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Experimental investigation of geyser boiling in a two-phase closed loop thermosyphon with high filling ratios

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ABSTRACT

The geyser boiling instability in a two-phase closed loop thermosyphon (TPCLT) is experimentally investigated through flow visualization and simultaneous measurement of pressure and temperature fluctuations. Wide ranges of filling ratios of R134a fluid from 90% to 53%, and heat flux from 20 W cm^{-2} to 220 W cm^{-2} are examined. The Power Spectrum Density (PSD) method is applied to analyze the periodicity of geyser boiling, and the parameter Standard Deviation (SD) is used to characterize the oscillating amplitude. The effects of heat flux and filling ratio on the geyser boiling occurrence and the oscillation characteristics are discussed in detail. The results show that, the flow regimes experience the consecutive variation of single-phase flow, bubbly flow, churn flow, bubbly flow, and single-phase flow within each geyser boiling cycle, leading to the fluctuation of flow and heat transfer characteristics. The geyser boiling is more liable to occur in the conditions of higher filling ratio and moderate heat flux. The initiating heat flux for the onset of geyser boiling decreases with the increase of filling ratio, but the range of heat flux for the geyser boiling occurrence is narrow under the high filling ratio conditions. The frequency of geyser boiling increases with the increase of heat flux for a certain filling ratio. With the increase of filling ratio, the oscillating frequency firstly decreases and then increases. The minimum oscillating frequency occurs at the combination of filling ratio of 76% and heat flux of 90 W cm^{-2} under the experimental conditions in this work. Both the fluctuation amplitude of pressure and temperature increase with the increase of heat flux, while decrease with the increase of filling ratio. Compared to R134a under the same filling ratio of 76%, the water has higher heat flux for geyser boiling occurrence, smaller oscillating amplitude of pressure, and lower oscillating frequency due to the difference in thermophysical properties.

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1. Introduction

With the ever-increasing power density of electronic devices, the high heat generation rate during operation becomes a major obstacle that prevent the further development of the electronics industry and micro-computer technology. In the aerospace vehicles and gas turbines, efficient techniques of thermal protection and temperature control are in urgent need to quickly remove the high heat flux from the local hot spots to the surroundings.

The two-phase thermosyphon, namely the wickless heat pipe, including the closed loop and the closed-ends types, is one of the most promising solutions due to their simple structure, low cost, and no external driving force. In addition, by eliminating the high flow resistance and the capillary limit associated with conventional heat pipes with porous wick structure, the thermosyphons allow higher heat transfer rate. Thus they are extensively applied in industries, such as the cooling of electronic components and gas turbine [1–3], solar energy systems [4,5], air-condition systems [6] and heat-recovery systems [7]. Among the thermosyphons, the closed loop type with low filling ratio is capable of transferring higher heat flow rate, and is adaptive to a large range of heating load variation. However, the disadvantage of the low filling ratio is that local dry-out is easier to occur in the evaporator section, especially in the situations of wobbling, tilting and variable acceleration. In contrast, the closed loop thermosyphon with high filling ratio, in which the vapor bubbles could provide sufficient driving force for fluid circulation and condensate return, is able to remove high heat flux from local hot spots since all the thermosyphon surface except the heating section could act as condenser or subcooler, so as to provide a huge heat sink. The high filling ratio is also helpful to avoid the possible dry-out of the evaporator even

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Nomenclature

f	frequency (Hz)
h_{evap}	heat transfer coefficient (kW m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
N	the total number of selected data
$(\Delta p)_{\mathrm{cooler}}$	pressure drop at cooler (Pa)
$(\Delta p)_{\mathrm{evap}}$	pressure drop at evaporator (Pa)
q	heat flux (W cm^{-2})
$S(f)$	power spectrum density ((kPa)^2 s)
T	temperature (°C)
T_t	time period (s)
$T_{\mathrm{cooler,\ inlet}}$	temperature at cooler inlet (°C)
$T_{\mathrm{cooler,\ outlet}}$	temperature at condenser outlet (°C)
$T_{\mathrm{evap,\ outlet}}$	temperature at evaporator outlet (°C)
$T_{\mathrm{wall,\ inner}}$	temperature at evaporator inner wall (°C)
x	distance (m)

Abbreviations

FR	Filling Ratio
PC	Personnel Computer
PCC	Phantom Camera Control
PSD	Power Spectrum Density
RTD	Resistance Temperature Detector
SD	Standard Deviation
TPCLT	Two Phase Closed Loop Thermosyphon

Greek letters

$\emptyset_{PP}$	autocorrelation function
τ	time delay (s)

Subscripts

cooler	cooler section
Evap	evaporator
i	item
in	inner
pp	pressure signal
T	temperature
wall	evaporator wall

in wobbling and variable tilt angle situations, such as in the thermal management of vehicle carried, ship carried or aircraft carried electronics, and in the thermal protection of flying objects. Another advantage of the thermosyphon with high filling ratio is that both the positions and areas of the evaporating and condensing sections could be multiple and variable.

