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High gravity influence on boiling heat transfer in helical coils

Liyao Xie [a], Yongqi Xie [a,*], Hongwei Wu [b], Jianzu Yu [a]

[a] *School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China*
[b] *School of Engineering, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*

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ABSTRACT

Experiments were conducted to investigate the flow boiling heat transfer in helical coils under high gravity operating conditions. The centrifuge used for this study has a two meter-long arm allowing providing the high gravity up to 11 g. The heat flux can be up to 15100 W m^{-2} and the mass velocity ranging from 40 to 200 kg m^{-2} s^{-1}, and the outlet quality ranging from 0% to 50%. Flow visualization and wall superheat in two high gravity direction configurations were analyzed. Experimental results showed that the high gravity acceleration had an adverse superheat influence on the flow boiling heat transfer, particularly at the low mass and the low vapor quality. The heat transfer in radial acceleration configuration was found to be superior to that in axial configuration. The helical coil curvature in itself could be utilized as a high gravity resistance.

1. Introduction

High-power compacted electronic equipment employed in aircraft enhances its overall performance. As massive bulk of the electronic devices has been employed, the heat fluxes will increase and therefore, it is a strong need to remove the heat dissipation from the avionics. Among cooling techniques for electronic devices, the use of two-phase heat transfer approach is attracting increasingly wide attention. It is known that military aircrafts often perform maneuvers with acceleration profiles in high elevated acceleration, while the civilian planes are also subjected to high gravity at turbulence for short durations. Rockets and other spacecraft will experience a high gravity stage during launching. Generally, high gravity conditions would make the flow and heat transfer more complicated and make the experiment more difficult to conduct. For this reason, to investigate the effects of the elevated high gravities on the boiling flow and heat transfer characteristics in a systematic manner is becoming one of the most challenging issues and an important subject in regard to the cooling system performance. Overall, two techniques are implemented to simulate the high gravity overload which are conducting experiments in sounding rocket and constantly rotating tray or arm. It is recognized that, among the above mentioned two techniques, the rotating platform may meet the most demanding requirements since it can provide high magnitude of acceleration and long-time stable duration, although the rotational acceleration is not exactly equivalent to the acceleration of the high gravity due to the varying acceleration direction.

Kim et al. [1] were perhaps the first ones to study the boiling flow in high gravity when they took images of the subcooled bubbles under micro and high gravity conditions. Recently, Raj and Kim [2] further investigated the subcooled pool boiling in variable gravities in a parabolic flight and investigated the effects of the gravity and wall superheat on the heat flux. In their study, the maximum magnitude of high gravity is 1.8 g which was quite small. Barry and Crowley [3] performed a numerical investigation of the transient gas–liquid two-phase systems under both the reduced and time-varying gravity conditions. It was found that good agreement between the predicted results and experimental data was achieved. Zhukov and Lutcet [4] experimentally studied the heat transfer towards liquid nitrogen at the centrifugal platform with overloads up to 5000 g. Their results showed that the heat transfer intensity under the regime of the developed nucleated boiling was proportional to the $-1/6$ power of acceleration. Yao et al. [5] investigated the flow and heat transfer characteristics of steam water flow in a horizontal pipe under high gravity using a rotating platform. It was found that the dynamic load significantly influenced the characteristics of two-phase flow. Kim et al. [6] performed a combined experimental and numerical study of the heat transfer in the rotating ribbed ducts. Their results indicated that the effects of the duct turning curvature and rotation on the heat transfer became less significant for the higher aspect ratio. Some research efforts were also devoted to the loop heat pipe (LHP) since the evaporation and condensation flows in LHP were susceptible to both the micro and high gravity in space [7–9]. Fleming et al. [7]

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[*] Corresponding author. Tel.: +86 10 82338081.
E-mail address: xyq@buaa.edu.cn (Y. Xie).

