International Communications in Heat and Mass Transfer 96 (2018) 69–79

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Experimental investigation of in-tube condensation in microgravity

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ARTICLE INFO

Keywords:
Convective condensation
Microgravity
Heat transfer coefficient
Flow pattern visualization
HFE-7000

ABSTRACT

This work is aimed at studying the effect of gravity when convective condensation occurs inside a small diameter channel. An experimental apparatus has been specifically designed to perform microgravity experiments during the 62nd ESA Parabolic Flight Campaign. Convective condensation heat transfer tests have been carried out at mass velocity between 70 kg $m^{-2} s^{-1}$ and 170 kg $m^{-2} s^{-1}$ using HydroFluoroEther HFE-7000 (1-methoxyheptafluoropropane) as the working fluid in a circular cross section channel with an internal diameter equal to 3.4 mm. The data of heat transfer coefficient and the flow pattern visualizations show that, when gravity acts perpendicular to the channel flow, it has a beneficial effect on the heat transfer coefficient by acting on the liquid distribution along the channel perimeter. In microgravity conditions this mechanism leads to a penalization which is proportional to the mass velocity.

1. Introduction

Condensation is the change of the physical state of aggregation of matter from a vapor phase into a liquid phase. The condensation involves a heat transfer process in which the heat is released from the condensing fluid to a cold element. The condensation process is encountered in many engineering fields (e.g. energy conversion, ORC systems, chemical, pharmaceutical and food industries) and also in space applications. In a reduced gravity environment, the presence of a condensation process can be found in life support systems, thermal management systems for satellites, energy production and power management systems for long time missions or manned space platforms, waste water treatment for long duration space exploration missions. Considering that future space missions and human space explorations are expected to be longer, more challenging and complex, two-phase thermal management systems should be more reliable and able to meet the demand for improved efficiency, compactness, and higher thermal loads. In order to increase the performance of condensers and to develop reliable tools for heat exchanger design, both in space and ground environments, a proper understanding of the condensation mechanism in these conditions is necessary. Microgravity experiments allow to better understand the two-phase heat transfer mechanism; in the case of condensation inside channels, they allow to study the influence of gravity level, shear stress and surface tension on two-phase flow pattern and heat transfer coefficient.

Although the experimental study of in tube convective condensation in microgravity conditions is only at its beginnings, on ground the study of condensation inside channels and namely small channels (e.g. diameter below 3 mm) has received in the recent years an increasing attention (Del Col et al., [1, 2]) and more and more research laboratories have started to deal with it. From some of these works (Del Col et al., [3]; Liu et al., [4]) it is clear that, at low mass velocity, results obtained with conventional channels (diameter around 10 mm) cannot be extended to small diameter channels. Such operating conditions (small diameters and low mass velocities) are of great interest for many applications but unfortunately are poorly investigated, also because it is a real challenge to perform accurate measurements of heat transfer coefficient when the heat flow rate is in the order of few watts. New data at low mass flux were recently published by Toninelli et al. [5]. They stressed the importance of the three forces affecting the liquid film distribution: shear, gravity and surface tension. An attempt to account for the relative influence of these forces was recently made by Garimella et al. [6]. These authors developed a model for the prediction of the heat transfer coefficient dividing the condensing flow in two zones: shear/gravity dominated and shear/surface tension dominated. Marchuk et al. [7] presented a numerical study of laminar condensation inside a circular smooth tube that includes surface tension, gravity, and shear stresses at the vapor-liquid interface. The numerical analysis showed that, for a horizontal channel, the average heat transfer coefficient increases when increasing the gravity level. In normal gravity

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https://doi.org/10.1016/j.icheatmasstransfer.2018.05.013

Nomenclature

A	Area[m^2]
c	Specific heat[$J\,kg^{-1}\,K^{-1}$]
d	Diameter[m]
dp/dz	Pressure gradient[$Pa\,m^{-1}$]
Eo	Eötvös number–
f	Friction factor–
G	Mass velocity[$kg\,m^{-2}\,s^{-1}$]
g	Gravity acceleration[$m\,s^{-2}$]
g_s	Standard gravity acceleration = $9.8066\,m\,s^{-2}$–
h	Specific enthalpy[$J\,kg^{-1}$]
H	Enthalpy per unit volume[$J\,m^{-3}$]
$\dot{m}$	Mass flow rate[$kg\,s^{-1}$]
P	Wetted perimeter[m]
Ra	Arithmetic mean deviation of the assessed profile according to ISO 4287:1997 [17][μm]
Re	Reynolds number
T	Temperature[°C]
t	Time[s]
x	Vapor quality–
Y, Y^*	Dimensionless inclination parameter–
z	Axial position[m]

