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Research Paper

Experimental investigation on heat transfer performance of high-temperature thermosyphon charged with sodium-potassium alloy

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HIGHLIGHTS

- A Na-K (wt. 55% K) thermosyphon is experimentally studied.
- The periodic fluctuation of temperature occurs and finally eliminates.
- Optimal working temperature is more than 700 °C for Na-K thermosyphons.
- Heat source, condenser length and angle greatly affect performance of thermosyphons.

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ABSTRACT

Sodium-potassium alloy (Na–K), which is liquid at room temperature and pressure, is a promising working fluid for high-temperature heat pipes. Although several researches have been performed over the past decades, the experimental data for Na–K thermosyphons, especially for Na–K (wt. 55% K), was limited and needed. This study is to use Na–K (wt. 55% K) as working fluid to fabricate a high-temperature thermosyphon. The outside wall temperatures were measured to estimate the heat transfer performance of the fabricated thermosyphon by using 10 thermocouples, which were made of 0.2 mm-diameter Ni–Cr and Ni–Al wires. The thermal characteristics of the Na–K thermosyphon were studied at various heating temperatures (650, 675, 700, 725, 750, 775, 800, 825, 850 and 875 °C), condenser lengths (0.250, 0.220, and 0.190 m) and inclination angles (0° and 50°) to determine the influence of working conditions. Those factors considerably affected the heat transfer performance of the Na–K thermosyphon.

1. Introduction

High-temperature heat pipes can transfer a large amount of thermal energy within a small temperature difference by evaporating and condensing alkali metal fluids. Those pipes have been intensively considered as an effective heat transfer device in the area of high-temperature engineering [1]. Alkali metals, such as sodium and potassium which are important high-temperature working fluids, are solid at room temperature and thus lead to a risk of start-up from the frozen state [2]. However, sodium-potassium alloy (Na–K) exists in the liquid state at room temperature and pressure and thus can be used to avoid failure start-up of sodium or potassium heat pipe in the high-temperature engineering [3].

Na–K has been used in waste heat recovery [4,5], radioisotope Stirling systems [6,7], turbine cooling [8,9], molten salt reactor [10], and medium-temperature heat pipe furnace [11]. To our best knowledge, nonuniform temperature distribution occurs in the outside wall of the Na–K heat pipe. For example, Anderson et al. [6,7] reported a temperature difference of 16 °C in the condenser. A heat pipe furnace filled with Na–K cannot provide a satisfactory temperature distribution inside the furnace [11]. A low temperature or pressure difference is important to efficiently enhance heat transfer through heat pipes. Thus far, no studies have been conducted to elucidate reasons for nonuniform distribution in Na–K heat pipes. Operational conditions, such as inclination angle, heating source, and condenser length, significantly influence the behavior of heat pipes [12–15]. Thus, future works must focus on determining the influences of heating source, condenser length and inclination angle to enhance the heat transfer performance in Na–K heat pipes.

In this study, a thermosyphon charged with Na–K (wt. 55% K) was

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Nomenclature

D	diameter, m
g	gravity, m s^{-2}
L	length, m
P	point
q	heat flux, W m^{-2}
Q	quantity of heat, W
t	temperature, °C
T	time-averaged temperature, °C
ΔT	temperature difference, °C
W	winds, m s^{-1}

Greek symbols

α	heat transfer coefficient, W m^{-2} K^{-1}
φ	inclination angle (against vertical), °
λ	thermal conductivity, W m^{-1} K^{-1}

Subscripts

a	adiabatic section
c	condenser
e	evaporator
f	fluid
i	placement of measurement points
m	average value

experimentally fabricated. This study is the first to use Na–K (wt. 55% K) as working fluid applied to high-temperature thermosyphon. The effects of heating source, condenser length, and inclination angle on the thermal characteristics of the Na–K thermosyphon were experimentally investigated to establish a feasible working condition.

