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Flow condensation pressure oscillations at different orientations

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ABSTRACT

Investigation of two-phase flow dynamic behavior and instabilities has traditionally centered on phenomena present in boiling flows due to the safety critical nature of boiling in a variety of cooling applications. Analysis of pressure signals in condensing systems reveal the presence of relevant oscillatory phenomena during flow condensation as well, which may impact performance in applications concerned with precise system control. Towards this end, the present study presents results for oscillatory behavior observed in pressure measurements during flow condensation of FC-72 in a smooth circular tube in vertical upflow, vertical downflow, and horizontal flow orientations. Dynamic behavior observed within the test section is determined to be independent of other components within the flow loop, allowing it to be isolated and interpreted as resulting from physical aspects of two-phase flow with condensation. The presence of a peak oscillatory mode (one of significantly larger amplitude than any others present) is seen for 72% of vertical upflow test cases, 61% of vertical downflow, and 54% of horizontal flow. Relative intensities of this peak oscillatory mode are evaluated through calculation of Q Factor for the corresponding frequency response peak. Frequency and amplitude of peak oscillatory modes are also evaluated. Overall, vertical upflow is seen to exhibit the most significant oscillatory behavior, although in its maximum case amplitude is only seen to be 7.9% of time-averaged module inlet pressure, indicating there is little safety risk posed by oscillations under current operating conditions. Flow visualization image sequences for each orientation are also presented and used to draw parallels between physical characteristics of condensate film behavior under different operating conditions and trends in oscillatory behavior detected in pressure signals.

1. Introduction

1.1. Importance of flow condensation dynamic behavior

A key trend across all energy applications in recent years has been that of miniaturization coupled with increased capacity. System modifications following these trends have led to increased performance and smaller size, both advantageous features from product design standpoints. From a heat transfer perspective, however, this leads to a necessity of higher flux thermal management systems to reject heat [1].

To satisfy these increasingly stringent thermal management requirements, engineers have begun turning to schemes relying on phase change heat transfer. These systems typically rely on boiling to acquire heat from the device being cooled and condensation to reject heat from the working fluid and return it to a pre-boiling (subcooled or saturated liquid) state. Many prior studies have investigated boiling through a variety of mechanisms, including capillary-driven devices [2–4], pool boiling thermosyphons [5–7], falling film [8,9], channel flow boiling [10,11], micro-channel boiling [12–16], jet impingement [17–20], and spray [21–27], as well as hybrid configurations [28–31] involving two or more of these schemes. Similarly, condensation has been investigated in several configurations, including falling film [32–34], flow through single circular mini-channels [35–41], and flow through parallel micro-channel arrays [42–44]. A common deficiency found across most studies on condensation, however, is lack of emphasis on transient flow behavior and analysis of potential instability modes brought on by the condensation process.

Transient flow behavior is particularly important for aerospace applications (for which phase change thermal management systems are attractive due to their ability to offer superior heat

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Nomenclature

A	amplitude
c_p	specific heat at constant pressure
D	diameter
D_h	hydraulic diameter
f	frequency
Fr	Froude number
G	mass velocity
g	Earth's gravitational constant
H	digital filter transfer function
h_{fg}	latent heat of vaporization
$\dot{m}$	mass flow rate
P	pressure
P'	mean-subtracted pressure fluctuations
Pwr	power input
Q	Q Factor, measure of oscillatory mode intensity
Re	Reynolds number
T	temperature
t	time
We	Weber number
x_e	thermodynamic equilibrium quality
z	variable indicating digital domain; stream-wise position

Greek symbol

μ	dynamic viscosity
υ	specific volume
ρ	density
σ	surface tension

Subscripts

A	amplitude
ave	average
BH	bulk heater
f	saturated liquid
FC	FC-72, condensate
FWHM	full width half maximum
g	saturated vapor
H2O	water, cooling fluid
i	inner (refers to diameter)
in	inlet to condensation length (refers to condensate)
max	max value over range evaluated
mean	mean value over range evaluated
o	outer (refers to diameter)
out	outlet to condensation length (refers to condensate)
P	pressure

Acronyms

CM-FV	condensation module for flow visualization
CM-HT	condensation module for heat transfer measurements
DWO	density wave oscillation
FBCE	Flow Boiling and Condensation Experiment
PCI	parallel channel instability
PDO	pressure drop oscillation

transfer performance while allowing reductions in system weight and volume) due to the likelihood of encountering many different operating environments. Whether utilized in aircraft performing a variety of high-acceleration maneuvers at a range of altitudes, or in spacecraft intended to launch, travel through space, and operate in a distant planetary environment, thermal management systems for these applications will be required to operate across a wide range of thermal conditions and body force fields. Operation across a variety of body force conditions is particularly important for thermal management systems capitalizing on phase change, as the orders of magnitude difference in phase densities can cause these systems to respond strongly to changes in body force [45].

Due to the difficulty of performing system tests under microgravity, partial-gravity, and hyper-gravity conditions associated with intended use environments, precise knowledge of how changes in operating conditions affect system performance is imperative to design of phase-change thermal management systems for these applications. In particular, the potential for changes in operating environment to cause instabilities to manifest within the system and adversely affect performance mean a detailed understanding of two-phase flow dynamics and instabilities and their effects on thermal and hydrodynamic characteristics is critical.

1.2. Two-phase flow instabilities

Two-phase flow instabilities are commonly described as resulting from interactions between the many thermal and hydraulic phenomenon present in two-phase flows. A significant body of work investigating these phenomena exists, with key instability modes including density wave oscillations (DWOs) [46–50], pressure drop oscillations (PDOs) [51–54], and parallel channel instability (PCI) [55–58]. Much of the work performed is summarized in review articles, including the seminal work of Boure et al. [59] and more recent reviews of Tadrist [60], Kakac and Bon [61], and Ruspini et al. [62].

The vast majority of work on two-phase flow transient behavior and instabilities concerns only boiling, however, due to the perception that condensation is a more stable process. While this may be true by comparison with boiling, pressure and mass flow rate fluctuations are also commonly seen during flow condensation, meaning it may be that instabilities are present which have not been as thoroughly investigated as those for boiling.

One of the earliest studies including transient flow condensation results was performed by Westendorf and Brown [63] in the mid 1960's, who saw that, for condensation occurring between concurrent flow of saturated vapor and subcooled liquid, high and low frequency oscillatory modes do occur and could be related to subcooling of the liquid phase.

Around the same time, Goodykoontz and Dorsch [64] investigated flow condensation in a more traditional tube-in-tube counterflow configuration. They observed pressure oscillations with frequencies in the 1–10 Hz range, although only for moderate condensation lengths of 1.7–3.7 feet (longer and shorter test sections did not exhibit any fluctuations). Amplitude of oscillation remained below 1 psi in all cases, indicating the oscillations posed no appreciable threat to safe system operation.

Also around this period, Soliman and Berenson [65] performed a detailed investigation of flow condensation in a multi-tube condenser in multiple orientations (vertical upflow, vertical downflow, and horizontal flow) using Freon-113 as working fluid. They observed two distinct oscillatory modes for pressure, one for horizontal and vertical downflow orientations and another for vertical upflow orientation, and correlated amplitude of oscillation for each using experimental data. Also of interest is their observation that amplitude of oscillation is always less than 5% of inlet pressure for vertical downflow and horizontal orientations, and less than 10% of inlet pressure for vertical upflow. This study in particular