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Thermal performance of horizontal closed-loop oscillating heat-pipe with check valves †

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Abstract

This research investigated the thermal performance of various horizontal closed-loop oscillating heat-pipe systems with check valves (HCLOHPs/CVs). Numerous test systems were constructed using copper capillary tubes with assorted inner diameters, evaporator lengths, and check valves. The test systems were evaluated under normal operating conditions using ethanol, R123, and distilled water as working fluids. The system's evaporator sections were heated by hot water from a hot bath, and the heat was removed from the condenser sections by cold water from a cool bath. The adiabatic sections were well insulated with foam insulators. The heat-transfer performance of the various systems was evaluated in terms of the rate of heat transferred to the cold water at the condenser. The results showed that the heat-transfer performance of an HCLOHP/CV system could be improved by decreasing the evaporator length. The highest performance of all tested systems was obtained when the maximum number of system check valves was 2. The maximum heat flux occurred with a 2 mm inner diameter tube, and R123 was determined to be the most suitable working fluid.

Keywords: Thermal performance; Closed-loop oscillating heat pipe; Check valve

1. Introduction

An oscillating heat pipe (OHP) is a type of heat- transfer system used in heat recovery systems. It is primarily used for cooling and controlling the temperature of electronic devices and is considered an improvement over less efficient conventional heat pipes. The advantages of the OHP system include simplicity of construction (only one tube is required), no wick structure, high thermal performance, and operational flexibility. Heat transfer in this type of system occurs as a result of a self-excited oscillation driven by fast fluctuating pressure waves caused by the oscillatory flow of the fluid. There is, however, a limitation to the operation of the OHP: the circulation of the cooling fluid can become inhibited and can restrict heat transfer. A dry-out condition can occur as a result of the insufficient amplitude of the oscillatory flow of the fluid. The installation of check valves in a looped channel appears to be an effective method of preventing the dry-out condition. We call this looped channel system a "closed-loop oscillating heat- pipe with a check valve (CLOHP/CV)" ([see Fig. 1 (a)]. This system not only prevents dry -out, but it is also capable of operating in either a vertical or a horizontal orientation. However, it normally performs better when oriented vertically. Unfortunately, vertical orientation is not always practical. For example, horizontal orientation is commonly favored in cooling electronic devices, solar collectors, temperature regulation systems for the human body, etc. Despite these common applications, limited reliable experimental research findings are available on the operation of a horizontal closed-loop oscillating heat-pipe system with check valves (HCLOHP/CVs). In response to the lack of detailed data, this study focuses on determining the design and actual thermal performance of such a system. Initially, researchers have attempted to find the maximum inner diameter of an HCLOHP/CV. It was first [1] assumed that vapor bubbles formed alternately with

the liquid slug within the tube; the bubbles depended on the properties of the working fluid as

$$d_{max} \le 2\sqrt{\frac{\sigma}{\rho g}} . \quad (1)$$

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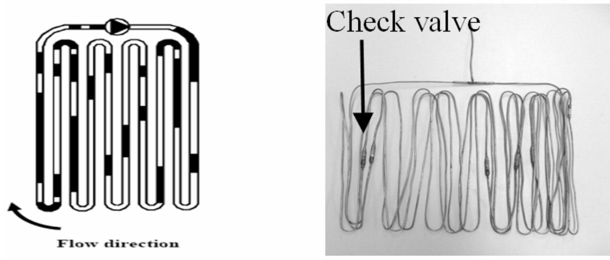
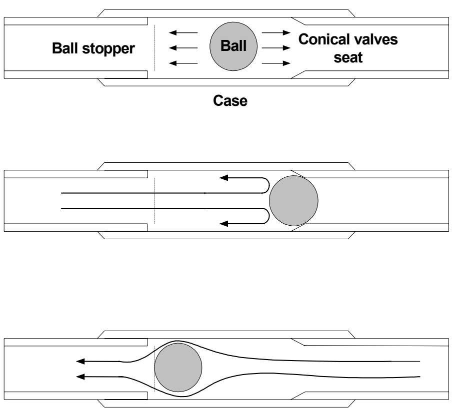


(a) HCLOHP/CV



(b) Principle operation of the check valve

Fig. 1. (a) HCLOHP/CV (b) Principle operation of the check valve.

