Applied Thermal Engineering 62 (2014) 433–443

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

# Effect of tube diameter on pressure drop characteristics of refrigerant–oil mixture flow boiling inside metal-foam filled tubes

Haitao Hu [a], Yu Zhu [a], Hao Peng [b], Guoliang Ding [a,*], Shuo Sun [a]

[a] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Key Lab of HVAC, Beijing University of Civil Engineering and Architecture, Beijing 100044, China

## HIGHLIGHTS

- New pressure drop data of refrigerant–oil mixture in metal-foam tubes are obtained.
- Effect of tube diameter on pressure drop is analyzed.
- Pressure drop in metal-foam tubes decreases with decreasing tube diameter.
- A pressure drop correlation reflecting the effect of tube diameter is developed.

## ARTICLE INFO

*Article history:*
Received 23 April 2013
Accepted 29 September 2013
Available online 16 October 2013

*Keywords:*
Correlation
Flow boiling
Metal foam
Oil
Pressure drop

## ABSTRACT

The objective of this study is to analyze the effect of tube diameter on pressure drop characteristics of refrigerant–oil mixture flow boiling in metal-foam filled tubes. Experiments on metal-foam filled tubes with an inner diameter of 7.9 mm were performed, and the analysis of the diameter effect was done based on the experimental data of 7.9 mm tubes together with those of 13.8 mm and 26.0 mm from literature. The research results show that, the pressure drop increases with increasing PPI, and the impact of PPI becomes insignificant as the tube diameter decreases. When the diameter decreases from 13.8 mm to 7.9 mm, the pressure drop decreases due to the incomplete cells and randomly chopped ligaments nearby tube wall, and the maximum decrements are 22% and 35% for 5 PPI and 10 PPI metal-foam filled tubes, respectively. A new pressure drop correlation was developed, and it agrees well with the experimental data for different diameter tubes.



## 1. Introduction

Due to the complex spatial structure and large specific surface area, metal foam has shown great advantages in thermal transport [1], and metal-foam filled tubes have shown 2–4 times higher heat transfer performance than traditional smooth tubes [2–7]. Therefore, the use of metal foam in efficient compact heat exchangers has become one of the most effective cooling techniques [1], making it possible to develop new compact heat exchangers with metal-foam filled tubes for refrigeration systems. In addition, the presence of metal foam also increases the pressure drop of refrigerant during flow boiling [8], resulting in higher power consumption of the compressor. Near the confining tube wall, metal foam has incomplete cells and randomly chopped ligaments, and this affects the velocity field and the pressure drop characteristics [9]. As the tube diameter decreases, the number of incomplete cells on the cross section of metal-foam filled tube decreases, and the ratio of the local pressure drop near the confining tube wall to that for the whole cross section will change, resulting in different pressure drop characteristics for different diameter tubes. For a vapor-compression refrigeration system, the working fluid is the refrigerant–oil mixture, and the presence of oil has a significant effect on pressure drop characteristics [10,11]. Therefore, the effect of tube diameter on two-phase pressure drop characteristics of refrigerant–oil mixture in metal-foam filled tubes should be known in order to optimize the metal foam heat exchanger for refrigeration system.

The researches on two-phase pressure drop characteristics of refrigerant or refrigerant–oil mixture flow boiling in metal-foam filled tubes have been reported in literature [8,12]. Experiments on the flow boiling pressure drop characteristics of R134a show that, metal foam pore size has a significant effect on the pressure drop characteristics, and two-phase flow encounters much more flow resistance for metal foam with smaller cell size [8].

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

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.09.051

**Nomenclature**

| | |
|---|---|
| $a$, $b$ | coefficient in Eq. (9) |
| $c_1 - c_8$ | coefficient in Eqs. (11)–(13) |
| $C$ | coefficient in Eq. (10) |
| $D$ | tube diameter (m) |
| $D_{Pore}$ | pore diameter (m) |
| $G$ | mass flux (kg m$^{-2}$ s$^{-1}$) |
| $L$ | length of test tube (m) |
| $m$ | mass flow rate (kg s$^{-1}$) |
| $n_0$ | reference pore number |
| $PF_{Oil}$ | oil effect factor |
| $PPI$ | number of pores per inch |
| $\Delta P$ | pressure drop (kPa) |
| $S$ | specific surface area (m$^2$ m$^{-3}$) |
| $V$ | fluid flow velocity (m s$^{-1}$) |
| $x$ | vapor quality |
| $X_{tt}$ | Martinelli parameter |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | void fraction |
| $\varepsilon_0$ | porosity |
| $\omega$ | oil concentration |
| $\rho$ | density (kg m$^{-3}$) |
| $\Phi$ | frictional two-phase multiplier |
| $\mu$ | dynamic viscosity (N s m$^{-2}$) |
| $\nu$ | kinematic viscosity (m$^2$ s$^{-1}$) |
| $\sigma$ | surface tension (N m$^{-1}$) |

