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Heat transfer measurements and correlation of refrigerant flow boiling in tube filled with copper foam

Yu Zhu, Haitao Hu, Shuo Sun, Guoliang Ding*

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

Flow boiling heat transfer characteristics of refrigerant in tubes filled with metal foams were experimentally investigated at a saturation temperature of 7 °C, mass flux from 10 to 90 kg m^{-2} s^{-1}, vapor quality from 0.1 to 0.8 and heat flux from 3.1 to 18.3 kW m^{-2}. The refrigerant is R410A. The test sections are tubes with inner diameter of 23.4 or 13.8 mm, filled with 5 or 10 PPI copper foam. The experimental results reveal that, metal foam enhances the flow boiling heat transfer by a maximum of 220% and promotes the flow pattern transition from stratified flow to stratified-wavy flow and from stratified-wavy flow to annular flow. The heat transfer coefficient decreases with vapor quality under low mass flux, while it increases with vapor quality under high mass flux. A correlation for predicting the flow boiling heat transfer was developed and it agrees well with the experimental data.

Mesures du transfert de chaleur et corrélation entre les mesures et l'ébullition en écoulement du frigorigène à l'intérieur d'un tube rempli de mousse de cuivre

Mots clés : mousse métallique ; écoulement ; ébullition ; configuration de l'écoulement ; transfert de chaleur ; corrélation

1. Introduction

Heat transfer enhancement of flow boiling in tubes has been studied for decades, due to its important role in the performance improvement in all vapor-compression power cycles and refrigeration systems (Lienhard and Lienhard, 2000). The researches on the development of conventional enhanced tubes, e.g. micro-fin tubes, focus on the

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* *Corresponding author*. Tel.: +86 21 34206378; fax: +86 21 34206814.
E-mail address: glding@sjtu.edu.cn (G. Ding).

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Nomenclature

A	heat transfer surface area (m^2)
a_{sf}	specific surface area ($m^2\ m^{-3}$)
D	diameter (m)
EF	effect factor, dimensionless
G	mass flux ($kg\ m^{-2}\ s^{-1}$)
g	local gravity acceleration ($m\ s^{-2}$)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_{lv}	latent heat ($J\ kg^{-1}$)
IF	impact factor, dimensionless
M	molecular weight ($g\ mol^{-1}$)
$\dot{M}$	mass flow ($kg\ s^{-1}$)
P	pressure (kPa)
PPI	pores per inch of metal foam
porosity	porosity of metal foam, dimensionless
Pr	Prandtl number, dimensionless
Q	heat input (W)
Re	Reynolds number, dimensionless
T	temperature (K)
x	vapor quality, dimensionless

Greek symbols

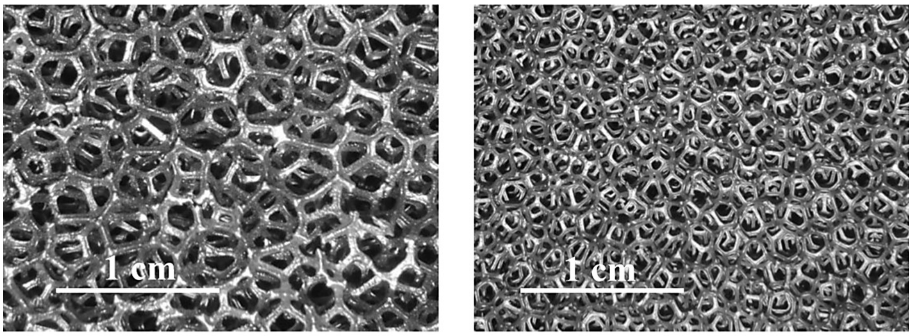
δ	liquid film thickness (m)
ε	void fraction, dimensionless
θ	angle, dimensionless
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension ($N\ s^{-1}$)
μ	dynamic viscosity (Pa s)

Subscripts

cb	convective boiling
crit	critical
dry	dry angle
in	inlet
l	liquid phase
MF	tube filled with metal foam
Non-MF	tube without metal foam
nb	nucleate boiling
pre	pre heater
r	reduced
sat	saturation
smooth	smooth tube
strat	stratified angle
test	test section
tp	two phase
v	vapor phase
w	wall
wavy	wavy flow
wetted	wetted surface

optimization for heating surface characteristics. The optimized heating surface extends the heat transfer area of the tube, providing more nucleation sites and destroying the boundary layer. However, such enhanced tubes have little influence on the fluid at the center of the tube, thus only increases the flow boiling heat transfer coefficient by up to 40% (Hu et al., 2008). Open-cell metal foam is one kind of porous material with porosity up to 98%, as shown in Fig. 1. It has very large specific surface area (1000 $m^2\ m^{-3}$ or more), and provides much more heat transfer area as well as nucleation cites (Lu et al., 1998). Moreover, the high thermal conductivity solid structure of metal foam can extend from the heating wall to the center of the tube, not only providing strong mixing capability for the fluid everywhere inside the tube, but also quickly transferring the heat to the tube center and making the liquid at the center of tube boil. The existing research results reveal that embedding metal foam into tubes greatly enhances the flow boiling heat transfer (Zhao et al., 2009). It is concluded that metal foam has potential in the performance improvement of heat exchangers in vapor compression systems (Zhao, 2012).

The geometry of metal foam has a major influence on the flow boiling heat transfer characteristics, and is determined by two independent parameters (Calmidi and Mahajan, 2000): porosity (void volume fraction) and PPI (pores per inch). PPI is of primary importance to heat transfer enhancement, because the specific surface area of metal foam is directly proportional to PPI (Calmidi, 1998), making metal foam with larger PPI provide more heat transfer area and stronger mixing capability to fluid (Lu et al., 2006). But larger PPI metal foam has



a) $PPI = 5, porosity = 95\%$ b) $PPI = 10, porosity = 95\%$

Fig. 1 – Photos of copper foam used in the present study.