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Nomenclature

A	coils inner surface area [mm^2]
a	acceleration [m s^{-2}]
a_c	acceleration induced by curvature [m s^{-2}]
c_p	specific heat [J kg^{-1} K^{-1}]
D_{coil}	coil diameter [mm]
De	Dean number
d_i	coil inner diameter [mm]
d_o	coil outer diameter [mm]
g	gravitational acceleration [ms^{-2}]
G	mass velocity [kg m^{-2} s]
h	heat transfer coefficient [W m^{-2} K]
I	DC current [A]
i	vaporization latent heat [J kg^{-1}]
L	coils length [m]
$\dot{m}$	mass flow rate [kg s^{-1}]
N	circling laps
Nu	Nusselt number
p	pressure [kPa]
P	pitch [mm]
Pr	Prandtl number
q	heat flux delivered to the fluid [W m^{-2}]
Q	heating power on coils [W]
Q_{eff}	effective heating power delivered to the fluid [W]
Re	Reynolds number
T	temperature [°C]
t_d	acceleration duration time [min]
t_s	startup time [min]
u	velocity [m s^{-1}]
V	DC voltage [V]
x	vapor quality

Greek letters

Δp	pressure drop [kPa]
λ	thermal conductivity [W m^{-1} K^{-1}]
μ	viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]

Subscripts

amb	ambient
avg	average
g	high gravity
in	inlet
out	outlet
sat	saturated
w	coils wall

examined the behavior of a titanium–water LHP under both the standard and elevated 10 g acceleration fields from a rotating table. The evaporative heat transfer coefficient and the thermal resistance were found to be insignificantly dependent on the acceleration, whereas the wall superheat was found to increase slightly in high gravity. In addition, researches on the heat transfer in high gravity are still not fully understood due to different test facilities and experimental conditions used. For this reason, it was difficult to give a uniform evaluation or correlation for the heat transfer in high gravity.

Over the past two decades, curved pipes including the helical coils evaporators have been widely employed in energy and cooling systems such as air conditioning, heat exchangers, and steam generators. A fundamental investigation into water flow in curved ducts can be traced back to Dean [10]. A dimensionless Dean number was proposed to measure the intensity of the secondary flow induced by the curvature. In a recent study, Guo et al. [11] and Chen et al. [12] experimentally investigated the two-phase flow in the helical coils and new correlations were obtained. Several investigations on the helical coils primarily concentrated on the numerical simulation and visualization of the boiling heat transfer [13–15], whereas it is still lack of available experimental data concerning the heat transfer characteristics in the helical coils especially in high gravity. Most recently, Xie et al. [16] carried out experimental studies on the effect of the rotational acceleration on the flow and heat transfer in the parallel straight and swirl microchannels. It was concluded that the swirl microchannels had a larger resistance against centrifugal acceleration compared with the straight ones. To the best of the authors' knowledge, however, the boiling heat transfer characteristics in the helical coils under high gravity have been far from complete and there is still much room to be enhanced in this area.

The present research aims to investigate the effects of the high gravity on the boiling flow and heat transfer in the helical coils in a systematic manner. For the purpose of comparison, two directional acceleration configurations (axial and radial), different magnitudes and flow visualization are applied in the present study.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

A new experimental test rig, High Gravity Helical Coils Heat Transfer Test Rig (HGHCHT), was constructed at Reliability and Environmental Engineering Laboratory at Beihang University, Beijing, China. The rig was designed to be operated at both the terrestrial gravity and high gravity. The system mainly consisted of a centrifuge in a circular pit, liquid circulation system, test section, control and data acquisition system. Fig. 1 showed the schematic diagram of the experimental apparatus and Fig. 2 showed a photo of the centrifuge and the rotating system including the test section. A thermostatic water tank kept the working fluid temperature constant. Fluid flows were maintained by a gear pump via a variable-frequency drive under both terrestrial and high gravity conditions. A Coriolis force flow meter was chosen to measure the mass flow rate with an accuracy of ±0.5%. After the working fluid flowed through the Coriolis force mass flow meter, it entered a pre-heater which was used to heat the fluid to the required temperature at the test section inlet. The test section coils were used as the electrical resistance and connected across two cooper electrodes, which were connected to a DC power supply, to deliver the heating power to the flowing fluid. After the working fluid exited the helical coils, it entered a condenser where it was cooled to a low temperature before recycling back to the thermostatic tank. All the signals measured by the temperature and pressure transducers were achieved by utilizing digital interface and recorded by a remote computer. All the connecting tubes, signal wires and electrifying wires used for heating went through the centrifuge axis to the test section. As the whole system was rotating during the experiment, the liquid collecting rings and the electric slip rings in the axis were designed to keep the flow and electric current working properly and prevent the leakage. The centrifuge driven by an electric motor provided up to 15 g rotational acceleration at the end of the rotating arm. The rotational speed of the centrifuge could be well controlled by a control terminal with an accuracy of ±5% of the indicated speed.