Proceedings of the 6th World Congress on Momentum, Heat and Mass Transfer (MHMT'21)
~~Lisbon, Portugal~~ Virtual Conference – June 17 – 19, 2021
Paper No. ICMFHT 303
DOI: 10.11159/icmfht21.lx.303

Evaluation of a Phenomenological Model for Diabatic CO_2 Two Phase Pressure Drop with Experimental Data inside Horizontal Tubes

Lixin Cheng[1,2], **Guodong Xia**[1]
[1]Beijing Key Laboratory of Heat and Energy Conversion, Beijing University of Technology,
Beijing, China
[2]Department of Engineering and Mathematics, Sheffield Hallam University,
Sheffield, UK
lixincheng@hotmail.com; xgd@bjut.edu.cn

Abstract - This paper presents a comparative study of the Cheng et al. [Heat Mass Transfer 51 (2008) 111-124] flow pattern based phenomenological model for diabatic CO_2 two phase frictional pressure drop inside horizontal tubes. First, analysis of the existing experimental studies of flow boiling two phase pressure drop is presented and the physical mechanisms are discussed. Then, generalized CO_2 flow pattern map and flow pattern based two phase frictional pressure drop model specially developed for CO_2 are discussed. Next, new experimental database of diabatic CO_2 two phase frictional pressure drop has been set up to evaluate the models. Comparative results of the two phase frictional pressure drop models to the experimental database are analysed. According to the analysis, the physical mechanisms and prediction model of the CO_2 two phase flow pressure drop have been well understood. Future research needs in two phase flow frictional pressure drop of CO_2 inside channels are recommended according to this comparative study.

***Keywords*:** Phenomenological model, two phase pressure drop, CO_2, evaporation, experimental data, evaluation, analysis

1. Introduction

Over the past decades, CO_2 (R744) has been receiving renewed and intensive interest as an efficient and environmentally safe refrigerant in a number of applications, including mobile air conditioning, residential heat pump and hot water heat pump systems and as the secondary refrigerant in refrigeration systems at low temperatures [1-10]. Compared to other conventional refrigerants, flow boiling heat transfer, flow patterns and two-phase pressure drop are quite different from those of conventional refrigerants [2, 3, 5-8, 10]. For example, for CO_2 evaporation processes in an evaporator, CO_2 evaporates at much higher pressure than conventional refrigerant R134a. The physical and transport properties of CO_2 are quite different from those of conventional refrigerants at the same saturation temperatures. The physical properties have a significant effect on the evaporation processes. Furthermore, due to the channel size effect, the characteristics of flow boiling heat transfer, flow patterns and two-phase frictional pressure drops in the compact heat exchangers with micro-channels are quite different from those in conventional channels [10-16]. Therefore, conventional flow pattern maps, flow boiling heat transfer and two phase pressure drop correlations do not work for CO_2 in micro-channels.

The predictions of two-phase flow frictional pressure drop with the leading methods often cause errors of more than 50% [17-21], therefore, efforts are increasingly being made to improve on the two phase frictional pressure drop prediction methods and models. Furthermore, the leading two phase frictional pressure drop prediction methods do not usually contain any flow pattern information, which is intrinsically related to the two-phase frictional pressure drop. Due to the effects of thermal physical and transport properties of CO_2, the leading prediction two phase frictional pressure drop methods do not work well. The reason is that these methods do not usually cover the much lower liquid-to-vapor density ratios and very small surface tension characteristics of CO_2 at high pressures. In general, the two-phase frictional pressure drops of CO_2 are much lower than those of other refrigerants. Some researchers proposed two phase frictional pressure drop correlations for CO_2 based on their own experimental data but such methods do not work properly when extrapolated to other conditions. In the practical applications, both macro- and micro-scale tubes are used in the CO_2 evaporators and heat exchangers.

