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Effect of inclination angle and fill ratio on geyser boiling phenomena in a two-phase closed thermosiphon – Experimental investigation

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ABSTRACT

Geyser boiling is a complex phenomenon which may occur in heat pipes causing high temperature and pressure oscillation leading to noticeable vibration. Therefore, understanding of such process is essential to improve heat pipes thermal performance and avoid damage. In this experimental study, a comprehensive investigation of several parameters on the characteristics of the geyser boiling has been conducted during the operation of two-phase closed thermosiphon (TPCT) using water as the working fluid. The effect of different inclination angles (90, 60, 30 and 10°) at various fill ratios defined as volume of liquid in the evaporator to the volume of the evaporator (25%, 65% and 100%) on the geyser boiling has been investigated at a broad range of heat load and for various mass flow rates and inlet temperatures of the cooling water. These important parameters have been examined to report the occurrence and period of the geyser effect at each heat input. The results showed that the orientation and the liquid charge have a significant impact on the occurrence and period of the geyser boiling at low and high heat inputs. For example, at a fill ratio of 100%, the geyser boiling occurs at a lower heat input compared with that for fill ratios 25%, 65% at all inclination angles, while it happens at a higher heat load at a low inclination 10° compared with other angles at all fill ratios. In addition, at high input energies, it almost disappears at orientations of 90 and 60° for all liquid charges. Also, comparing with fill ratios of 25% and 65%, a shorter period is observed for a fill ratio of 100% at angles of 90, 30 and 10°, whereas it is longer at 60° and low heat inputs. This work highlights the effects of the operating conditions on geyser boiling in heat pipes.

1. Introduction

Solar thermal system is one of the most cost-effective renewable energy technologies and has presented significant global market prospect. It has been widely utilised for producing hot water, providing space heating and cooling, and supplying heat needed for industrial processes. Production of hot water consumes a significant amount of thermal energy and majority of solar water heating systems are used in buildings [1]. The key element in the solar water heater is the solar collector. The conventional solar collectors which depend on working fluid circulation suffer from many drawbacks such as low thermal performance, corrosion problems, freezing in cool climate, reverse heat flow at night and others related to space and weight. However, using heat pipe as an energy convertor in the solar collector can eliminate most of these disadvantages [2,3].

Heat pipes are two-phase devices which can transfer high heat rate at a relatively low-temperature gradient between two points depending on the latent heat of the working fluid in a closed container by utilising evaporation and condensation processes. Due to their various advantages of the relatively low-temperature difference between the evaporator and condenser sections, compact and employing a small amount of working fluid, they can be used in various types of applications such as heat exchangers [4], cooling of electronics [5], and solar systems [6,7]. The evaporator and condenser represent the heat pipe main sections in which the working fluid absorbs heat in the evaporator side and rejects it in the condenser. The vapour provides its latent heat to the coolant at condenser section to condense and drop back to the evaporator by gravity, if the heat pipe is wickless (Thermosiphon) or by capillary force, if a wick heat pipe is used. As a result of simplicity in construction and cost effectiveness of wickless Two-Phase Closed Thermosiphon (TPCT) heat pipes, A substantial attention has been paying to investigate their thermal performance to be used in suitable applications [8,9].

Although several experimental investigations have been conducted to examine the influence of different parameters affecting the performance of the thermosiphon heat pipe, challenges regarding the two-phase process still need to be considered to enhance the thermal performance and to predict the operating limits of this device [10]. Table 1

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Table 1
Experimental studies testing the effect of different parameters on the performance of the heat pipe.

Ref.	Working fluid	Studied parameters	Findings
[11]	R-134a	Bending position, fill ratio, tilt angle	Optimum angle and fill ratio are 40° and 100.8% The lowest thermal resistance is found for two ends bending
[12]	Water, ethanol, ethylene glycol	Working fluid, inclination, mass flow rate	Ethanol exhibits the lowest thermal resistance at 90°, The highest heat output is obtained at angle 90°
[13]	Water	Geometry cross section, aspect ratio, Fill ratio	The highest heat transfer rate is reported for circular cross-section, heat flux increases with aspect ratio
[14]	Water	Fill ratio, Aspect ratio	Changing fill ratio can reduce thermal resistance depending on aspect ratio
[15]	Water	Fill ratio	Fill ratio depends on geometry and heat input
[16]	Water, FC-84, FC-77, FC-3283	Working fluid, Fill ratio	Fluorinate fluids show the highest performance at low heat loads (under 40 W), while Water outperforms other fluids at higher heat inputs
[17]	Water, methanol, acetone	Fill ratio, Working fluid	Acetone exhibits the highest performance, The optimum fill ratio is 85%
[18]	R-134a	Fill ratio, Adiabatic length	The best fill ratio and heat flux suiting shorter adiabatic section are 15% and 5.92 W
[19]	Water	Fill ratio, Inlet cooling temperature, Mass flow rate	Optimum fill ratio between 7 and 10% Shorter start-up time is needed at optimum fill ratio
[20]	Water	Cooling location, Inclination angle	The thermal performance of the heat pipe is highly affected by the position of cooling source The new cooling approach can be suitable for cooling systems with multi-heat sources at all orientations
[21]	Water	Fill ratio, Boiling visualisation	Neutron radiography is a good technique to visualise two-phase process The best fill ratio depends on the vapour pressure and heat capacity inside the TPCT

illustrates some of the experimental studies that have been conducted to investigate the performance of the heat pipe. It is observed that all experimental investigations shown in Table 1 did not report the boiling phenomenon occurring during transient operation of the two-phase closed thermosiphon which so-called geyser boiling phenomenon.