The major focus of research on heat-pipe systems has been on the effects of inner diameter, evaporator length, and number of check valves on the system's operational performance. Authors of some early research papers [2] studied a horizontal closed-end oscillating heat-pipe (HCEOHP) system and established a correlation that predicted the heat- transfer characteristics of the system. The CLOHP/CVs under normal operating conditions is capable of controlling the flow direction of the working fluid [3]. Previous research [4] established a correlation that predicted the heat-transfer performance of such a system at a bottom mode orientation (when evaporator sections are over the condenser sections). Meena et al. [5] studied the effect of the inner diameter and inclination angles on the operational limits of CLOHP/CVs. Charoensawan and Terdtoon [6] studied the thermal performance of horizontal closed-loop oscillating heat-pipes. The operation startup of a horizontal closed-loop oscillating heat-pipe depends on the evaporator temperature that is related to the number of turns. However, the results for the horizontal orientation of that system are relatively limited. To attain systematic results on the performance of HCLOHP/CVs and to confirm some of the available data, an experimental study of the thermal performance of such system under normal operating conditions is still required. Therefore, the objective of the present work is to study the thermal performance of HCLOHP/CVs by varying some of the system parameters, that is, the number of check valves, the inner diameter of the tubes, the evaporator lengths/effective length, and the working fluid.

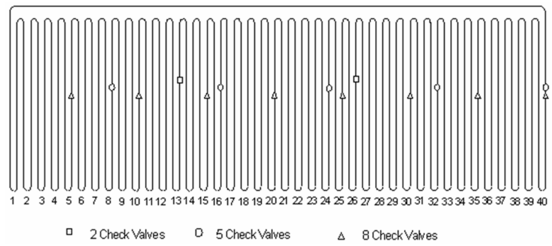


Fig. 2. Position of check valve on the HCLOHP/CV.

2. Experimental

2.1 Check valves

The check valve system in this study [see Fig. 1(b)] has a floating-type valve that consists of a stainless steel ball and a copper tube, in which a ball stopper and a conical valve seat are provided at the ends of the check valve case. A conical valve seat is provided at the bottom of the case, and a ball stopper is provided at the top of the case. The ball can move freely between the ball stopper and the conical valve seat. The stainless steel ball touches the conical valve seat to prevent a reversal of the flow of the working fluid. The ball stopper allows the working fluid to travel to the condenser section for heat transfer. The position of the check valve is shown in Fig. 2. The flow direction is from right to left.

2.2 Experimental setup

Figs. 3 and 4 show the horizontal system with the heating bath for the evaporator section and the cooling bath for the condenser section, respectively. The HCLOHP/CV is made of copper tubing. The temperatures of the evaporator and condenser section were maintained at 80 and 20°C, respectively. A data logger (Yokogawa DX 200 with a ±0.1°C accuracy, a 20-channel input, and a -200 to 1100°C measurement temperature range) was used with type-K thermocouples (Omega with a ±1° C accuracy) attached to the inlet and outlet of the cooling jacket to monitor the temperatures. To calculate the heat-transfer characteristics using the calorific method, four sets of thermocouples were attached to the inlet and outlet of the condenser section. To measure the oscillating temperature, two sets of thermocouples were attached to the left and right sides of the adiabatic section. A hot bath system (TECHNE TE-10D with an operating range of -40 to 120°C and ±0.01°C accuracy) was used to pump hot water into the heating jacket at a temperature of 80°C, while the cold bath system (EYELACA 1111, with a volume of 6.0 L, an operating temperature range of -20 to 30°C, and a ±2°C accuracy) was used to pump the cooling water into the cooling jacket. The cooling water inlet temperature was maintained at 20°C, and a floating rotameter (PlatonPTF2ASS-C for a flow rate of 0.2–1.5 L/min) was used to measure the flow rate of the cooling medium. During the experiment, the volumetric flow rate was set at 1.3 L/min with an inclination of 0° (horizontal mode). When a steady state was achieved, the temperature and the

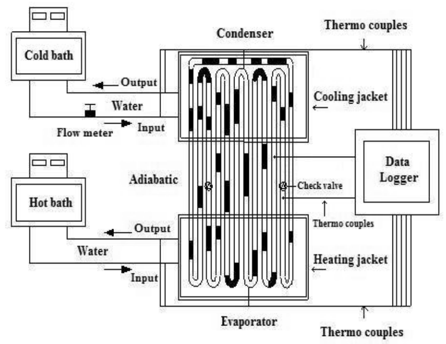


Fig. 3. Experimental setup.

