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An experimental study of flow boiling frictional pressure drop of R134a in a horizontal 1.002 mm tube under hypergravity

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ABSTRACT

An experimental study with a horizontal 1.002 mm inner diameter mini-tube is conducted to investigate the two-phase frictional pressure drop of R134a flow boiling under hypergravity. Totally 1718 data points under the gravity from 1 to 3.16*g* were obtained, with mass fluxes of 400–1075 kg/m^2 s, vapor qualities of 0.05–0.85, heat fluxes of 24.0 and 31.5 kW/m^2, and saturation pressures of 0.6 and 0.7 MPa. The hypergravity conditions were achieved using a centrifugal acceleration machine. The results show that with increasing gravity the flow boiling frictional pressure drop increases at high vapor quality but decreases at low vapor quality, and the trend reversals take place roughly in the range of $0.07 < x < 0.45$, depending on saturation pressure and mass flux. The comparison between the experimental data and the predictions of 28 correlations of two-phase frictional pressure drop is made, and the results show that the best correlation has a mean absolute deviation of 12.8% for the entire data, 10.6% for normal gravity, and 13.7% for hypergravity.

1. Introduction

Due to the increasing demand for cooling capacity and small volume and lightweight cooling devices, flow boiling heat transfer in mini/micro-channels attracts more and more attention in modern high-performance flight vehicles. Because some flight vehicles often perform hypergravity maneuvers, it is necessary to investigate the flow boiling characteristics in mini/micro-channels under hypergravity. Previous investigations of the two-phase frictional pressure drop under hypergravity are described below.

Xu et al. [1] used a centrifugal acceleration machine to generate hypergravity conditions. They measured the flow boiling frictional pressure drop of R134a in a horizontal tube with inner diameter (ID) of 2.168 mm and length of 0.2 m under different gravity levels from normal gravity (1*g*) to 3.16*g*. The experimental conditions were mass flux $G = 725$ and 910 kg/m^2 s, heat flux $q = 19.0$ and 28.5 kW/m^2, saturation pressure $p = 0.71$ and 0.82 MPa, and vapor quality $x = 0$–0.65. They found that the frictional pressure drop increases with increasing gravity at high vapor quality but decreases at low vapor quality. However, the difference caused by gravity variation is not significant. The comparative results of the experimental data with the best existing correlations developed for normal gravity showed that the best correlation has a mean absolute deviation (MAD) of 14.5% for normal gravity and 15.4% for hypergravity.

Ohta et al. [2] carried out the experiments aboard an MU-300 aircraft, which could create 2*g* hypergravity lasting 15 s during a parabolic flight. They measured the two-phase frictional pressure drop of air-water in a vertical upward 8 mm ID and 0.723 m long acrylic tube. The experiments covered the conditions of $p = 0.093$ MPa, $t = 20$ °C, superficial liquid velocity $V_{sl} = 0.0497$–0.199 m/s, and superficial gas velocity $V_{sg} = 1.99$–15.9 m/s. In most experimental conditions, annular flow regime was achieved independently of gravity level. It was found that the frictional pressure drop increased with increasing gravity. At higher V_{sl} or V_{sg}, the effect of gravity became weak. At low V_{sl}, the frictional pressure drop for normal gravity and hypergravity was not sensitive to V_{sg}. Ohta [3] showed the similar experiments and results.

Choi et al. [4] also presented experiments aboard an MU-300 aircraft with a hypergravity of 2*g*. The experimental set-up was similar to that presented in Ohta et al. [2] except that the test section was a 10 mm ID and 0.6 m long horizontal tube. The experiments covered the ranges of $V_{sg} = 0.03$–21 m/s and $V_{sl} = 0.1$–2.6 m/s. They found that the frictional pressure drop was influenced by flow patterns. In general, the differences of the frictional pressure drop among different gravity levels were within ± 11%, except for some low V_{sl} regions. The maximum difference of the frictional pressure drop between hypergravity and normal gravity was about 45%.

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Nomenclature

a_a	centrifugal acceleration vector parallel to the axis of the test section (m/s^2)
a_h	acceleration of gravity (m/s^2)
a_p	centrifugal acceleration vector perpendicular to the axis of the test section (m/s^2)
D	inner diameter (m)
Fr	Froude number
G	mass flux (kg/m^2 s)
g	normal gravity (1g = 0.981 m/s^2)
L_a	arm length (m)
L_c	distance to center of turntable (m)
p	pressure (Pa)
q	heat flux (W/m^2)
Re	Reynolds number
V_{sg}	superficial gas velocity (m/s)
V_{sl}	superficial liquid velocity (m/s)
x	vapor quality

