International Journal of Heat and Mass Transfer 82 (2015) 170–178

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental investigation of the thermal performance of a novel concentric condenser heat pipe array

Yaxiong Wang, Xiaoxing Han, Qianqing Liang *, Wenxiu He, Zhongmin Lang

School of Chemical Engineering, Inner Mongolia University of Science & Technology, Baotou, Inner Mongolia 014010, China

ARTICLE INFO

Article history:
Received 5 October 2013
Received in revised form 10 November 2014
Accepted 11 November 2014
Available online 1 December 2014

Keywords:
Concentric condenser
Heat recovery equipment
Heat pipe array
Maximum heat transport capacity
Thermal resistance

ABSTRACT

A novel concentric condenser heat pipe array is developed and expected to be utilized in integrated waste heat recovery equipment with higher heat transfer efficiency at lower temperature heat sources. The investigation of the overall thermal performance of the concentric condenser heat pipe array was experimentally conducted in this work. The parameters considered in this study are operating temperature, input power, inclination angle, and the length of evaporator section. The results showed that the maximum heat transport (Q_{max}) increased with the augment of the operating temperature, the length of evaporator section, and condensation area, while decreased with increasing the inclination angle. The present investigation also discovered that, when the inclination angle was 60° and the length of evaporator section was 270 mm, the novel waste heat recovery equipment (concentric thermosyphon heat pipe array) delivered a better heat transfer performance.

1. Introduction

The rapid development of national economy results in huge energy consumption and serious damage to the environment [1–4]. Solving the conflict between rising of energy consumption and energy crisis became imperative [5,6]. In general, waste heat recovery system has been operated with heat pipe exchangers for commercial and industrial applications [7,8], which were honored as effectively thermal superconductors and energy saving equipments due to their high thermal performance. Sequentially, these heat pipes for the heat recovery could be currently classified as three types: the conventional heat pipe (CHP), two-phase closed thermosyphon (TPCT) and oscillating heat pipe (OHP) [9]. A heat pipe is an efficient heat transfer device and operates with a phase change working fluid, to transport heat from one end to the other [10,11]. In the conventional heat pipe, circulation of the working fluid is predominantly completed by return flow of the condensate to the evaporator section through capillary action in the CHP. But few study has discussed that how the parameters, such as capillary, sonic and entrainment limitations, confine the heat transport in CHP and how to effectively avoid the dry-out phenomenon.

First introduced by Akachi [12,13] in 1990, OHPs, or pulsating heat pipe (PHPs), is a passive heat transfer device capable of handling high heat fluxes while maintaining a low thermal resistance and presents a promising application in future thermal management. Although the OHP has attracted considerable interest due to its unique features over the CHP and TPCT, a complete theoretical understanding of the operational characteristics of the OHP is not yet achieved [14–17]. Meanwhile, the mechanism of a dry-out of OHP has not been fully understood [15–17].

Unlike the CHP, TPCT is an essentially heat pipe with a simple structure without wick, which performs its heat transfer performances mainly through gravitational force. Generally, it has been recognized that thermosyphon transport heat by evaporation and condensation of the working fluid respectively in the evaporator section and the condenser section, which transport heat exactly the same way as the conventional heat pipe but under the effect of gravity. Normally, the thermosyphon heat pipe may lead to the dry-out phenomenon so as to affect the total stability of the heat recovery system [18–24]. However, the novel concentric thermosyphon heat pipe array which was discussed in this article could eliminate the negative effect from the dry-out phenomenon and keep the stability of the waste heat recovery system because of its special structure. In brief, we aim to report the feasibility and thermal performance of the concentric thermosyphon heat pipe array in waste heat recovery system for industrial applications. A systematical investigation has been carried out on the thermal performance of the novel concentric condenser heat pipe array in the following section.

