2012

Saturated Flow Boiling Heat Transfer in Horizontal Square Tube

Juan Shi
juanzi84@gmail.com

Anthony M. Jacobi

Zhenqian Chen

Shi, Juan; Jacobi, Anthony M.; and Chen, Zhenqian, "Saturated Flow Boiling Heat Transfer in Horizontal Square Tube" (2012). *International Refrigeration and Air Conditioning Conference.* Paper 1231.
http://docs.lib.purdue.edu/iracc/1231

Saturated Flow Boiling Heat Transfer in Horizontal Square Tube

Juan Shi[1, 2], Anthony M. Jacobi[2*], Zhenqian Chen[1]

[1] School of Energy and Environment, IIUSE
Southeast University
Nanjing, Jiangsu 210096, *PR* China

[2] Department of Mechanical Science and Engineering,
University of Illinois at Urbana-Champaign
Urbana, IL, USA 61801
Tel: +1 (217) 333-3115 Fax: +1 (217) 333-1942 Email: a-jacobi@illinois.edu

* Corresponding Author

ABSTRACT

This work is focused on the saturated flow boiling of refrigerants in horizontal square tubes. The relevance and novelty of the study is established in a literature review. The experimental apparatus, methods and data interpretation are described in detail. Experimental data from flow boiling experiments performed in a square tube having 7 mm × 7 mm cross section are presented, for R134a at mass fluxes ranging from 100 to 250 $kg/(m^2 \cdot s)$, and a controlled inlet quality from 0 to 90%. The system pressure was maintained at about 500 kPa for these experiments. The experimental data are compared to correlations available in literature. The departure of the experimental data from these correlations suggests the need for developing similar correlations for tubes having rectangular cross sections.

1. INTRODUCTION

Flow boiling heat transfer in metal tubes has been an active area of research. The mechanism of the boiling heat transfer is complex with dependence on a wide variety of flow parameters such as vapor quality, presence of different flow regimes and the distribution of nucleation sites. This explains the presence of a large number of flow boiling heat transfer correlations in the literature. Some of the most extensively used correlations are by Chen (1966), Shah (1982), Kandlikar and Thakur (1982) and Kattan *et al.* (1998).

Chen's (1966) correlation postulated that, flow boiling heat transfer is governed mainly by two important mechanisms: nucleate boiling and forced convection. Shah (1982) proposed a correlation using the boiling number, Bo, and the convective number, Co. Kandlikar and Thakur (1982) proposed an additive correlation with nucleate boiling and convective contributions. Kattan *et al.* (1998) developed a diabatic two-phase flow pattern map. The new flow pattern map consists of stratified flow, stratified wavy flow, intermittent flow, annular flow and mist flow. Based on the flow pattern map, Kattan *et al.* (1998) proposed a new heat transfer model to predict flow boiling data.

Most of the previously published heat transfer correlations for flow boiling were developed for tubes having circular cross sections. Tran (1996) conducted experiments on boiling in small circular and rectangular channel with two refrigerants. The two channels had approximately the same hydraulic diameter. It was concluded that for small channels, nucleation is the dominant heat transfer mechanism for flow boiling. The results showed that there was no significant geometry effect for the two channels tested. Yen (2006) studied the convective boiling heat transfer in microchannels having different cross-sections. They observed that the boiling number for square cross-sections followed a power law relation with the number of nucleation sites. This implied that corners in square microchannels can serve as active nucleation sites. Therefore an enhancement in heat transfer in square microchannel compared to circular microchannels was observed. The significant differences in the observations from these two articles suggest dependence of heat transfer on channel geometry and size. Therefore it is imperative to study the flow boiling in rectangular channels.

In the recent past, open cell metal foams have received significant research attention (Zhao *et al*., 2009, Ghosh *et al*., 2008, Kopanidis *et al*., 2010). High porosity, open-cell metal foams have potential in thermal management applications, because they have high flow permeability and a large surface-area−to-volume ratio. Metal foam tubes have been shown to improve the heat transfer coefficient by almost three times over that of a plain tube (Zhao *et al*., 2009). From a manufacturing perspective, metal foam tubes having a square cross section may be easier to manufacture than a circular cross section. Moreover, since the complexity in heat transfer mechanism in metal foam tubes is much higher than a plain tube. Understanding flow boiling in square tubes becomes more important, as they provide a good baseline for the metal foam. The present work is aimed at finding the heat transfer coefficient in square tubes. Due to the absence of correlations for mini square tubes, the experimental data are compared to correlations for circular tubes (having same area of cross section as the square tube).