As opposed to the completely empirical two-phase frictional pressure drop methods, a flow pattern based phenomenological frictional pressure drop model relating the flow patterns to the corresponding two-phase frictional pressure drops is a promising approach in the two-phase pressure drop predictions. Ould Didi et al. [17] used local flow patterns to analyse two-phase flow pressure drops, which resulted in a significant improvement in accuracy. Based on that, a new flow pattern based phenomenological model of two-phase frictional pressure drops was developed by Moreno Quibén and Thome [18, 19]. The model physically respects the two-phase flow structure of the various flow patterns while maintaining a degree of simplicity as well. The model predicts their experimental data well but not the CO_2 experimental database which was used in developing the Cheng et al. [7] pressure drop model. Therefore, Cheng et al. [7] developed a phenomenological two phase pressure drop model for CO_2 and it predicts the database reasonably. However, there are many experimental studies on CO_2 two phase pressure drop since Cheng et al. [7] developed their model in 2008. It is essential to evaluate the model with new experimental data and identify the future research and model development needs, which is the main purpose of this study.

2. The Cheng et al. [7] Flow Pattern Based Phenomenological Two Phase Flow Pressure Drop for CO_2 evaporation inside Tubes

The Cheng et al. [7] two-phase frictional pressure drop model for CO_2 was developed by modifying the model of Moreno Quibén and Thome developed for R-22, R-410a and R-134a and incorporating the updated Cheng et al. CO_2 flow pattern map, using the CO_2 pressure drop database by Cheng et al. [7]. In developing this pressure drop model, two-phase frictional pressure drop data were used. The total pressure drop is the sum of the static pressure drop (gravity pressure drop), the momentum pressure drop (acceleration pressure drop) and the frictional pressure drop:

$$\Delta p_{total} = \Delta p_{static} + \Delta p_m + \Delta p_f \tag{1}$$

For horizontal channels, the static pressure drop equals zero. Furthermore, the momentum pressure drop can be calculated as

$$\Delta p_m = G^2 \left\{ \left[\frac{(1-x)^2}{\rho_L\left(1-\varepsilon\right)} + \frac{x^2}{\rho_V \varepsilon} \right]_{out} - \left[\frac{\left(1-x\right)^2}{\rho_L\left(1-\varepsilon\right)} + \frac{x^2}{\rho_V \varepsilon} \right]_{in} \right\} \tag{2}$$

Thus, diabatic experimental tests that measure total pressure drops can be reduced using the above expressions to find the two-phase frictional pressure drops.

Cheng et al. [7] compiled a large database of CO_2 two-phase frictional pressure drop and compared the database to the leading two-phase frictional pressure drop methods before 2007. The data were taken from tables where available or by digitizing the pressure drops from graphs in these publications. All together 387 two-phase pressure drop data points were obtained. Thus, diabatic experimental tests that measure total pressure drops can be reduced using Eq. (2) to find the two-phase frictional pressure drops. In the Cheng et al. [7] pressure drop model, for non-circular channels, the equivalent diameter D_{eq} is used in the two-phase frictional pressure drop model to remain consistent with that in the flow pattern map. Using the equivalent diameter gives the same mass velocity as in the non-circular channel and thus correctly reflects the mean liquid and vapor velocities, something using hydraulic diameter in a two-phase flow does not. Thus, equivalent diameter D_{eq} is used in their prediction methods for various flow regimes.

A number of prediction methods have been proposed for various flow patterns: for example, CO_2 frictional pressure drop model for annular flow (A): The basic equation of the two phase frictional pressure drop model is as follows:

$$\Delta p_A = 4 f_A \frac{L}{D_{eq}} \frac{\rho_V {u_V}^2}{2} \tag{3}$$

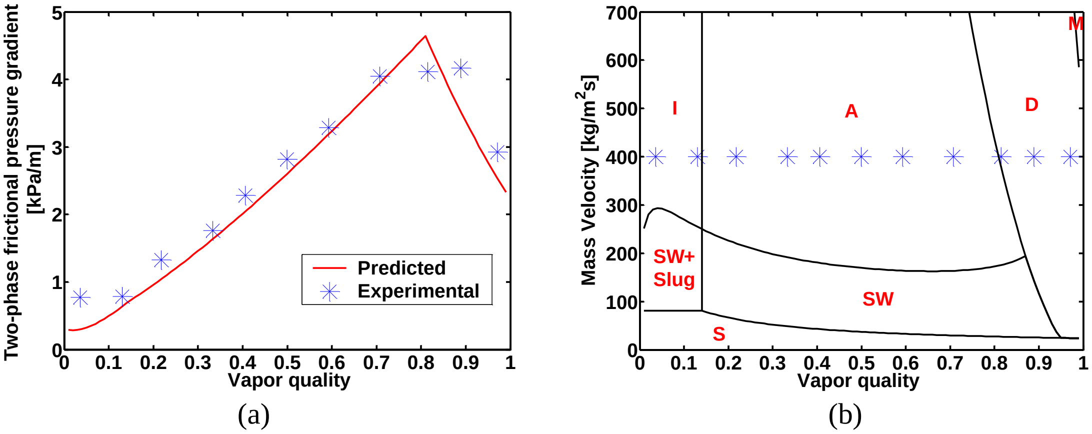
where the two-phase flow friction factor of annular flow f_A was correlated according to CO_2 experimental data here (considering the main parameters which affect the two-phase pressure drops for CO_2) as:

