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Confinement and vapour production rate influences in closed two-phase reflux thermosyphons Part A: Flow regimes

K. Smith [a], R. Kempers [b,a], A.J. Robinson [a,*]

[a] Department of Mechanical & Manufacturing Engineering, Parsons Building, Trinity College, Dublin, Ireland
[b] Department of Mechanical Engineering, York University, Toronto, Canada

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ABSTRACT

This study investigates the boiling regimes in a small diameter (D = 8 mm) transparent thermosyphon. The influence of confinement on the boiling regimes was studied using a range of fluids. The confinement of the vapour phase leads to boiling regimes that differ from those traditionally described for thermosyphon evaporator boiling physics, widely considered as a combination of pool boiling and film evaporation. The boiling behaviour of small dimension thermosyphons was investigated by designing and constructing a fully transparent thermosyphon, enabling simultaneous thermal and visual analysis. Three working fluids, water, ethanol and HFE-7000, were used to characterise the thermosyphon behaviour with varied characteristic bubble length scales. The observed flow regimes could be characterised in terms of the degree of confinement and rate of vapour production. A flow regime map was developed based on these observations to predict thermosyphon flow in terms of both confinement and the rate of vapour production. It was determined that for low confinement and high rates of vapour production, the boiling regimes resemble those of pool boiling. In contrast, at high levels of confinement and high heat flux, an unsteady regime exists where relatively large bubbles and vapour generation rates result in a pulsatile geyser-type flow regime.

1. Introduction & background

Two-phase reflux thermosyphons are simple and inexpensive devices to construct which provide reliable heat transfer performance. Although they have been used extensively in the past, thermosyphons are now being considered for new and challenging applications including thermal management of electronics, [1], solar applications and HVAC amongst others, as recently reviewed by Jafari et al. [2].

Typically, a thermosyphon consists of an evacuated tube filled with a small amount of liquid and sealed at both ends. Heat is applied in the evaporator section. As the liquid phase absorbs the applied heat it boils and evaporates converting it to latent heat. The generated vapour rises to the condenser section due to the pressure differential. The vapour is cooled in the condenser section, releasing the latent heat and condenses back to the liquid phase. Under the influence of gravity, the condensed liquid flows back from the condenser to the evaporator to complete the cycle.

Thermosyphons are relatively simple heat transfer devices in construction, however the mechanisms of boiling and condensation occurring within can be more complex and there are a number factors which influence their performance. As the thermosyphon relies on gravitational forces to complete the flow cycle, they are generally orientation specific and will not operate against gravity. Thermosyphon operation may become more sensitive to limitations in smaller diameter tubes where the liquid and vapour phases flow counter-currently in the core of the device. The Entrainment Limit is generally encountered at higher heat fluxes as the vapour velocities are increased [3]. When this limit is reached, liquid condensate droplets flowing to the evaporator are entrained and pulled into the upward flowing vapour core. The result is a decrease in the amount of liquid returning to the evaporator and eventual dryout of this section, while the liquid droplets are held in the condenser which becomes flooded. When this limit is reached the thermosyphon is no longer able to transfer heat between the evaporator and condenser. If the evaporator section is not wet by returning fluid the wall temperature significantly increases and the thermosyphon may be permanently damaged. These limitations can be avoided with appropriate liquid fill volumes and monitoring the applied heat flux.

In addition, as heat exchangers become smaller and more compact, the two-phase flow within the thermosyphons can become influenced by confinement effects, which can significantly alter

* Corresponding author.
E-mail address: arobins@tcd.ie (A.J. Robinson).

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Nomenclature

A	area (m^2)
Bo	Bond number
Co	confinement number
D	diameter (m)
FOM	Figure of Merit
Fr	Froude number
G	mass flux (kg/m^2 s)
g	gravitational acceleration (m/s^2)
h_{fg}	latent heat of vaporization (J/kg)
j_v^*	superficial vapour velocity or vapour production rate
k	thermal conductivity (W/mK)
P	pressure (bar)
P_{crit}	critical pressure (bar)
P_r	reduced pressure ($P_r = P/P_{crit}$)
Q	power (W)
q	heat flux (W/m^2)
T	temperature (°C)
ΔT	temperature difference (°C)
t	time (s)
V	voltage (V)
We	Weber number