Greek symbols

α	heat transfer coefficient[$W\,m^{-2}\,K^{-1}$]
β	inclination angle[°]
ε	void fraction–
$\Delta\rho$	density difference[$kg\,m^{-3}$]
ρ	density[$kg\,m^{-3}$]

Subscript

c	coolant
cond	condensation
ext	external
f	friction
G	vapor
h	hydraulic
HFE	HFE-7000
in	internal
L	liquid
out	outside
sat	saturation
w	wall

conditions, Lips and Meyer [8] presented an experimental research on convective condensation of R134a at 40 °C saturation temperature in a smooth tube (8.38 mm inner diameter) for a wide range of inclination angles, from vertical downward to vertical upward, and for mass velocities spanning from 200 $kg\,m^{-2}\,s^{-1}$ to 600 $kg\,m^{-2}\,s^{-1}$. They highlighted that, at high mass velocities, the shear stress is the dominant force and there is no effect of inclination on the heat transfer but, at low mass flux and low vapor quality, the flow pattern is strongly dependent on the inclination angle. In a recent paper, Del Col et al. [9] measured the heat transfer coefficient during condensation of R134a in a square minichannel with 1.23 mm internal hydraulic diameter with different inclinations, both upflow and downflow. They found that, when varying the inclination angle, at high mass flux, the heat transfer coefficients display a trend that one would expect for condensation inside conventional tubes. Instead, for low mass fluxes ($G < 200\,kg\,m^{-2}\,s^{-1}$) the vapor shear stress reduces its effect whereas gravity force and surface tension become important. This implies that the gravity force has a fundamental role in the distribution of the liquid film around the channel wall. Using data from these studies, a gravity dependent region, where gravity has a relevant effect, can be determined as a function of fluid properties, channel diameter, mass velocity and vapor quality. A tube with an internal diameter of 8.38 mm has been used by Mohseni et al. [10] to study the flow pattern and the heat transfer during condensation of R134a. Experiments have been conducted at 35 °C saturation temperature and at mass flux ranging between 53 $kg\,m^{-2}\,s^{-1}$ and 212 $kg\,m^{-2}\,s^{-1}$ highlighting an important effect of the channel orientation on the two-phase flow structure. The authors noticed that, in horizontal configuration, when decreasing vapor quality, the flow pattern changes from annular to wavy annular and finally to stratified-wavy. In vertical downflow, the dominant flow pattern is annular, regardless of vapor quality and mass flux and, in vertical upflow, annular, annular-wavy, churn and slug flows have been observed as condensation proceeds.

Some studies analyzed condensation inside capillaries at low mass velocity. In that case, it is expected that the surface tension effects, as well as the viscous effects, are greater compared to the gravity effect (Médéric et al., [11–13]).

Considering convective condensation experiments performed during microgravity conditions, the only work that has been published so far in the literature is the one by Lee et al. [14]. They tested two different condensation modules using FC-72 as working fluid: the first one has an inner diameter of 7.12 mm and was dedicated to the evaluation of the heat transfer coefficient during in-tube convective condensation; the second was used for the visualization of FC-72 condensation on the outside of a tube with an inner diameter equal to 5.49 mm and 0.254 mm wall thickness. The authors found that the condensation heat transfer coefficient is a strong function of the mass velocity; at low mass velocities, the decrease of the heat transfer coefficient along the condensation length is monotonic and the influence of gravity is very significant; at high mass velocities there is a heat transfer coefficient enhancement due to both turbulence and increased waviness.

The availability of large experimental database in microgravity covering different fluids and conditions is important for three reasons:

- new relations between adimensional parameters can be deduced for the identification of the conditions at which the gravity level affects the condensation heat transfer. This is very important for devices that are expected to operate in space conditions;
- the absence of the gravity force leads to a reduction of the parameters affecting the condensation phenomenon and thus can help in the development of new physically based heat transfer correlations;
- find a link between gravity level, two-phase flow patterns and condensation heat transfer.

The present paper studies convective condensation in normal gravity and microgravity conditions inside a 3.4 mm diameter circular cross section channel; heat transfer coefficient measurements and flow pattern visualizations have been performed. Microgravity conditions have been achieved onboard the Novespace Airbus A-310 during the 62nd ESA Parabolic Flight Campaign. A parabolic flight campaign is one of the different ways to simulate microgravity on Earth; it allows to achieve approximately 20 s of microgravity, preceded and followed by a period of hyper-gravity due to the parabola maneuver.

The main objectives of the present research are:

- measurement of the heat transfer coefficient during condensation in microgravity to obtain new data and get a better understanding of the condensation phenomena;
- perform visualizations of flow patterns and liquid-vapor distribution