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The feasibility of solid sorption heat pipe for heat transfer

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ABSTRACT

A novel type solid sorption heat pipe (SSHP) is developed for continuous heat transfer. In contrast to conventional heat pipe (HP), SSHP utilizes the composite sorbent-sorbate as working media to replace the wick structure inside HP. Such a technology is expected to alleviate the heat transfer limits of conventional HP. NaBr is chosen as the sorbent, and the expanded natural graphite treated with sulfuric acid serves as the matrix. A certain molar amount of the sorbate (NH_3) is complexed with the composite sorbent. The desorption, condensation and chemisorption processes of NaBr-NH_3 working pairs are investigated for both vertical and horizontal placed SSHP. The results show that the desorption process of NaBr-NH_3 solid-gas reaction can be carried out while the heating temperature reaches up to 60 °C or above. The highest radial heat flux in both vertical and horizontal placed SSHP is around 22.1 and 12.4 kW/m^2, respectively, while the axial heat flux for both SSHPs is not less than 400 kW/m^2. It can be concluded that the SSHP is characterized by the non-isothermal heat transfer performance and verified to be available for continuous heat transfer. The vertical SSHP has a better overall heat transfer performance than horizontal SSHP under the same condition and NaBr-NH_3 working pairs applied in SSHP is suitable for low-grade thermal energy transfer above 60 °C.

1. Introduction

Heat transfer is involved in various energy utilization processes. HP is known as an efficient, reliable and passive heat transfer device in which continuous evaporation/condensation cycle with a small temperature drop is accomplished by capillary forces. The idea of the HP was first suggested in 1942 and the first patent was applied in 1944 [1]. After that Grover put forward the independent invention in the early 1960s [2], and then the remarkable properties of the HP became appreciated extensively. The most obvious point to the success of the HP is the wide range of applications where its unique properties have proved beneficial [3–5]. 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 [6,7].

The heat transfer capacity of HP is limited by several heat transfer limitations, which mainly include viscous, sonic, capillary, entrainment and boiling limits [8,9]. Within them the limitations caused by wick structure are the key factors. As the core part of HP, wick structure has two main functions in heat and mass transfer. First it generates capillary pressure to transport the working fluid from condenser section to evaporator section; secondly it provides the path for liquid distribution. There are three fundamental parameters associated to the capillary structure of the HP, and they are equivalent thermal conductivity, permeability and the maximum capillary pressure. HPs are experimentally discriminated in terms of maximum heat transfer capability and minimum thermal flow resistance which are fully related to the capillary structure inside it [3,6].

A kind of wickless structure pipe where the evaporation section must be positioned vertically below the condensation section is called two-phase closed thermosyphon. A thermosyphon does not have the large flow resistance or low boiling limit, as the condensate liquid in the thermosyphon is returned to the heated side under the effect of gravity, instead of capillary forces in wicked HPs [10]. They are reliable for widely applications in waste heat recovery systems [11], solar heating systems [12] and thermal management components [13]. For the thermosyphon at a high heat input, the liquid-vapor (L-V) interface near the exit of the evaporator, where vapor flow is highest, will become agitated and wavy. Such a process decreases the rate of liquid returning to the evaporator at the expense of increasing the thickness of the liquid film. A mismatch between the rate of liquid return to the evaporator and the heat input could eventually cause a dryout of the liquid film in the evaporator section. This is known as the "onset of flooding" or counter-current flow limit (CCFL) of thermosyphon as the condenser becomes flooded [14–16].

