

Fig.7. Heat flux in condenser section for two modes. (a) Cooling temperature: 20ºC; (b) Cooling temperature: 25ºC

4.3. Comparison of different sorbents

As mentioned above, the operation process of cooling mode gradually is in favor of reducing the influence of liquid and the solid sorbent reaction and sensible heat on the overall heat transfer. Heat transfer per unit molar of ammonia and heat flux in sorbent section of No.1, No.2 and No.3 can be seen in Fig.8 and Fig.9. Heat transfer per unit molar of ammonia in No.1 is larger than that of No.2 and No.3 means the augmentation of heat transfer is smaller than that of filling amount of ammonia. Under the condition of heating temperature of 90ºC and cooling temperature of 20ºC, the maximum value of heat transfer per unit molar ammonia is 400.29 W/mol and the minimum value is 240.83 W/mol corresponding to the heat flux in sorbent section of 5.76 kW/m^2 and 14.84 kW/m^2. Based on optimization design, the sorption quantity of 3.01mol (No.2 SSHP) is considered to be a good choice to achieve a better overall heat transfer performance so far.

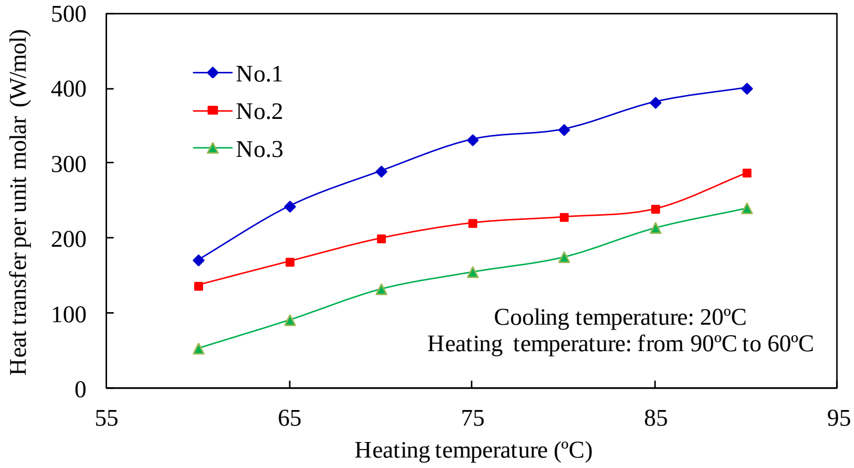


Fig.8. Heat transfer per unit molar of ammonia

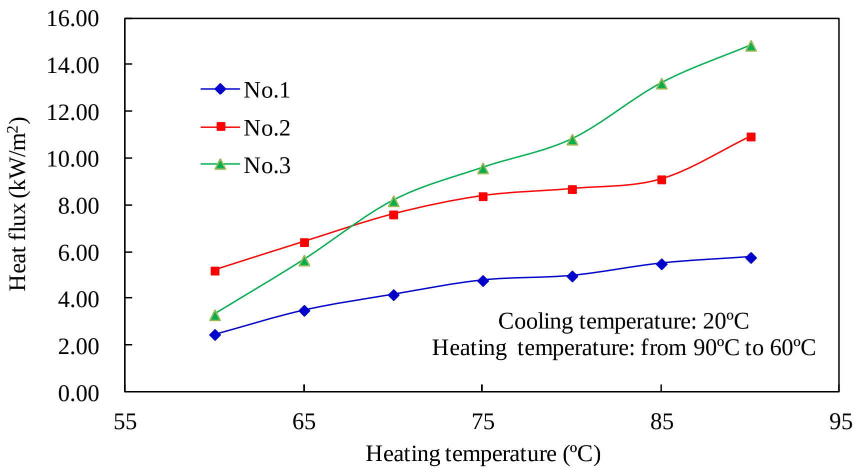


Fig.9. Heat flux in sorbent section of No.1, No.2 and No.3

5. Conclusions

SSHP filled with solid sorbent and sorbate applied for heat transfer, which can overcome the major limits of conventional HP and achieve heat transfer continuously and effectively, is introduced. Experiments under different heat source and heat sink conditions are carried out to investigate the heat transfer performance. The conclusions are as follows:

(1) The difference of heat transfer between sorbent section and condenser section is significantly large for

heating mode of sorbent section. For cooling mode of sorbent section the maximum heat transfer in sorbent section occurs under the condition of heating temperature 80^{o}C and cooling temperature 20^{o}C respectively and its value is 0.87 kW.

(2) In condenser section, heat transfer quantity changes approximately linear with heating temperature. The difference of heat transfer between two modes is relatively close and the maximum heat flux is 22.11 kW/m^2 and 17.61 kW/m^2 respectively.

(3) Compared with three different sorption quantities, No.1 SSHP has the maximum heat transfer quantity per unit molar and No.3 SSHP obtains the largest heat flux quantity while the values of No.2 SSHP are both in the middle. When heating temperature is 90^{o}C and cooling temperature is 20^{o}C, the maximum value of heat transfer per unit molar ammonia is 400.29 W/mol and the minimum value is 240.83 W/mol corresponding to the heat flux in sorbent section of 5.76 kW/m^2 and 14.84 kW/m^2, respectively.

Acknowledgements

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