Geyser phenomenon occurs when a vapour gathering at the lower part of the evaporator inside the thermosiphon forming a large bubble size occupying the whole inside diameter. This bubble collapses causing liquid at the evaporator pushing severely up to the condenser section and may result in vibration of the TPCT [22]. Lin et al. [22] investigated experimentally the geyser phenomenon in an annular vertical thermosyphon heat pipe charged with water and ethanol as working fluid. Different parameters were tested namely, heat input, fill ratio, condenser temperature and evaporator length to examine their effect on the geyser effect. The study revealed that the geysering period is shorter at a higher heat input, a smaller fill ratio and a shorter length of the evaporator. Also, a correlation was suggested for calculation of the heat transfer coefficient. Negishi and Sawada [23] studied heat transfer performance of the TPCT filling with water and ethanol as working fluids at different inclination angles and fill ratios with visualisation of unsteady behaviour of thermosiphon. The study revealed that to achieve a steady heat transfer performance, a 25–60% fill ratio and inclination angle between 20 and 40° should be used when water is the working fluid, whereas 40–75% fill ratio and more than 5° tilt angle for ethanol. Also, a uniform temperature distribution and higher heat transfer rate result after the fluid in evaporator pushes up to the condenser and they called this strange situation as a water hammer phenomenon which occurs when fill ratio exceeds 60%. However, the evaporator of the TPCT was fixed at a constant temperature of 85 °C preventing investigation of the effect of heat input on the occurrence of this phenomenon.

An experimental investigation has been carried out to observe the geyser effect in a two-phase close thermosiphon filled with water at different values of pressure and heat flux [24]. The study showed a visualisation of geyser phenomenon inside the TPCT and concluded that this phenomenon can occur by decreasing the pressure at a constant heat flux. Also, a link for the heat transfer coefficient of the evaporator with the pressure and heat flux was proposed. The mechanism of the geyser boiling in a vertical glass two-phase closed thermosiphon filled with water and R-113 as working fluids has been investigated experimentally by Kuncoro et al. [25]. The study showed that inducing geyser effect can be highly related to the temperature distribution which depends on the geometry of TPCT, the heat transfer mechanism and the physical properties of the charged liquid. It was also reported that even if the pressure increases during the bubble formation, occurring of geysering may continue when the driving force of initiating geysering is the superheat. However, these studies did not examine the effect of the inclination angle on the characteristics of geyser phenomenon.

Abreu et al. [26] studied the effect of different parameters on the thermal performance of the TPCT with a straight evaporator and semi-circular condenser for a compact solar water heater. They reported the occurrence of the geyser boiling at a low heat input during the test, but the effect of this phenomenon has not been analysed. An experimental study to investigate the influence of the tilt angle and fill ratio on the heat transfer characteristics of a thermosiphon heat pipe with water as a working fluid has been carried out by Noie et al. [27]. They found that the heat transfer coefficient of condensation increases with increasing of the fill ratio and the highest value was obtained at 22% and 30% for the inclination angle of 30°, whereas for the inclination angle of 45°, it was obtained at fill ratio 15%. In addition, the amount of heat transfer rate increases as fill ratio increases, and for the three fill ratios, the highest output amount of heat transfer was achieved at an inclination angle between 15° and 60°. They also observe the occurrence of geyser phenomenon and provided a conventional explanation, but they did not investigate the effect of the studied parameter on the geyser boiling. Emami et al. [28] investigated the effect of fill ratio, orientation, inside diameter of thermosyphon and coolant flow rate on the geyser boiling in the TPCT. They reported that shorter geyser period and lower temperature oscillation is observed at lower fill ratio and inclination and no effect for the water mass flow rate on the geyser boiling was noticed. In addition, the geyser effect can be avoided below a fill ratio of 30% and it does not occur at an angle of 15° and inside diameters of 20 and 24 mm. However, their conclusion about the effect of inclination angle was accomplished at one value of heat input and fill ratio which may differ at other heat inputs and fill ratios. This is also true for their findings about the effect of fill ratio and the coolant mass flow rate.

Khazaee et al. [29] carried out an experimental study to test the effect of input energy, fill ratio, coolant flow rate and the evaporator length on geyser phenomenon in the TPCT with methanol as a working fluid. The study showed, the period of the geysering and the amplitude of the temperature oscillation increase as fill ratio increases, whereas the geysering disappears at fill ratio less than 30%. In addition, the heat input plays an important role by affecting the period and intensity of the geyser phenomenon in which the period and intensity of the geysering decrease as heat input increases until disappears completely at higher heat input. They also observed that the period of geyser effect is longer as the coolant flow rate decreases. However, they did not examine the effect of the inclination angle on the characteristics of the