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Flow boiling in tube in microgravity

E. TREJO PEIMBERT\textsuperscript{a}, M. NARCY\textsuperscript{a}, C. COLIN\textsuperscript{a}

\textsuperscript{a} IMFT, Toulouse University, CNRS, INP, UPS, 2 Allée Camille Soula 31400 Toulouse France
eetrejope@imft.fr, colin@imft.fr

Abstract:

Liquid-vapor phase-change processes have important roles in an innumerable amount of technological applications. An experimental device was built at IMFT for studying different flow regimes in a circular tube of 6 mm diameter, heated and transparent. Experiments have been conducted in the laboratory and in microgravity during parabolic flight campaigns. These experiments highlight the different behavior of the flow and heat transfer in normal and microgravity, especially for low liquid velocities. The objective of this project is to complement the existing experiments and develop models to predict the behavior of two-phase flow in microgravity. During the experiments, pressure drops, void fraction and wall temperatures are measured. A high-speed camera is also used to visualize the flow. The data were collected in normal gravity and during a series of parabolic trajectories flown in an airplane. All data are analyzed to obtain flow patterns, heat transfer coefficient, wall friction data and liquid film thickness. Along with these experiments, theoretical models were studied to predict the pressure drops and heat exchange at the wall.

Mots clefs: two-phase flows, microgravity, annular flow, bubbly flow, heat transfer, void fraction
1 Introduction

Liquid-vapor flows are present in many industrial and space applications like: propellant management and re-ignition of cryogenic engines of launchers and cooling systems of electronic components for satellites. In flow boiling, the usual variables of interest for the design of industrial processes are the heat transfer rates and the pressure losses.

2 Experimental set-up

The experimental set-up BRASIL (Boiling Regimes in Annular and Slug flow In Low gravity) is installed in a single rack system with two frameworks that are fixed by the common large base plate (Narcy et al. [1]). One of the frameworks contains the hydraulic loop, which is mainly composed of a gear pump, preheaters, a test section and condensers. In the loop there is also included a pressure management system and a Coriolis flow meter for the liquid mass flux measurement. The structure is sealed by a containment made up of Lexan walls, aluminum plate walls and aluminum base plate to prevent any leakage in the aircraft during the parabolic flights.

All the data acquisition and power supply systems are fixed on the second framework. Since there is no liquid on this side of the experiment this part is not sealed and contains the three control and acquisition computers, the camera and the power supply. Here we have free access to all the measurement devices. The design of most of the set up is determined by the requirements of the parabolic flight campaigns.

2.1 Test section

The core of BRASIL is the test section. It is composed of a transparent sapphire tube with two adiabatic parts located at both ends. Thermoplastic elements made of polyether ether ketone (PEEK) serve as an interconnection for these three sections and give space for the elements of the measuring system.

The two adiabatic parts are made of a stainless steel tube with an inner diameter of 6mm whose lengths are of about 15 and 22cm, respectively. To approach the adiabatic system, the tubes are covered with thermal insulation. The length of the first tube is adapted to its purpose of flow establishment before the sapphire tube. The second adiabatic section is long enough to enable the measurement of pressure drop along it.

The section between the two stainless tubes is a 20cm long sapphire tube with an inner diameter of 6mm and a thickness of 1mm. The outer surface is coated with ITO (Indium Tin Oxide), an electrical conductive coating that enables a uniform heating of the outer surface.

This coating does not affect the transparency of the sapphire tube; therefore the flow can be filmed during tests with a high-speed video camera, which allows the flow pattern identification.

2.2 Measurement techniques

The two-phase flow loop is equipped with several temperature and pressure sensors for the measurements of the flow parameters and for safety control in parabolic flights. Pressure and temperature are measured at different locations. Differential pressure transducers are used to measure the pressure drop and the wall and interfacial shear stresses. Capacitance probes are used for the measurements of the mean void fraction and the liquid film thickness in annular flow. The power delivered to the ITO coating is measured simultaneously with the temperatures of the outer surface of
the tube and the fluid temperature. These data are used to determine the heat transfer coefficient. The acquisition system consists of a 72 channels National Instrument deck, two laptops with LabVIEW interfaces and a computer for the acquisition of camera images using Cameware software.

2.2 Void Fraction Sensors

A specific void fraction probe has been developed for the purpose of the experiment. It is mainly made of two measurement electrodes and four guard electrodes, which are placed in a face-to-face configuration using plain PEEK-made mountings, the electrodes compartments are filled with PEEK part that maintain the electrodes pressed against the wall near the tube. The actual geometrical shape of the measurement electrodes is characterized by an axial length of 14 mm and a width of 14 mm. The dimensions of the guard electrodes are 10 mm x 14 mm, and the separation between the parallel electrodes amounts to 16 mm. All the electrodes are made of a thin copper sheet that is very conductive. A copper shield also covers the outer surface of the PEEK mounting to prevent noise. The electronics circuit is embedded into a metallic case and fixed as close as possible to the measuring electrodes to avoid stray capacitance due to important wire lengths. Calibration of the probe is performed by using the software COMSOL Multiphysics and by using Teflon rods of known diameter to mimic the annular flow configuration.