Sorption is a general term to cover both solid sorption and absorption. Sorption reaction could use low grade heat (below

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Nomenclature

A	heat transfer area, m^2
C	specific heat, $kJ\ kg^{-1}\ K^{-1}$
L	latent heat, $kJ\ kg^{-1}$
m	mass, kg
p	pressure, MPa
Q	heat transfer rate, kW
q	heat flux, $kW\ m^{-2}$
T	temperature, K
t	time, s
$\dot{V}$	volumetric flow rate of water, $m^3\ s^{-1}$
$\triangle H$	reaction enthalpy, $kJ\ kg^{-1}$
$\triangle T$	the difference of temperature, T
ρ	density of water, $kg\ m^{-3}$

Subscripts

ads	adsorption
axi	axial
amm	ammonia
c	cross-section
con	condensation/condenser section
cs	composite sorbent
cw	cold water
des	desorption
Eq	equilibrium
H	high
hw	hot water
in	input/inlet
L	low
l-s	reaction of liquid sorbate and solid sorbent
M	middle
out	output/outlet
rad	radial
s	sorbate
sens	sensible heat
sor	sorbent section
ss	stainless steel

Abbreviations

CCFL	counter-current flow limit
ENG-TSA	expanded natural graphite treated with sulfuric acid
GWP	global warming potential
HP	heat pipe
L/G	liquid/gas
L-V	liquid-vapor
S/G	solid/gas
SSHP	solid sorption heat pipe

150 °C) and optional working medium. In recent years, solid sorption technology has gained a lot of interests for thermal energy storage in large-scales or long terms, due to its high reaction heat and energy density [17,18]. It can utilize environmental friendly refrigerants with zero global warming potential (GWP) and use solar energy or waste heat as the main source of energy [19,20]. However, the solid sorption processes are never proposed for continuous heat transfer mainly because they are intermittent that features the intermittent cooling and heating phases.

Most previous studies for heat pipe hadn't concentrated on the solid sorption principle for substituting the wick and working fluid in conventional HP. Vasiliev et al. earlier proposed sorption HP in previous publications [21,22]. They combined the conventional HP with the sorption and desorption phases of solid sorbents. In his work the desorption phase can be fulfilled with the condensation phase of conventional HP, and the sorption phase can be served as the storage phase of liquid fluid of conventional HP. i.e. in their research work the conventional HP is used for the desorption and refrigeration processes of sorption system, and the working phases are intermittent for that the desorption and sorption phases need to be switched.

Combining the desorption between solid and gas, sorption between liquid and gas, and condensation processes, a new concept of solid sorption heat pipe (SSHP) is proposed in this paper. It is supposed to fulfill the continuous heat transfer and alleviate the drawbacks of both conventional HP and thermosyphon. The experiments are conducted under different operation conditions to investigate the overall performance of the SSHP and to verify that the test unit could utilize and transfer the thermal energy continuously and effectively.

2. Fundamentals of SSHP and solid sorbent

2.1. Fundamentals of SSHP

In order to state the advantages of SSHP clearly, two types of SSHP (vertical and horizontal) are presented in Fig. 1. The SSHP in Fig. 1a transfers the thermal energy from heat source to heat sink vertically, which similar with the conventional thermosyphon. The SSHP in Fig. 1b transfers the heat horizontally, for such type conventional HP the wick structure is essentially required.

In Fig. 1a and b the solid sorbent is filled in the sorbent section, i.e. the evaporator section of the conventional HP, and the sorbate is sorbed inside the solid sorbents, i.e. the working fluid in conventional HP is substituted by the solid sorbent and sorbed sorbate. 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. 1). 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. 1). After that, the condensed liquid sorbate reflows to the sorbent part along the inner wall by gravity (Fig. 1a) or sorption effect (Fig. 1b) to the sorbent section, and is sorbed there by solid sorbent.

These two phases ensure a continuous heat transfer process. Three types of heat exist in these two working phases as Fig. 1a and b show: desorption heat (Q_{des}) between solid sorbent and vapor sorbate, reaction heat of the solid sorbent and liquid sorbate ($Q_{l\text{-}s}$), and condensation heat (Q_{con}). The reaction between the solid sorbent and liquid sorbate will release heat and the bonding effect of Q_{des} and $Q_{l\text{-}s}$ equals to Q_{in} (heat input), i.e.:

$$Q_{in} = Q_{des} - Q_{l-s} \tag{1}$$

Taking the whole SSHP as one system, the heat input should be equal to the heat output, i.e.:

$$Q_{in} = Q_{con} \tag{2}$$