*Subscripts*

| | |
|---|---|
| acc | acceleration |
| in | inlet |
| local | local |
| L | liquid |
| no | nominal |
| MF | metal foam |
| o | oil |
| out | outlet |
| r | refrigerant |
| total | total |
| V | vapor |

Experiments on flow boiling pressure drop characteristics of R410A-oil mixture show that, the presence of oil increases the pressure drop by a maximum of 25% and 50% for 5 PPI and 10 PPI metal foams, respectively, and the enhancement effect of oil for high PPI metal foam is more obvious than that for low PPI metal foam [12]. However, the metal-foam filled tube with only one diameter was used in each of the above researches, and the effect of tube diameter on two-phase pressure drop characteristics of refrigerant–oil mixture flow boiling in metal-foam filled tubes was not investigated.

For the effect of tube diameter on pressure drop characteristics in metal-foam filled tubes, the existing researches are focused on air [9], and there is no published research on two-phase fluid. Experiments on air forced convection inside metal-foam filled tubes show that, there is a critical diameter corresponding to negligible wall and size effects; when the tube diameter is less than the critical value, the pressure drop decreases as the tube diameter decreases [9]. This trend is not the same as that for smooth or mircofin tube [13–18]. For a refrigerant–oil mixture, due to the presence of phase change during flow boiling, the flow velocity field and pressure drop characteristics are different from those of air forced convection, causing that the research related to air forced convection [9] may not be extended to refrigerant–oil mixture flow boiling inside metal-foam filled tubes.

For refrigerant–oil mixtures, the effect of tube diameter on pressure drop characteristics for smooth or microfin tubes has been investigated [10,11,19–22]. The research results show that, the effects of tube diameter on the pressure drop characteristics for smooth or microfin tubes are different under various conditions of oil concentration [10,21]. It can be imaged that, due to the combined effect of metal foam and oil, the effect of tube diameter on the pressure drop characteristics for refrigerant–oil mixture flow boiling inside metal-foam filled tubes must be different from those for refrigerant–oil mixture in smooth tubes or microfin tubes, and should be investigated.

For predicting two-phase pressure drop characteristics of refrigerant–oil mixture inside metal-foam filled tubes, Hu et al. [12] proposed a correlation, in which the effects of metal foam structure, oil concentration and operation conditions were reflected. However, this correlation was developed based on the experimental data for one single diameter tube, and the effect of tube diameter was not considered. In order to develop a new pressure drop correlation to reflect the effect of tube diameter, new experimental data of refrigerant–oil mixture in metal-foam filled tubes are needed besides the existing experimental data of R134a in 26.0 mm inner diameter (I.D.) tubes [8] and R410A-oil mixture in 13.8 mm I.D. tubes [12].

The purpose of this study is to obtain new experimental data of refrigerant–oil mixture flow boiling inside metal-foam filled tubes, to investigate the effect of tube diameter on pressure drop characteristics by comparing new experimental data with the existing ones in literature [8,12], and to propose a new correlation that reflects the effect of tube diameter on the pressure drop characteristics.

## 2. Design of experiments

### 2.1. Experimental conditions needed for analyzing the effect of tube diameter

In order to investigate the effect of tube diameter on pressure drop characteristics of refrigerant–oil mixture flow boiling inside metal-foam filled tubes, the experimental data for three diameter tubes are used, as shown in Table 1.

The experimental data of R134a in 26.0 mm I.D. tubes and R410A-oil mixture in 13.8 mm I.D. tubes are quoted from Zhao et al. [8] and Hu et al. [12], respectively. The experimental data of R410A and R410A-oil mixture in 7.9 mm I.D. tubes will be obtained in the

**Table 1**
Data source for analyzing the effect of tube diameter.

| Fluids | I.D. (mm) | Porosity | PPI | Data resource |
|---|---|---|---|---|
| R134a | 26.0 | 90% | 40 | Zhao et al. (2009) |
| R134a | 26.0 | 90% | 20 | Zhao et al. (2009) |
| R410A | 13.8 | 95% | 5 | Hu et al. (2013) |
| R410A | 13.8 | 95% | 10 | Hu et al. (2013) |
| R410A with oil | 13.8 | 95% | 5 | Hu et al. (2013) |
| R410A with oil | 13.8 | 95% | 10 | Hu et al. (2013) |
| R410A | 7.9 | 95% | 5 | Present study |
| R410A | 7.9 | 95% | 10 | Present study |
| R410A with oil | 7.9 | 95% | 5 | Present study |
| R410A with oil | 7.9 | 95% | 10 | Present study |