2. EXPERIMENTAL METHODS

2.1 Experimental Apparatus and Test Section

The experimental apparatus is shown in Figure 1. It consisted of a gear pump for circulation of the liquid refrigerant 134a. A Coriolis-effect mass flow meter was used to measure the mass flow rate in the system. An insulated preheater was used to control the inlet vapor quality of refrigerant at the inlet of the test section. As shown in Figure 1, the pressure and temperature at both the inlet and outlet of the test section were measured. A sight glass was fixed at the outlet of the test section for the visualization of the flow. The system pressure can be maintained by controlling the flow rate in the condenser.

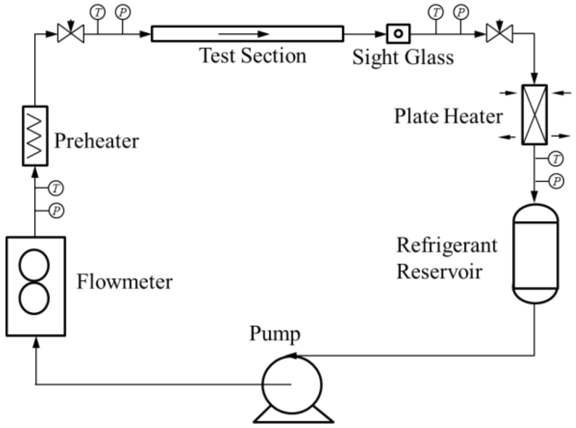

Figure 1: Schematic of the closed-loop experimental apparatus

A schematic of the test section is shown in Figure 2. The test section is a square copper tube. It is 300 mm long with 7 mm x 7 mm cross section. Along the flow direction in the test section, temperatures were measured at three locations. At each location, four thermocouples were placed around the tube. A DC power supply was used to maintain constant heat flux for the test section through heating tape.

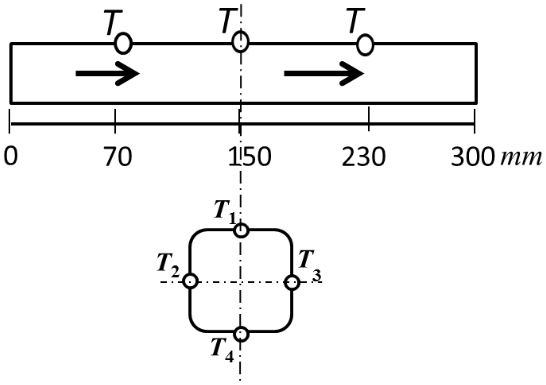

Figure 2: The schematic of the test section

3.2 Measurement

The thermophysical properties of pure R134a were evaluated by commercial software (Engineering Equation Solver, EES). The local heat transfer coefficient h (W/m$^{2\cdot o}$C) was calculated as follows:

$$h = \frac{q}{T_{wall} - T_{fluid}} \tag{1}$$

where, q is the heat flux, W/m^2; T_{wall} is the surface temperature of the copper tubing, ^{o}C; T_{fluid} is the saturated temperature of refrigerant in the test section, ^{o}C.

The wall temperature at each section was taken as an average of four thermocouple readings:

$$T_{wall} = \frac{T_1 + T_2 + T_3 + T_4}{4} \tag{2}$$

The uncertainty in the pressure sensor was 0.25%. The uncertainty of temperature was 0.1 ^{o}C.

3. RESULTS AND DISCUSSIONS

The test conditions in the experiment were as follows:

- The mass flux range of R-134a: 80 - 250 kg/ (m$^{2\cdot}$s)
- The heat flux range: 2 ~ 12 W/m^2
- Test section exit quality: 0 – 90 %
- System pressure: 510 kPa (T_{sat} ≈16℃)

3.1 Verification of Experimental Data with Current Correlations

As shown in Figures 3-6, the experimental results were compared to the Bennett model (Bennett *et al.*, 1980), the Chen model (Chen, 1966), the Yang model (Yang, 1999), the Shah model (Shah, 1976) and the Kandlikar model (Kandlikar, 1990). The comparison was made by assuming that the cross sectional area of the circular tube was same as the square tube.

