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# Heat transfer and pressure drop characteristics of ammonia during flow boiling inside a horizontal small diameter tube

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ABSTRACT

In this article, a series of experiments was conducted to investigate the flow boiling heat transfer and pressure drop characteristics of ammonia in a 4 mm horizontal plain tube. The experiments were performed for heat fluxes at 9 and 21 kW $m^{-2}$ $K^{-1}$, mass flux from 50 to 100 kg $m^{-2}$ $s^{-1}$, and saturation temperature from −15.8 to 5 °C. The experimental results show that with the increase of heat flux, the heat transfer coefficient increases. Meanwhile, it also increases with a rise in mass flux in the low vapor quality region, whereas reversed situation can take place in the high vapor quality region when the saturation temperature is decreased. The saturation temperature has little effect on the heat transfer coefficient in the low vapor quality region, however at higher mass fluxes, the heat transfer coefficient can decrease with decreasing saturation temperature in the high vapor quality region. The comparisons of the experimental data with existing correlations for flow boiling heat transfer coefficient show that Gungor and Winterton correlation can give good agreement with mean absolute deviation of 19.6% even though it is developed for turbulent flow. The adiabatic two-phase frictional pressure gradient increases with the increase of vapor quality and mass flux, while decreases with the increase of saturation temperature. The comparisons with existing correlations for two-phase frictional pressure gradient indicate that Müller-Steinhagen and Heck correlation can predict the experimental data well with mean absolute deviation of 16.1% and 93.4% of the data is within the ±30% error band.



## 1. Introduction

After the chlorofluorocarbons (CFCs) were found to cause ozone depletion, they were banned under Montreal Protocol in 1987. Later, Kyoto Protocol in 1997 scheduled a phase out of the hydrochlorofluorocarbons (HCFCs) by 2020–2030 and hydrofluorocarbons (HFCs) by 2025–2040 under the background of ozone depletion and global warming. In this context, the researches on natural refrigerants are attracting growing interest. Ammonia, one of the natural refrigerants, has been successfully used as refrigerant in large industrial applications for more than a century [1,2]. Due to the excellent thermodynamic properties and environmentally friendly nature, the application of ammonia in small systems has also caused widespread concern recently [3–7]. Two projects supported by the European Union have been wholly or partly devoted to the development of small ammonia systems [7]. They are called as OSCAR (Innovation in Small Capacity Ammonia Refrigeration Plants) and SHERHPA (Sustainable Heat and Energy Research for Heat Pump Applications). Nevertheless, ammonia has the drawbacks associated with combustibility and toxicity, reduction of the charge in ammonia refrigeration systems will be of great importance [6–8]. The application of small diameter tubes can provide larger contact area and offer higher heat transfer coefficient [9], which has the potential to improve the compactness of heat exchanger and reduce the refrigerant charge.

The accurate predictive methods for heat transfer coefficient and pressure drop are vital to the application of refrigerants, which must be based on an accurate database covering a wide range of experimental conditions [10–13]. Thome et al. [12] presented an extensive literature review on ammonia flow boiling, and they concluded that the database in the literatures should be improved in terms of both accuracy and range of experimental conditions. Recently, Wang and Fang [13] collected a new database for ammonia flow boiling, but still found that few experimental data were available. Some related studies on the flow boiling heat transfer

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**Nomenclature**

| | |
|---|---|
| $c_p$ | specific heat (kJ kg$^{-1}$ K$^{-1}$) |
| $D$ | diameter (m) |
| $G$ | mass flux (kg m$^{-2}$ s$^{-1}$) |
| $h$ | heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |
| $H$ | latent heat (kJ kg$^{-1}$) |
| $I$ | current (A) |
| $k$ | thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $L$ | length (m) |
| $\dot{m}$ | mass flow rate (kg s$^{-1}$) |
| $N$ | number of points |
| $Nu$ | Nusselt number |
| $\Delta P$ | pressure drop (kPa) |
| $P_r$ | reduced pressure |
| $q$ | heat flux (kW m$^{-2}$) |
| $Q$ | heat power (W) |
| $Re$ | Reynolds number |
| $T$ | temperature (K) |
| $U$ | voltage (V) |
| $\dot{V}$ | volume flow rate (m$^3$ s$^{-1}$) |
| $x$ | vapor quality |

*Abbreviations*

| | |
|---|---|
| MAD | mean absolute deviation |
| MRD | mean relative deviation |
| RD | relative deviation |
| WGM | water-glycol mixture |