However, the various instabilities during the operation of thermosyphons [8,9], including pressure drop oscillations [10], density wave oscillations [11], thermal instabilities [12], and geyser boiling [13–15], etc. may lead to the fluctuation of temperature, pressure, and mass flow rate, which may induce the thermal fatigue of the devices [16,17], and may consequently reduce the equipment life cycle, or even cause serious accidents. Among the various instabilities, the geyser boiling, as a commonly encountered type of instability in the two-phase thermosyphons, are drawing much attention of the international researchers.

The geyser boiling, also called intermittent boiling, is induced by the interaction between the vapor buoyancy and the flow resistance. The geyser boiling often occurs when the heat input is insufficient to maintain continuous and steady boiling. A large slug of bubbles or coalesced bubble cluster is gradually formed at the heating section, grows to the size comparable to the inner diameter of the thermosyphon, but is suppressed by the upper liquid column. The abrupt vapor eruption would occur until the interface of vapor and liquid ruptures when the disturbance of the interface is greater than the tolerance of the interface. The liquid column above the large bubbles is propelled from the evaporator to the condenser. When the vapor mixes with the subcooled liquid, the bubbles suddenly collapse and release heat by condensation, and then returned to the heating section by gravity. Then the vapor void is accumulated again in the heating section for the next geyser boiling cycle. In summary, the geyser boiling process can be divided into three stages, namely the boiling delay (or the thermal storage) stage, the vapor eruption stage, and the liquid returning stage [18]. The periodical changing flow patterns in geyser boiling might lead to the fluctuations of pressure and temperature, which is disadvantageous for the precise temperature control of the targeted devices, so to understand the formation conditions of geyser boing would provide important guidelines for preventing its occurrence.

The geyser boiling in two-phase closed thermosyphon (TPCT) is extensively studied in both experimental and theoretical aspects. This phenomenon is investigated first in thermosyphon by Griffith [19]. Casarosa et al. [20] studied experimentally the geyser effect at low pressure. The heat transfer coefficient at the thermosyphon evaporator was measured and a correlation was given, which links the heat transfer coefficient with the working pressure and the specific thermal flux. Xia et al. [21] presented their experimental studies related to the geyser boiling in a flat closed-end thermosyphon. The experimental results show the effects of the heat flux, filling ratio, coolant temperature and working fluid type on the geyser boiling. Moreover, this instability mechanism related to the heat transfer modes was investigated. Emami et al. [22] experimentally investigated the effects of the inclination angle, filling ratio, input heat rate, mass flow rate of coolant, and inside diameter of the tube on the geyser boiling phenomenon in a closed-end thermosyphon. The results discussed in detail the operational conditions for the occurrence of geyser boiling. Kuncoro et al. [23] studied experimentally the mechanism of the geyser boiling in a closed-end thermosyphon by temperature and pressure measurements and visual observations. Lin et al. [24] investigated experimentally the effects of the heat load, condenser temperature, degree of liquid fill and length of the evaporator on the characteristics of the geyser boiling in a closed-end thermosyphon for both water and ethanol as working fluids. They proposed an empirical equation to correlate the data for the heat transfer coefficient and suggested a criterion for the occurrence of geyser boiling. Jouhara et al. [25] carried out a three-dimensional CFD simulation of geyser boiling in a closed-end thermosyphon. In their work, a comprehensive three-dimensional CFD model, simulating the evaporation and condensation processes in two-phase closed thermosyphon, was developed. The three-dimensional CFD simulation successfully predicted and visualized the geyser boiling. Smith at al. [26] investigated the boiling regimes in a diameter of 8 mm in a closed-end thermosyphon. In their study, an unsteady regime of geyser-type flow regime exists at high levels of confinement and high heat flux. Tong et al. [27] proposed a dimensionless number GEY to identify the progress in the geysering and also to obtain the period of geysering. Visualization experiments on the geyser boiling in a vertical circular tube with the working fluid of water were also carried out by Tong [28]. Through the visualization, four typical flow patterns, bubbly, slug, churn and annular flow were observed. The results indicate that the geyser boiling occurs obviously at low-pressure of below

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