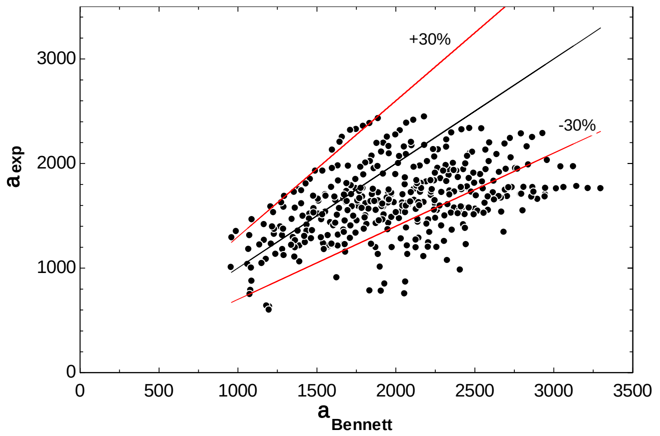

Figure 3: Experimental results compared to the Bennett model

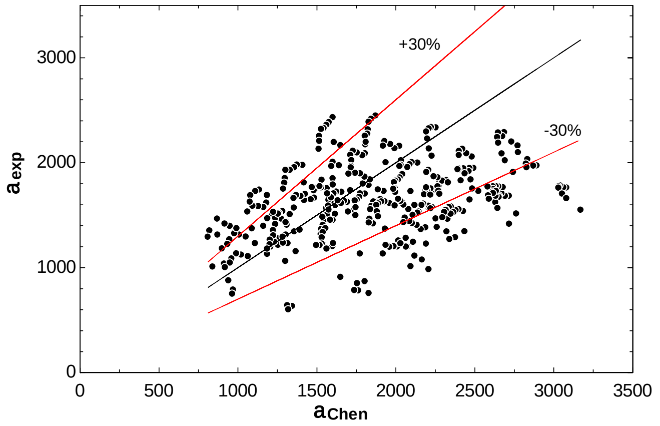

Figure 4: Experimental results compared to the Chen model

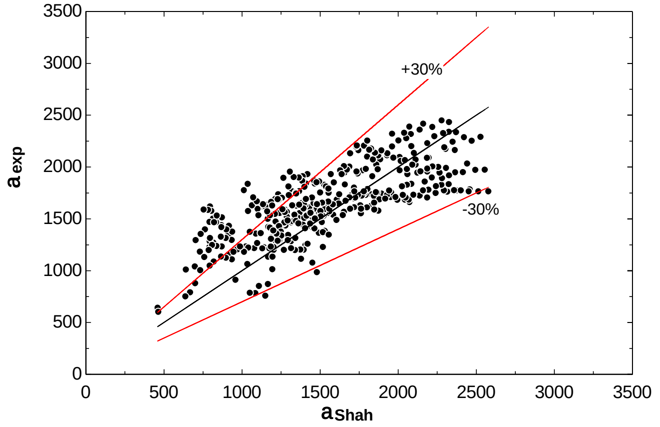

Figure 5: Experimental results compared to the Shah model

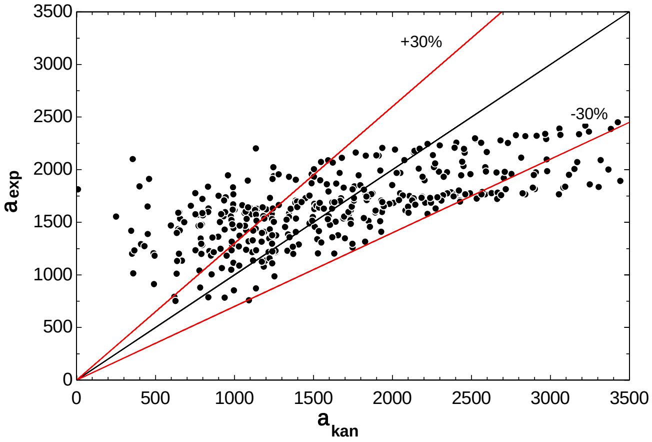

Figure 6: Experimental results compared to the Kandlikar model

Table 1: Agreement of the experimental data compared with different correlations

	Bennett	Chen	Kandlikar	Shah
Mean Deviation (%)	22.5	32.4	88.4	20.5
Within 30% Deviation (%)	70.9	56.8	62.3	79.6

It is observed from Figures 3-6 and from Table 1 that the experimental data compared reasonably well with the existing models (± 30% deviation). It is believed that the existing correlations can be modified to account for the square geometry of the test section. The analysis in the following section explains the importance of the geometric effect on the heat transfer.

3.2 Geometry Difference between the Square Tube and Circular Tube

In order to understand the influence of the square cross-section with respect to the circular section on the heat transfer correlations, the following assumptions are proposed:

1. The mass flux in both tubes is the same.
2. The cross-section tube area is same in each case.
3. The flow pattern is the same at same mass flux.

Based on these assumptions, two flow pattern cases are analyzed: stratified flow and annular flow.