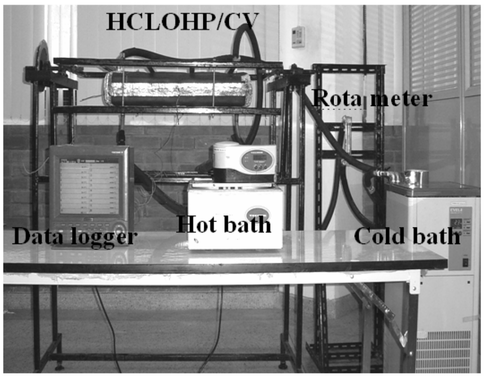


Fig. 4. Photograph of the test rig.

flow rate of the cooling water were recorded. The following equations are used to calculate the heat-transfer rate of the test HCLOHP/CV:

$$Q = m^{\bullet} Cp\left(T_{out} - T_{in}\right). \quad (2)$$

The controlled parameters are as follows:
- filling ratio = 50% (by total volume)
- number of turns = 40
- working temperature = 50°C
- diameter of the ball = 4 mm
- weight of the ball = 0.25 g
- 0 inclination (horizontal mode)

The variable parameters are as follows:
- number of check valves = 2, 5, or 8
- tube inner diameter = 1.77 or 2.03 mm
- evaporator length = 50, 100, and 150 mm
- working fluid = R123, ethanol, or water

3. Results and discussion

At the startup of the HCLOHP/CVs, the expected flow direction behavior was tested to confirm the flow direction of the working fluid. Flow direction can be detected by measuring temperature oscillations on the left and right sides of the adiabatic section (see Fig. 3). Fig. 5 shows a comparison of temperature oscillation between the horizontal closed-loop

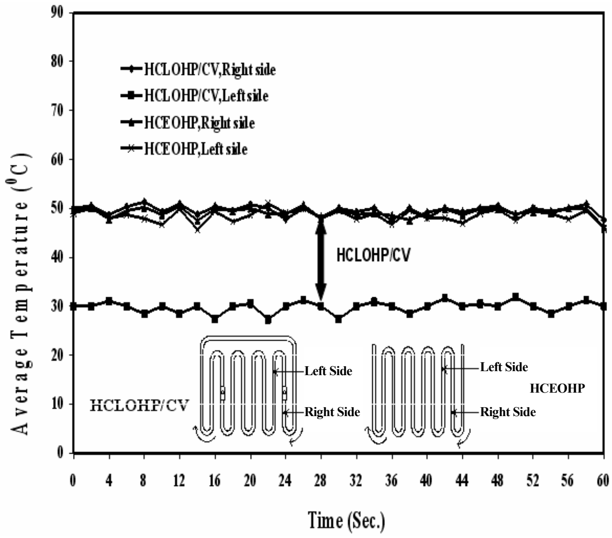


Fig. 5. Profile of the oscillation temperature at the adiabatic section.

system with a check valve and the HCEOHP. Both systems were made from long capillary copper tubes with an inner diameter of 2.03 mm. The evaporator length of 50 mm was used, and R123 was the working fluid. The horizontal closed-loop system with a check valve had two check valves located at the adiabatic section (Fig. 2). The results show that the oscillation temperature on the left and right sides of the horizontal closed-loop system with check valves is higher than the oscillation temperature of the horizontal closed-end system. This may be because the circulation of the working fluid in the horizontal closed-loop system with check valves flowed in one fixed direction. When the high temperature working vapor flowed upward through the condenser on the right side, it condensed and became fluid at low temperature after the downward flow through the evaporator on the left side. The temperature difference between the right and left sides is measurably high as opposed to the horizontal closed-end system, where the oscillation temperature is nearly constant. This may be because the circulation of the working fluid cannot be fixed in a particular direction; the temperature oscillation on the right and left sides fluctuated.

The heat-transfer rate (Q) of the horizontal closed-loop system with a check valve (see Figs. 6-10) varies and can be calculated using the following equation:

$$q = \frac{Q_0}{A_c} \quad (3)$$

3.1 Effect of the number of check valves on heat flux

In this experiment, the effect of the number of check valves on the heat flux of HCLOHP/CVs was considered (Figs. 6-8). These figures show the relationship between the number of check valves and the heat flux of a system with a tube having an inner diameter of 2.03 mm, 40 meandering turns, and evaporator lengths of 50, 100, and 150 mm. The numbers of check valves evaluated were 2, 5, and 8, respectively. It was found that the least number of check valves yielded the highest heat flux. The maximum heat flux of each working fluid was obtained with a minimum number of check valves. This may be because an increase in the number of check valves reduced the working fluid pressure between the evaporator and condenser sections, thereby preventing the movement of the ball, which subsequently terminated any heat transfer. As the number of check valves decreased, the pressure of the working fluid increased and the ball moved normally inside the pipe. The heat flux of the horizontal closed-loop system