2. Experimental setup and analysis

Fig. 1 shows the schematic of the experimental setup. Table 1 presents the design parameters of the experimentally fabricated Na–K thermosyphon. Table 2 lists the thermal-physical of Na–K. Heating source was an electrical heating system, which can provide uniform heating temperature < 1000 °C to the evaporator and has a body can turn 360° with an accuracy of 10°. Inclination angle (φ) is defined as the included angle between the axial direction of thermosyphon and the vertical direction of gravity (Fig. 1). The condenser was in direct contact with air (17 °C) and cooled by radiation and natural convection. The test system is placed in a single laboratory to avoid air turbulence, and an air ejector fan works to maintain a constant room temperature. All of ten K-type thermocouples with an uncertainty of 1.2 K were attached on the outer surface of the tube. The thermocouples, particularly those in the evaporator, were shielded against radiation. They were made of 0.2 mm-diameter Nickel-Chromium and Nickel-Aluminum wires and calibrated. The temperature is more than 17 °C, and the maximum relative uncertainty caused by thermocouples is $\sqrt{1.2/(17+273.15)} = 0.414\%$. Temperature was recorded using an Agilent 34972A data acquisition system with an accuracy of $1/2^{16}$ and frequency of 3 s. The relative uncertainty of temperature is $\sqrt{(0.414\%)^2 + \left(\frac{1}{2^{16}}\right)^2} \approx 0.414\%$, which is accepted for high-temperature measurement (> 500 °C). The thermal insulation layer is a type of cellucotton containing aluminum silicate. In this work, the working temperature of the adiabatic section is less than 850 °C. Based on the design code "GB 50264-97", maximum heat loss through the thermal insulation layer is below 375 W m^{-2}, which corresponds to the maximum working temperature. The outside wall temperature of the thermal insulation layer is

$$t_O = t_f + \frac{q}{\alpha_s} \tag{1}$$

where α_s is the surface heat transfer coefficient,

$$\alpha_s = 1.163 \times (10 + 6\sqrt{W}) \tag{2}$$

where W is the average winds and is equal to 1.9 m s^{-1}. The thermal insulation layer is aluminum silicate cellucotton, and its thickness is estimated by the following equation,

$$\frac{D}{d}\ln\frac{D}{d} = \frac{2\lambda}{d}\cdot\left(\frac{t_{I_a}-t_f}{q} - \frac{1}{\alpha_s}\right) \tag{3}$$

where t_{I_a} is the maximum temperature at the adiabatic section, the D is the outer diameter of the thermal insulation layer, and λ is the thermal conductivity

$$\lambda = 0.056 + 0.0002t_m \tag{4}$$

where t_m is the average temperature and equal to

$$t_m = \frac{1}{2}(t_O + t_I) \tag{5}$$

Based on the result, a 165 mm-diameter thermal insulation layer was wrapped around the adiabatic section.

In contrast to our previous works [16–18], a series of heating temperature (650, 675, 700, 725, 750, 775, 800, 825, 850 and 875 °C) was uniformly provided by the furnace to the evaporator of the Na–K thermosyphon. The optimal length of the evaporator was set as 580 mm according to our previous works [19]. The Na–K thermosyphon was also tested under different condenser lengths of 250, 220, and 190 mm considering the influence of heat transfer area. Ten temperature measurement points of P_i(i= 1,2,3... and 10) were non-uniformly distributed in the outside wall of the thermosyphon from the bottom to top. The

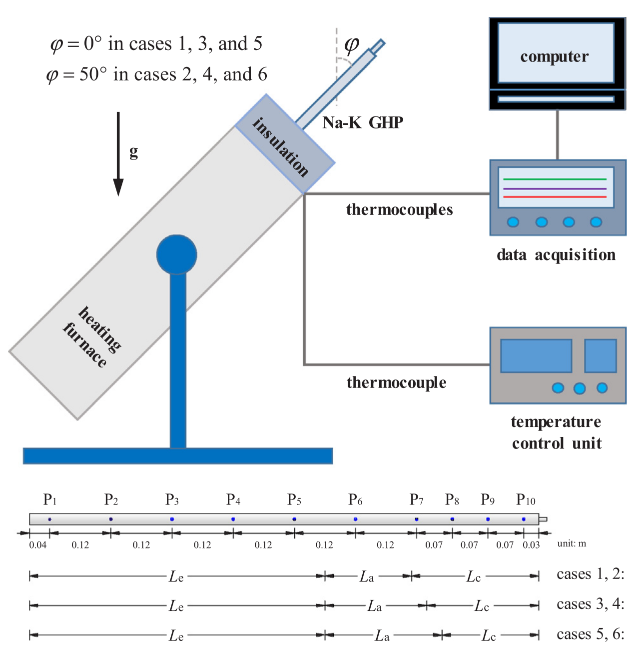

Fig. 1. Experimental apparatus and measurement point distribution.