3.2.1 Stratified Flow

Figure 7 shows a schematic of the stratified flow in circular tube and square tube, respectively. It is assumed that the mass flux, $\dot{m}$ and the cross section, *A* of both the tubes is same. Accordingly,

$$\dot{m}_c = \dot{m}_s ; A_c = A_s \quad or, \quad a = \sqrt{\pi} R \tag{3}$$

Where, the subscripts *c* and *s* denote circle and square, respectively. The mass flux in the tube is given by the volume averaged properties as:

$$\dot{m} = \rho_{tp} A_t V ; \;\; \rho_{tp} = \alpha \rho_g + (1-\alpha) \rho_l \tag{4}$$

Therefore, from Eqn. (3) and Eqn. (4), it can be concluded that the void fraction in both the tubes are same.

From Figure 7, the area wetted by the liquid for the circular and for the square cross section is given by:

$$
\begin{aligned}
A_{cw} &= R^2\theta - \frac{1}{2}\cdot 2R\sin\theta\cdot\cos\theta = \frac{R^2(2\theta-\sin 2\theta)}{2} \\
A_{sw} &= \sqrt{\pi}Rh
\end{aligned}
\tag{5}
$$

Since the void fraction in both the tubes is the same, using Equations (3) and (5) yields:

$$
\begin{aligned}
& A_{cw} = A_{sw} \\
& or, \\
& h = \frac{R}{2\sqrt{\pi}}(2\theta - 2\sin\theta)
\end{aligned}
\tag{6}
$$

The wetted perimeter in different tubes is given by:

$$
\begin{aligned}
P_{cw} &= 2R\theta && 0<\theta<\pi \\
P_{sw} &= \sqrt{\pi}R + 2h && 0<h<a
\end{aligned}
\tag{7}
$$

Therefore,

$$
\frac{P_{sw}}{P_{cw}} = \frac{\pi + (2\theta - \sin 2\theta)}{2\sqrt{\pi}\theta}
\tag{8}
$$

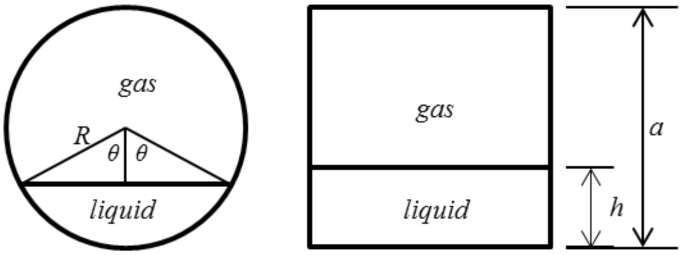

Figure 7: Schematic of the stratified flow in circular tube and square tube

The ratio of P_{sw}/P_{cw} against θ is shown in Figure 8.It is observed that in realistic situations P_{sw}/P_{cw} is greater than one. That means the liquid occupying the perimeter in the square tube is larger than that in the circular tube. As liquid has a higher heat transfer coefficient as does gas, the heat transfer in the square tube is expected to be larger than a circular tube. This effect becomes more prominent when θ ~ 0.5. When θ>2.5, P_{sw}<P_{cw}. However, such situations seldom exist.

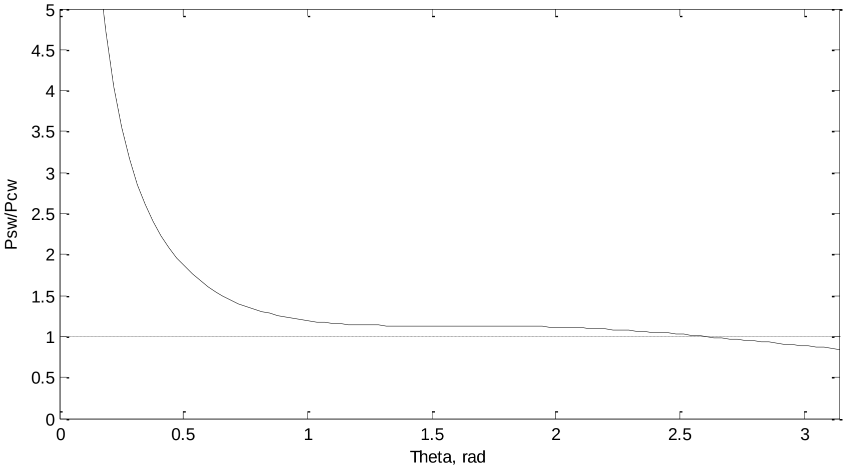

Figure 8: The ratio of P_{sw}/P_{cw} against θ

3.2.2 Annular Flow

Figure 9 shows a schematic of the annular flow in a circular tube and a square tube. The assumptions from the previous section yields:

$$\begin{aligned} P_{cw} &= 2\pi R \\ P_{sw} &= 4\sqrt{\pi} R \end{aligned} \tag{9}$$

Therefore, $P_{sw} > P_{cw}$. Since the wetted perimeter of the square section is different from the circular section, the heat transfer coefficient might be influenced.