Greek symbols

Δp	pressure drop (Pa)
ε	void fraction
ε_h	homogenous void fraction
θ	deflection angle (deg)
ρ	density (kg/m^3)
ω	rotational speed (RPS)

Subscripts

f	frictional
g	gas
in	inlet
l	liquid
lo	liquid only
out	outlet
sat	saturation

MacGillivray [5] conducted the experiments in a vertical upward 9.525 mm ID and 0.88 m long stainless steel tube on board the Novespace Zero-G Airbus microgravity simulator with a hypergravity of 1.8g. The working fluids were air-water and helium-water. The experimental conditions covered liquid mass fluxes of 76–314 kg/m^2 s, air mass fluxes of 14.3–47.7 kg/m^2 s, and helium mass fluxes of 5.0–11.6 kg/m^2 s. They found that the frictional pressure drop under hypergravity was about 20% higher for both air-water and helium-water two-phase fluids.

Brutin et al. [6] carried out experiments under 1.8g hypergravity produced by aircraft parabolic flights. The test sections were two identical vertical rectangular mini-channels with a hydraulic diameter of 0.84 mm, and the working fluid was HFE-7100. The experimental conditions were q = 15–55 kW/m^2 and G = 30–248 kg/m^2 s. It was found that the frictional pressure drop under hypergravity was about 30% higher than that under normal gravity for laminar flow. They deemed that these were related to the void fraction and buoyancy effects.

The extensive literature survey shows that the experimental studies of frictional pressure drop under hypergravity are scarce, among which most were conducted using parabolic flights with gravity not exceeding 2g, the available data were very limited with narrow parameter ranges, and the results regarding the mechanism of the two-phase frictional pressure drop under hypergravity are inconsistent. The present paper presents an experimental study of flow boiling frictional pressure drop in a 1.002 mm horizontal tube under hypergravity.

2. Experimental setup and procedure

2.1. Experimental setup

The experimental setup for investigating the flow boiling frictional pressure drop under hypergravity is composed of a centrifugal acceleration machine, a refrigerant loop, and a measuring system.

The centrifugal acceleration machine and the measuring system are the same as those presented in Xu et al. [1] and Fang et al. [7]. The centrifugal acceleration machine consists of a turntable, two electric brushes and a motor, as shown in Fig. 1. The hypergravity was simulated with the centrifugal force, and hypergravity levels were achieved through changing the rotational speed of the turntable.

The refrigerant loop and the measuring system were installed on the turntable. The refrigerant loop is composed of a receiver, a sub-cooler, a micro gear pump, a micro flow meter, a pre-heater, a test section, a condenser, and a pressure-regulating device with a piston and a screw motor, as shown in Fig. 2.

The working fluid used is refrigerant R134a. The R134a liquid pumped by the micro gear pump from the receiver passes through the sub-cooler during which it is subcooled. Coming out of the micro gear pump, it flows through the micro flow meter and the pre-heater, and then enters the test section. The pre-heater was made of the same copper tube to assure the same ID as the test section for flow development. The R134a liquid in the pre-heater is heated to two-phase flow, and then enters the test section to be heated to higher vapor quality. Passing through the test section, the two-phase R134a enters the condenser, in which it is condensed and subcooled, and then returns to the receiver, completing a cycle. Each of the pre-heater and the test section was wound with a heating wire, which was connected to a DC power supplies. The system pressure was adjusted accurately to the required value by using the piston driven by the screw. The mass flow rate of the working fluid was regulated by the frequency inverter of the micro gear pump. To avoid interference with the flow patterns, the interfaces of tube connections used in the refrigerant loop were polished and smooth. The refrigerant loop was well insulated.

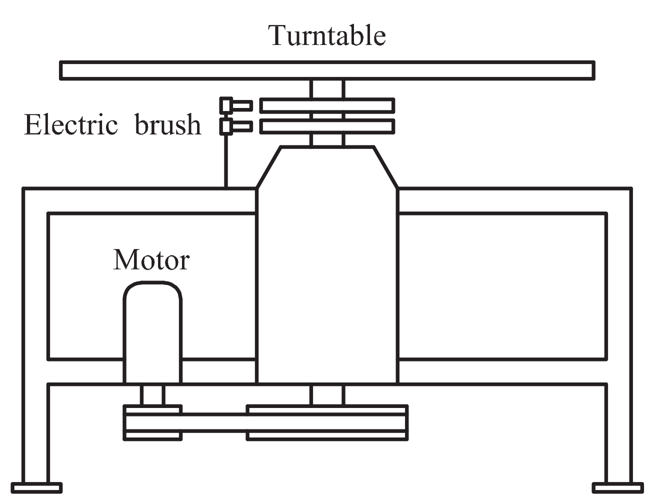

Fig. 1. Schematic of the centrifugal acceleration machine.