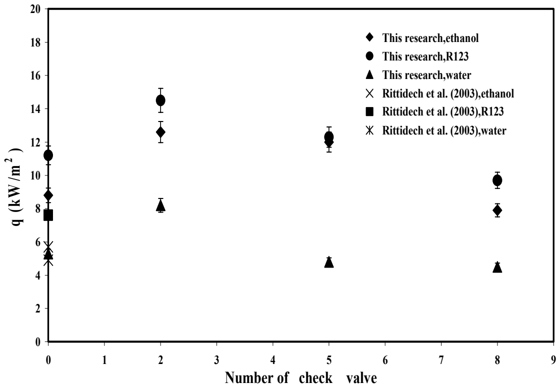


Fig. 6. Check valve to heat flux at evaporator length of 50 mm.

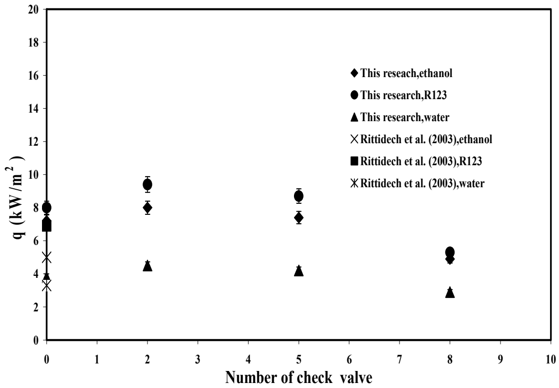


Fig. 7. Check valve to heat flux at evaporator length of 100 mm.

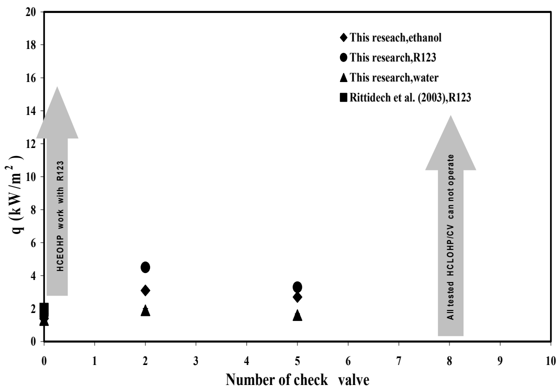


Fig. 8. Check valve to heat flux at evaporator length of 150 mm.

with check valves was greater than the heat flux of the horizontal closed-end system. It was noted that at an evaporator length of 150 mm, the horizontal closed-end system could be operated only with R123.

3.2 Effect of working fluid on heat flux

In this research, three types of working fluids were evaluated. Their properties (ASHRAE Handbook., 1993) are different with respect to their density, surface tension, and latent heat of vaporization. Concerning these three properties, the latent heat of vaporization is the major property that has the greatest effect on the motion of the liquid slugs and vapor bubbles in a tube, as well as the heat-transfer rate of the HCLOHP/CVs. Therefore, this study concentrated on this property. The effect of the latent heat of vaporization property was confirmed during the experiments. Consequently, the experimental results, which clearly present the effect of latent heat of vaporization on heat flux, are shown in Figs. 6–8. When the working fluid is changed from water or ethanol to R123, the heat flux also increases because R123 has lower latent heat of vaporization. As the latent heat of vaporization decreases, more bubbles are generated in the evaporator section. As more bubbles are generated, more heat is dissipated. It can be concluded from this result that the maximum heat flux is obtained when using R123 as the working fluid.