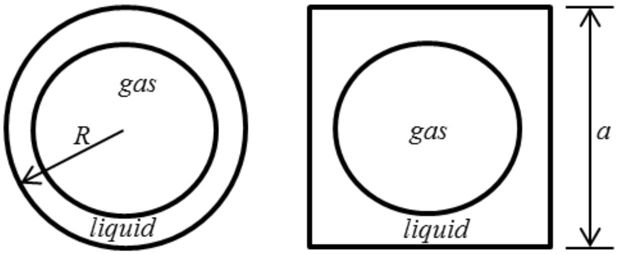

Figure 9: Schematic of the annular flow in circular tube and square tube

4. CONCLUSIONS

An experimental study of saturated flow boiling in a square tube was conducted. The experimental results were compared to correlations available in literature for circular cross section tubes. The magnitude of the experimental results compared reasonably with the existing correlations. However, the results were scattered. It was observed that the square cross section tube had a larger wetted perimeter than the equivalent circular tube. Therefore it was concluded that heat transfer correlations for rectangular cross sections are needed to be developed in order to predict the heat removal in a more accurate way.

REFERENCES

Bennett D. L., Davis M. W., *et al.*, 1980, The suppression of saturated nucleate boiling by forced convective flow, *AIChE Symporium Series*, vol. 76, no. 199: p. 91 – 103.

Carey V. P., 2008, Liquid-vapor phase-change phenomena, second edition, *Taylor & Francis Group, LLC*, New York, p. 614.

Chen J. C., 1966, Correlation for boiling heat transfer to saturated fluids in convective flow, *Industrial and Engineering Chemistry -- Process Design and Development*, vol. 5, no. 3: p 322-329.

Ghosh I., 2008, Heat transfer analysis of high porosity open-cell metal foam, *J. Heat Transfer*, vol. 130, no. 3: p. 034501-1-6.

Kandlikar S. G., 1990, A general correlation for saturated two-phase flow boiling heat transfer inside horizontal and vertical tubes", *J. Heat Transfer*, vol. 113, p 190-200.

Kandlikar S. G., and Thakur B. K., 1982, A new correlation for heat transfer during flow boiling, *Proc. 16th Southeastern Seminar on Thermal Sciences*, Miami, FL.

Kattan N., Thome J. R., Favrat D. 1998, Flow boiling in horizontal tubes: part 1 – development of a diabatic two-phase flow pattern map, *J. Heat Transfer*, vol. 120, no. 1: p 140-147.

Kattan N., Thome J. R., Favrat D. 1998, Flow boiling in horizontal tubes: part 3 – Development of a new heat transfer model based on flow pattern, *J. Heat Transfer*, vol. 120, no. 1: p 156-165.

Kopanidis A., Theodorakakos A., Gavaises E., *et al*, 2010, 3D numerical simulation of flow and conjugate heat transfer through a pore scale model of high porosity open cell metal foam, *Int. J. Heat Mass Transfer*, vol. 53, no. 11-12: p. 2539-2550.

Shah M. M., 1976, A new correlation for heat transfer during boiling flow through pipes, *ASHRAE Transactions*, vol. 82, part 2: p. 66-86.

Shah M. M., 1982, Chart correlation for saturated boiling heat transfer: equations and further study, *ASHRAE Trans.*, vol. 88, no. 1: p. 185-196.

Tran T. N., Wambsganss M. W., France D. M., 1996, Small circular- and rectangular- channel boiling with two refrigerants, *Int. J. Multiphase Flow*, vol. 22, no. 3 : 485-498.

Yen T. H., Shoji M., Takemura F., Suzuki Y., Kasagi N., 2006, Visualization of convective boiling heat transfer in single microchannels with different shaped cross-sections, *Int. J. Heat Mass Transfer*, vol. 49: 3884-3894.

Zhao C. Y., Lu W., Tassou S. A., 2009, Flow boiling heat transfer in horizontal metal-foam tubes, *J. Heat Transfer*, vol. 131: 121002-1 – 8.

ACKNOWLEDGEMENT

This work was financially supported by Air-Conditioning and Refrigeration Center, University of Illinois at Urbana Champaign.