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Geyser boiling phenomenon in two-phase closed loop-thermosyphons

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ABSTRACT

Geyser boiling is experimentally investigated in two-phase closed loop-thermosyphons, consisting of two parallel condensers and a shared evaporator. Heat sink conditions at each condenser vary from forced to natural convection in a multitude of thermal arrangements. A cartridge resistance provides input power ranging from 0.1 to 0.85 kW to the evaporator. Water is employed as working fluid with filling ratios of 0.5 and 0.9. The effects of thermal conditions in both condensers, filling ratio, heat flux and vapor pressure on geyser boiling phenomenon are investigated. Geyser boiling eventually yields intense evaporator vibrations inferred by acceleration measurements. The ratio of convective thermal resistances acting at each condenser affects the acceleration. Amplitudes up to 110 and 1100 m/s^2 were observed for filling ratios of 0.5 and 0.9, respectively. In unsteady regime, geysering occurs for heat fluxes less than 20 kW/m^2 and vapor pressures less than 25 kPa. The vapor pressure is increased with increasing heat flux, suppressing geyser boiling intensity. In steady-state regime geyser boiling occurs for heat fluxes higher than 12.5 kW/m^2 and vapor pressures below 25 kPa.

1. Introduction

Passive heat transfer devices based on heat pipe technology have been studied in several scientific and industrial applications with the aim of replacing electrically powered cooling systems [1]. Two-phase thermosyphons are wickless gravity-assisted heat pipes, consisting of a closed and evacuated tube, filled with a certain volume of working fluid, which allows passive heat exchange between a heat source and a heat sink, when subjected to low temperature differences [2]. Despite the high intrinsic heat transfer efficiency, thermosyphons can experience a particular unstable phenomenon, known as geyser boiling. This instability is related to abrupt vapor expansion that occurs within the thermosyphon evaporator. Longer periods of quietness followed by scattered, sudden and blistering vapor nucleation characterize the geyser boiling. The average geyser frequency is typically lower than 0.1 Hz with bubbles of the same size of the tube inner diameter [3]. Geyser boiling occurrence can eventually be noticed as a characteristic structural vibration due to the vapor expansion impact on the tube end caps.

Geyser boiling may be observed in simple and in loop-thermosyphons. An attempt to distinguish geyser boiling phenomenon in axial conventional and loop-thermosyphons is performed with the aid of Fig. 1. Vapor bubbles are formed at the evaporator wall when the liquid pool becomes superheated. In conventional thermosyphons a bubble, which dimensions are of the order of the pipe inner diameter, abruptly leaves the evaporator towards the condenser after detachment. Liquid on the bubble top is propelled towards the condenser end. A characteristic sound is produced owing to the liquid impact at the condenser end cap. The liquid is then subcooled and flows back to the evaporator. In loop-thermosyphons, the geyser boiling phenomenon can be affected by several aspects such as the evaporator geometry, the evaporator location in the two-phase flow circuit and the amount of working fluid. Here, emphasis is provided to cases where the evaporator dimensions are bigger than the pipeline diameter of the adiabatic region and the liquid fills the evaporator container partially. In these cases, the propelled liquid mainly collapses at evaporator walls and it is entrapped there. Coalescence of bubbles prior to detachment can play an important role. The geyser boiling effects on the condenser and adiabatic lines are dependent on the loop geometry and boundary conditions.

According to Jafari et al. [4], in general sense, there are no restrictions on thermosyphon thermal performance due to geyser boiling phenomenon. However, it must be avoided in order to prevent premature failure since structural vibrations induced by geysering occurrence can damage welding points, promoting vacuum leakage. Bezrodnyi and Beloivan [5] suggested performance limitations of thermosyphons with high amount of working fluid.

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Nomenclature

$\bar{v}_{AD}$	mean air velocity at the air duct, (m/s)	t	time, (s)
ΔT_{ln}	logarithmic mean temperature difference, (°C)	$T_{AD,in}$	mean temperature at the AD duct inlet, (°C)
$\dot{m}$	mass flow rate, (kg/s)	$T_{AD,out}$	mean temperature at the AD duct outlet, (°C)
$\bar{T}_{evap}$	evaporator mean temperature, (°C)	$T_{CA,in}$	mean temperature at the CA duct inlet, (°C)
A	area, (m^2)	$T_{CA,out}$	mean temperature at the CA duct outlet, (°C)
$a(t)$	acceleration, (m/s^2)	T_{tb}	thermal bath temperature, (°C)
c_p	specific heat at constant pressure, (J/(kg K))	T_v	vapor temperature, (°C)
p_{sat}	saturation pressure, (Pa)	v_{max}	evaporator maximum velocity, (m/s)
q_{AD}	heat transfer rate at the AD condenser, (W)	Δt^*	characteristic period of the vapor pressure oscillation, (s)
q_{CA}	heat transfer rate at the CA condenser, (W)	G	dimensionless pressure rate
q_{in}	input power, (W)	AD	air duct
q''_{in}	input heat flux, (W/m^2)	CA	calorimeter
$R_{h,AD}$	convective thermal resistance at the AD condenser, (°C/W)	FR	filling ratio
$R_{h,CA}$	convective thermal resistance at the CA condenser, (°C/W)	LHS	left hand side
T	temperature, (°C)	RHS	right hand side