Greek symbols

λ_c	characteristic bubble length (m)
μ	dynamic viscosity (Ns/m^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

c	condenser
CS	cross-sectional
E	evaporator
i	inner
in	input
l	liquid
$loss$	losses
o	outer
SA	surface area
sat	saturation
SH	superheat
tot	total
v	vapour

the flow and heat transfer. Subsequently, the ability to predict the performance and limitations of small diameter thermosyphons becomes more challenging. For confined thermosyphons, there is less space within channel for the upward vapour flow, leading to a complex interaction of capillary, buoyancy, and inertial forces at the confined liquid-vapour interface. The factors affecting heat transfer in small-scale thermosyphons, therefore, are the thermophysical properties of the working fluid, fill volume, and the dimension of the tube. Operating conditions, such as pressure and heat flux, should also be considered.

While confinement of boiling regimes has been studied in detail for flow boiling conditions, there is limited research in the area of two-phase closed thermosyphons. This investigation sets out to define the flow regimes encountered in small dimension two-phase closed thermosyphons, using flow descriptions consistent with those used in flow boiling.

The definition of *'small-scale'* can vary in the existing literature and is more commonly described in flow boiling channel characterisation. In a review of micro channel flow, Ribatski [4] discussed the existing transitions from micro to macro scale. In a comparison of 9 different studies using water and CO_2 it was evident that conventional scale behaviour is expected in diameters around 6 mm, with reduced pressure conditions ranging from $0.001 < P_r < 0.8$. With changes in the pressure of the system there will be a change in the size of the bubbles due to the change in thermophysical properties and bubble growth dynamics of the fluid with pressure. The rapid increase in vapour specific volume with reducing pressure means bubble growth is enhanced at lower pressures. For this reason, the reduced pressure, $P_r = P/P_{crit}$, for each experiment is important in the context of confinement and thermosyphon behaviour.

Effective bubble size has been studied in fundamental boiling research over a range of experimental conditions [5,6]. The Laplace length, or capillary length, λ_c, represents a balance of liquid surface tension and liquid-vapour buoyancy forces, Eq. (1). This length is used to describe the characteristic bubble size using the thermophysical properties of the fluid at the operating pressure.

$$\lambda_c = \sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}} \tag{1}$$

The Confinement number, Co, is a ratio of the bubble departure size, λ_c, to the channel diameter, D_i,

Eq. (2). This quantifies the level of confinement of growing bubbles for a given channel diameter, expressed as the following equation:

$$Co = \frac{\lambda_c}{D_i} = \frac{1}{D_i}\sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}} \tag{2}$$

Fluid and channel size conditions giving high values of the Confinement number, $Co \sim 1$, indicate a large bubble size relative to channel size, typical in micro-scale flow. Conversely, $Co \ll 1$ represents a situation resembling small bubbles in an infinitely large pool. For smaller diameter thermosyphons, the confinement number indicates the benefits of high vapour pressure fluids, as they should produce smaller bubbles.

For channel flow regimes, Ong and Thome [7] described a transition region between micro and macro scale flow behaviour, referred to as meso-scale, using Co. It was found that this transition regime was present for $0.3 < Co < 0.4$. Conventional unconfined channel flow is expected for $Co < 0.3$.

In relation to thermosyphons, Franco et al. [8], and Jouhara and Robinson [9], used the Laplace length scale to define small dimension thermosyphons as one where $D_i = 2\lambda_c$. The rationale for using this relationship is that the disturbance of the flow when two bubbles orientated in opposing directions grow, they will interact at half the tube diameter [9]. Admittedly, this hypothetical mechanism of confinement is quite simplistic. However, it illustrates that bubble size must be considered in relation to tube size in thermosyphons. As with forced convection two-phase systems, this relative size is important as confinement will affect the flow and heat transfer performance of thermosyphons. The resulting flow regimes will be quite different to the generally assumed nucleate pool boiling – filmwise condensation regimes [10].

The geyser effect describes nucleating bubbles which quickly grow to the size of the thermosyphon tube, trapping some volume of the liquid pool above. It is a result of bubble confinement in two-phase thermosyphons, where bubble generation or coalesced bubble cluster sizes are large relative to the thermosyphon dimension. A Taylor-like bubble is created, and evaporation from the surrounding liquid film causes rapid increase in bubble size. The