3.3 Effect of inner diameter on heat flux

There is a relationship between the inner diameter of the tube and the heat flux of HCLOHP/CVs. When using an evaporator length of 50 mm, various working fluids, and two check valves, the tube's inner diameter has an effect on the heat flux of the system as does the type of working fluid used, as shown in Fig. 9. An inner diameter of up to 2 mm was used in the experiments for all the working fluids. This inner diameter was smaller than the maximum inner diameter proposed in previous research [1]. Previous research offered an elementary operational principle for an oscillating heat-pipe system; that is, the liquid slugs and the vapor bubbles can coexist along the side of the tube along its length when the inner diameter of the capillary tube is sufficiently small. Fig. 9 shows the relationship between the inner diameter and the heat flux of the horizontal system with check valves. It can be seen that with each working fluid, the heat flux increases distinctly as the inner diameter increases. For all working fluids, the highest performance was attained at the maximum inner diameter of 2.03 mm. This may be because a smaller inner diameter leads to an increased frictional pressure drop and flow resistance. However, the maximum inner diameters of the tubes using water, ethanol, and R123 as working fluids from Eq. (1) were 5.30, 3.35, and 1.92 mm, respectively. In this research, the horizontal system with check valves tested tubes with an inner diameter range of 1.77-2.03, which are smaller than the maximum inner diameters of those using ethanol or water but slightly larger than the maximum inner diameters of pipes using R123. When considering all the tested working fluids, it was seen that heat could be transferred by the horizontal closed-loop system with check valves in tubes of 2.03 and 1.77 mm inner diameters. As the influence of the inner diameter of the tube is related to the working fluid, the effect of the working fluid on the thermal performance of the system with a specified inner diameter was considered, as shown in Fig. 9. The system with tubes with inner diameters of 2.03 and 1.77 mm had a higher thermal performance when using R123 than when using ethanol or water. This may be due to the effect of the inner diameter of the pipe. The chosen inner diameter for each working fluid was not only less than the maximum value proposed in previous research [1], but it had to be small enough to eliminate the undesirable effect of gravity on the vapor bubbles in the horizontal tube.

3.4 Effect of evaporator length on heat flux

In this experiment, the effect of evaporator length on the heat flux of HCLOHP/CVs was considered. Fig. 10 shows the relationship of the evaporator length to the heat flux of a system with inner diameters of 2.03 and 1.77 mm using various working fluids. The number of check valves was 2. As the evaporator length increased, the heat flux of each working fluid decreased. The maximum heat flux of each working fluid was obtained at the minimum evaporator length of 50 mm.

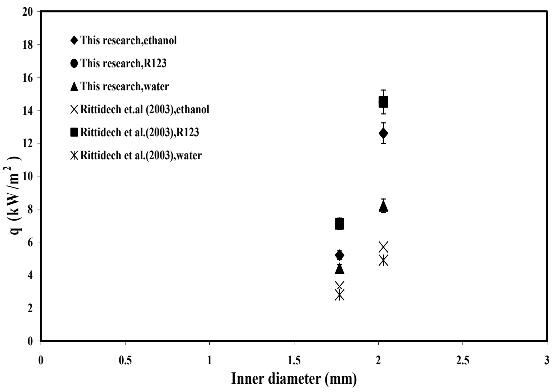


Fig. 9. Influence of the inner diameter.

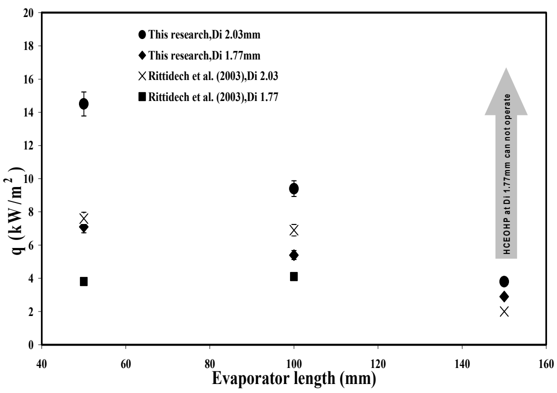


Fig. 10. Influence of the evaporator length.

This may be because in this experiment, the evaporator, adiabatic, and condenser lengths were of equal lengths. When the evaporator length decreases, the effective length between the condenser and the evaporator section also decreases. Therefore, heat can be transferred efficiently by the working fluid. It was also found that an evaporator length of 150 mm with an inner diameter of 1.77 mm rendered the horizontal closed-end system inoperable.

4. Conclusions

In sum, the best number of check valves for using HCLOHP/CV was 2. The working fluid had an effect on the heat flux of the HCLOHP/CV, and the heat flux values using R123 at all inner diameters were higher than those using water and ethanol. The heat-transfer performance of the HCLOHP/CV system could be improved by decreasing the evaporator length.

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Nomenclature

A : Area, m^2
C_p : Specific heat at constant pressure, kJ/kg ^oC
d : Diameter, m
g : Gravitational constant, m/s^2
m^0 : Mass flow rate, kg/s
Q : Heat-transfer rate, kW
q : Heat flux, kW/m^2
T : Temperature, ^oC

Greek letters

σ : Surface tension, N/m
ρ : Density, kg/m^3

Subscripts

in : Inlet
out : Outlet
c : Condenser section
0 : Horizontal position

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