Geyser boiling behavior can be affected by many factors such as heat sink thermal conditions, working fluid properties, device geometrical dimensions, heat flux at the evaporator and filling ratio (FR), defined as the volume ratio of working fluid to evaporator.

In this work an experimental analysis of geyser boiling phenomenon is conducted in loop-thermosyphons developed by Oliveira et al. [6]. The setup is a heat exchanger system composed of two parallel condensers and a shared evaporator as shown in Fig. 2. The effects of variable thermal conditions in both condensers, filling ratio, heat flux and vapor pressure on geyser boiling phenomenon are investigated. The thermal behavior of each condenser is analyzed with and without geyser occurrence in the evaporator. A criterion for geyser boiling occurrence is established based on abrupt oscillations in vapor pressure within the adiabatic line. Acceleration measurements of the evaporator axial axis allow to evaluate the geyser boiling influence on evaporator structural vibration.

The present study is motivated as follows:

- To the best of our knowledge geyser boiling phenomenon has been only analyzed by thermal aspects. However, the main concern during geyser boiling occurrence is the device structural integrity. High frequency and amplitude vibrations can induce the device failure by damaging junctions such as welding points. The present work aims to quantify the geyser boiling influence on the evaporator vibration;
- Evaluation of the geyser boiling phenomenon in a wide range of operating thermal conditions was poorly investigated. Particularly, results are unknown for large temperature differences (*e.g.* 60 °C) along the heat pipe investigated;
- Most of previous investigations studied geysering effects in straight or coaxial thermosyphons. However, geyser boiling on complex geometries such as loop-thermosyphons was never extensively investigated. As a consequence, the results reported herein can differ from usual geyser boiling studies, as the vapor expulsion is directly propelled to the condenser section.

2. Literature review

Geyser boiling effects on thermosyphons have been studied even before Boure et al. [7] used the term geysering for periodical rapid expulsions of a boiling liquid and its vapor in a tube. Griffith [8], for example, already studied geysering phenomenon characterized by cycles of a quiet condition and violent vapor expulsion at the liquid surface level. In this study, the main scientific contributions are summarized for two-phase closed and evacuated thermosyphons.

Casarosa et al. [9] evaluated the geyser boiling effects in conventional thermosyphons positioned vertically. The frequency of geyser occurrence was shown to increase with increasing heat flux in the evaporator at a nearly constant condenser pressure. However, in these conditions, the geyser intensity remained almost constant. Moreover, they found that by keeping the heat flux constant and by increasing the condenser pressure, the geyser occurrence falls progressively until it disappears completely.

The critical heat flux in thermosyphons, considering boiling and the geyser effect, was studied by Imura et al. [10]. They proposed an equation for the ideal filling ratio, according to the magnitude of the critical heat flux and the operating conditions. An optimum FR between 0.18 and 0.22 was reported. Imura [11], Larkin [12] and Harada et al. [13] also suggested similar ranges, as ideal filling ratios.

Niro and Beretta [3] presented experimental results and an analytical model for boiling regimes in thermosyphons. Unsteady operation occurred when the prototype was filled with medium and large working fluid quantities. Bubble dimensions mainly relied on liquid superheating and vapor mass density. The authors classified the boiling regime based on the bubble nucleation frequency and on the ratio of bubble to device diameter.

The experimental study conducted by Mantelli et al. [14] showed geyser boiling occurrence in thermosyphons developed for bakery oven applications. Results indicated that geyser boiling period decreases with increasing heat flux at the evaporator. A noteworthy physical discussion of how geyser boiling affects the temperature field along the thermosyphon is provided by the authors. The phenomenon has been widely noted in conventional thermosyphons mainly during start-up.

Lin et al. [15] investigated geyser boiling effects in vertical annular thermosyphons. Their experimental results indicated that the geyser boiling phenomenon occurs more frequently with high heat loads, short evaporator lengths and small filling ratios. The amplitude of temperature oscillations decreased with decreasing evaporation length and filling ratios. The geyser boiling period was reduced for low condenser temperatures.

By using a thermosyphon made of glass to allow two-phase flow visualization, Kuncoro et al. [16] revealed that the temperature field within the setup may play an important role on geyser boiling occurrence. When the superheated