3 Results

Experimental results obtained after data processing are the mean void fraction or liquid film thickness in annular flow, the wall and interfacial shear stresses, the wall heat transfer. These experimental results obtained in 1-g vertical upward flow and in microgravity conditions (0-g) are compared to correlations and models of the literature. High-speed video pictures of the flow are taken through the transparent test section. They allow identifying the flow pattern (Figure 1).

![Figure 1: Flow pattern evolution from bubbly to slug flow along the tube for G=100 kg/m²/s and a heat flux of 1 W/cm² in 1-g.](image)

3.1 Wall Friction

In microgravity the wall friction is directly related to the measured pressure gradient along the adiabatic test section downstream the sapphire tube \( \frac{dP}{dz} \): \( \tau_W = -\frac{(D/4)}{dP/dz} \). In normal gravity the hydrostatic pressure gradient is estimated from the void fraction measurement and has to be removed from the total pressure drop to calculate the wall friction. The frictional pressure gradient in two-phase flow is calculated by multiplying the frictional pressure gradient obtained in single-phase flow by a two-phase flow multiplier \( \frac{F_L}{2} \) (Lockhart and Martinelli [2]). In Figure 2, the value of \( \frac{F_L}{2} \) is plotted versus Martinelli parameter \( X \) for 2 mass fluxes \( G=200 \, \text{kg/m}^2/\text{s} \) and \( G=50 \, \text{kg/m}^2/\text{s} \) in normal and microgravity conditions and compared to the theoretical value [2]. The correlation of Lockhart and Martinelli is plotted in the case where either liquid and vapor phases are turbulent (tt) or only the vapor phase is turbulent (lt). For \( G=200 \, \text{kg/m}^2/\text{s} \), the two-phase multiplier is the same in 1-g and 0-g and is in good agreement with Lockhart and Martinelli correlation. For \( G=50 \, \text{kg/m}^2/\text{s} \), the two-phase multiplier and thus the wall friction is much lower in 0-g than in 1-g. The flow structure is affected by
the gravity level at this low mass flux. Lockhart and Martinelli correlation slightly underpredicts $F_L$ in 1-g and over predicts in 0-g.

![Experimental two-phase multiplier according to Martinelli parameter for 1-g (closed symbols) and 0-g (open symbols) conditions- comparisons with two correlations proposed by Lockhart and Martinelli [2]](image)

**Figure 2**: Experimental two-phase multiplier according to Martinelli parameter for 1-g (closed symbols) and 0-g (open symbols) conditions- comparisons with two correlations proposed by Lockhart and Martinelli [2]

### 3.2 Heat Transfer

There are several models and correlations to predict heat transfer, some are based on the superposition of the heat transfer by nucleate boiling and by forced convection [3, 4], others consider the heat transfer through an evaporating turbulent liquid film in annular flow [5]. These models correspond to two dominant heat transfer modes: nucleate boiling or convective heat transfer. In the case of nucleate boiling dominant heat transfer, the heat transfer coefficient (HTC) is very sensitive to the wall heat flux, whereas it is mainly sensitive to mass flux and quality in the convective heat transfer regime. The heat transfer coefficient is plotted versus quality $x$ for a heat flux $q=2W/cm^2$ and for $G=200$ kg/m$^2$/s and $G=50$ kg/m$^2$/s in Figure 3. At low qualities the HTC is lower in microgravity than in normal gravity, which is in agreement with the results obtained by Ohta and Baba [6]. For $G=200$ kg/m$^2$/s and quality larger than 0.15, the HTC is well predicted by the model of Cioncolini and Thome [5]. The dominant heat transfer mode is the convective heat transfer for both normal and microgravity conditions. This corresponds to annular flow regimes without bubble nucleation at the wall. For $G=50$ kg/m$^2$/s and for $G=200$ kg/m$^2$/s at low quality, the HTC is almost independent of quality. Nucleate boiling plays an important role in bubbly and slug flow regimes. Kim and Mudawar correlation [4]seems to over predict the HTC is this regime, probably because the surface of the sapphire tube is
very smooth and the density of nucleation sites very low (Figure 1) compared to a metallic tube.

![Heat transfer coefficient versus quality for 2 mass fluxes G=50 and 200 kg/m²/s in normal gravity (closed symbols) and in microgravity (open symbols).](image)

**Figure 3:** Heat transfer coefficient versus quality for 2 mass fluxes G=50 and 200 kg/m²/s in normal gravity (closed symbols) and in microgravity (open symbols).

**References**