* Corresponding author.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.11.045
0017-9310/

Nomenclature

Q_{max}	maximum heat transport capacity, W
T	temperature, °C
T_{ope}	operating temperature, °C
L	length of the heat pipe, m
Le	evaporation section length, mm
Lc	condensing section length, mm
Qe	heat fluxes of evaporation section, W
h	overall heat transfer coefficient, W/m^2·°C

Greek alphabet

θ	inclination angle, °

Abbreviations

CHP	conventional heat pipe
TPCT	two-phase closed thermosphon
OPH	oscillating heat pipe
PHP	pulsating heat pipe

Subscripts

a	adiabatic
av	average
c	condenser
e	evaporator
i	inside
max	maximum
ope	operating

2. Experimental investigation

2.1. The structure and mechanism of the novel concentric condenser heat pipe array

Test prototype of the novel concentric condenser heat pipe array as schematically shown in Fig. 1(a) was fabricated with five evaporator tubes vertically arranged in parallel sharing one horizontally placed condenser tube. Industrial aluminum alloy tube is used as a material for fabrication of the novel heat pipe array. Fig. 1(b) shows the schematic view of the heat recovery device, and the working principle of the novel thermosyphon concentric heat pipe array is schematically given in Fig. 1(c).

Once, thermal input at the evaporator region vaporizes the working fluid, and this vapor of quickly travels to the condenser section through the inner core of each thermosyphon. At the condenser region, the vapor of the working fluid condenses, and the latent heat is rejected through condensation [25]. The condensate respectively returns to each evaporator depended on the gravity. Thus the evaporator must be located vertically below the condenser to ensure the condensate return to the evaporator.

During the condensation process, the novel concentric heat pipe array could avoid the cross flow in the condenser owing to communicating junction structure between the evaporator tubes and condenser tube. Consequently, the vapor flow rate could automatically be adjusted according to the input thermal and dry-out could be effectively prevented in this novel concentric condenser heat pipe array.

2.2. Experimental setup

As illustrated in Fig. 2, the experimental testing system was composed of novel concentric condenser heat pipe array, heating system, data acquisition system, electromagnetic flow meter, and temperature control system (cooling bath). In this study, the actual industrial waste heat was simulated by 5 electric heating units. An insulating layer using glass wool was fully bonded to the surface of the concentric heat pipe array to keep the thermal insulation of the testing system in order to reduce temperature impact from the environment. Therefore, heat loss from the evaporator and condenser surface was negligible. In evaporation section and condensation section, three of thermocouples were set up, and one was fixed in thermal insulation section, the other two were respectively set on the inlet and outlet of the circulating cooling water. The water flow rate was measured using a rotameter with a flow rate range of 0.08 kg/min. In the novel heat pipe array, each heat pipe has its vacuum pumped out, and was charged with acetone. The operating parameters specifications of each heat pipe are given in Table 1.

2.3. Experimental procedures

Before each experiment, preliminary test of the system was conducted to keep an steady state in order to obtain the precise data in the following testing. The power supply was then turned on and the power was increased at a given rate. It took approximately 15–20 min for the preliminary experiment to reach the steady operation state of the novel heat pipe array with a temperature fluctuation of less than ±0.5 °C. After obtained the steady state of the system with a certain power input, the temperature distribution of the novel heat pipe array, ambient temperatures and other experimental parameters were promptly measured and recorded. Then, the power input was increased to obtain another steady state, and the process was repeated and the system was stopped until dry-out appeared. The uncertainty values of the operating parameters are given in Table 2.

2.4. Data reduction

The input power of the dummy heater can be calculated as [26]:

$$Q_{in} = VI \tag{1}$$

V and I are voltage and current applied on the heater respectively.

The heat transfer rate through the heat pipe array can calculated as

$$Q_{out} = m_c C_{pc}(T_{c,o} - T_{c,i}) \tag{2}$$

where $T_{c,o}$ and $T_{c,i}$ are the outlet and inlet temperatures of coolant through the inner tube of condenser [26–28].

The heat flux of evaporator section can be expressed as

$$Q_e = Q_{in}\eta - Q_{loss} \tag{3}$$

where η is the efficiency of the electric heater, Q_{loss} is the heat loss through the test fixture.

The surface temperature t_{ei} and t_{ci} are needed to determine the isothermal characteristic, thermal resistance, and maximum heat transport capacity of the novel thermosyphon heat pipe array. Here, the inside-wall temperature of evaporation section can be yielded by a modified equation given by

$$t_{ei} = t_{eo} - \frac{Q \ln\left(\frac{d_{eo}}{d_{ei}}\right)}{2\pi\lambda l_e} \tag{4}$$