*Greek*

| | |
|---|---|
| $\alpha$ | void fraction |
| $\varepsilon$ | percentage of points within an error band |
| $\rho$ | density (kg m$^{-3}$) |
| $\sigma$ | surface tension (N m$^{-1}$) |

*Subscript*

| | |
|---|---|
| *cal* | calculate |
| exp | experiment |
| *f* | frictional |
| *g* | gravity |
| *G* | gas |
| *h* | heat transfer test section |
| *in* | inlet |
| *L* | liquid |
| *m* | momentum |
| *mix* | mixture |
| *out* | outlet |
| *p* | pressure drop test section |
| *pre* | preheater |
| *r* | refrigerant |
| *sat* | saturation |
| *sp* | single-phase |
| *sub* | subcooling |
| *t* | total |
| *test* | test section |
| *tp* | two-phase |
| *w* | wall |

and pressure drop are presented as follows. Zürcher et al. [14,15] experimentally investigated the flow boiling heat transfer of ammonia in a 14 mm horizontal tube at the saturation temperature of 4 °C, and compared the test data with the prediction results. They found that the model of Kattan-Thome-Favrat [16] can predict well in most parts. However, the prediction accuracy for the onset of dryout and heat transfer model at the low vapor qualities should be improved. Then, they proposed an improved approach to predict the heat transfer coefficient in horizontal tubes through studying each flow pattern separately, which included a new criterion to define the onset of nucleate boiling. Kabelac and Buhr [17] measured the heat transfer coefficient and pressure drop of ammonia in a 10 mm horizontal plain tube with the saturation temperature ranging from −40 °C to 4 °C. The heat transfer coefficients for different cross-sections are calculated using a finite element model of the tube. The results showed that the model of Zürcher et al. [14] can predict the heat transfer data well at low mass fluxes. As for the pressure drop, the Chisholm [18] correlation gave better predictions for adiabatic flow, while Chawla [19] correlation was better for diabatic flow. Zamfirescu and Chiriac [20] studied the flow boiling heat transfer of ammonia in a 32 mm vertical plain tube from −5 °C to 10 °C, and they found the correlations of Steiner and Taborek [21] and Gungor and Winterton [22] give the best prediction for their experimental data. Pamitran et al. [23] conducted an experimental research on flow boiling of ammonia in a 3 mm horizontal tube. The test saturation temperature is from 0 °C to 10 °C. They observed laminar flow in the evaporative small tube, which was considered in their modified boiling heat transfer correlation. Maqbool et al. [24,25] investigated boiling heat transfer and pressure drop of ammonia in vertical mini tubes of 1.224 mm and 1.70 mm. The test saturation temperatures are 23 °C, 33 °C and 43 °C. The results showed that the heat transfer coefficient was observed to be higher for lower inner diameter tube. Meanwhile, they found Cooper [26] correlation can predict the heat transfer well, but none of the generalized correlation can agree well with the frictional pressure drop. Shah [27–29] measured the two-phase pressure drop of ammonia with mineral oil in a horizontal 26.2 mm tube with the saturation temperature ranging from −40 °C to 0 °C. However, the quantity of oil in circulation was not measured and considered. Lima et al. [5] examined the frictional pressure drop of ammonia in a horizontal smooth tube with 14 mm diameter. The tested saturation temperatures are −14 °C, −2 °C and 12 °C. They found that the pressure drops of the diabetic and adiabatic flow are similar. Base on the above research review, it can be found that most of the experimental studies on flow boiling heat transfer and pressure drop for ammonia were in the tubes with relatively large diameters (>8 mm). Moreover, there is rare research of heat transfer and pressure drop for ammonia in the small tube at the saturation temperature below 0 °C, which is of special interest in refrigeration applications.

Above all, ammonia as one of the natural refrigerants has caused increasing interest in the application of small systems under the imperious demand of refrigerant substitution. Besides, the charge reduction in ammonia systems is also very urgent. The small diameter tubes have the potential to reduce the refrigerant charge and are mostly used in small systems. However, the experimental studies on flow boiling heat transfer and pressure drop for ammonia in small diameter tubes are very limited. This study conducted experiments to investigate the characteristics of flow boiling heat transfer and pressure drop for ammonia in a horizontal smooth tube with an inner diameter of 4 mm. One of the objectives is to add new data for the application of ammonia in heat exchanger with small diameter tube due to the lack of published data in the literature. Furthermore, the experimental data are compared with some universal flow boiling heat transfer and frictional pressure drop prediction methods to seek out the