$$f_A = 3.128 {Re_V}^{-0.454} {We_L}^{-0.0308} \tag{4}$$

For the CO_2 frictional pressure drop model for mist flow (M), the friction factor of mist flow f_M was correlated according to the CO_2 experimental data as:

$$f_M = \frac{91.2}{\mathrm{Re}_M^{0.832}} \tag{5}$$

The details of all other prediction methods can be found in their paper [7].



(b)

Fig.1. (a) Comparison of the new CO_2 pressure drop model to the experimental data of Bredesen et al. [22] at the experimental conditions: G = 400 kg/m^{2}s, T_{sat} = -10 °C, D_{eq} = 7 mm and q = 3 kW/m^2; (b) The corresponding flow pattern map at the same experimental condition as that in (a) (I represents intermittent flow, A represents annular flow, D represents dyrout region, M represents mist flow, S represents stratified flow and SW represents stratified-wavy flow).

The Cheng et al. CO_2 two-phase frictional pressure drop model was compared to the CO_2 two-phase pressure drop database [7]. Figure 1 shows the comparison of the Cheng et al. CO_2 frictional pressure drop model to the experimental data of Bredesen et al. [22] at the indicated experimental conditions and the corresponding flow pattern map. The model predicts the data well and also captures the pressure drop trend. In general, the comparative results of the predicted frictional pressure gradients by the new model to the entire database in their study are shown in their paper [7]. Generally, the new pressure drop model reasonably predicts the database and importantly captures the trends in the data too. Nonetheless, there are not many experimental data available covering some flow patterns and future experimental work is recommended to address these conditions.

3. Comparative Results of the Cheng et al. CO_2 Pressure Drop Model to New Experimental Data

In the literature, the Cheng et al. [7] two phase frictional pressure drop model has been used to evaluate the experimental two phase pressure drop data by several researchers. Zhang et al. [26] conducted experimental study of the frictional pressure drop characteristics of flow boiling heat transfer of CO_2 in a horizontal microchannel with an inner diameter 1.5 mm at heat flux of 7.5 - 30 kW/m^2), mass flux of 50 - 600 kg/m2s, saturation temperature of −40 - 0 °C and vapor quality from 0 to 1. They compared their experimental results and the Cheng et al. [7] theoretical flow pattern map. The heat flux has little effect on the frictional pressure drop at high vapor quality which can be found in the paper of Zhang et al. [26] but it has a decisive effect on the dryout and mist flow as shown. Before the dryout, the Cheng et al. model favourably predicts the two phase pressure drop data with 81% in annular flow while it does not capture the data in the dryout and mist flow regimes as in the paper of Zhang et al. [26]. The reason is mainly due to the lack of experimental data in their model development. It should also be noted that a linear relationship is adopted in their model. However, according the available data, the linear correlation does not represent the actual pressure drop trends in these two regions. Therefore, the original method in these two regimes is only applicable the database of Cheng et al. [7]. Therefore, Zhang et al. [26] modified the model in these regimes according to the experimental data and the modified model favorably predicts their data. Wu et al. [24] have also obtained similar conclusion that the Cheng et al. [7] model does not capture their pressure drop data and modified the mist flow pressure drop of Cheng et al. The modified model by Wu et al. [24] has favourably predicted their two phase pressure drop data reported in their paper. Ducoulobier et al. [25] evaluated the Cheng et al pressure drop model with the microchannel pressure drop data and have found that the model gives very big errors. It should be mentioned that new mechanistic prediction methods in these two regimes should be developed according to physical mechanisms and parametric trends in the experimental data.

Table 1 Statistical analysis of the predicted results for the experimental diabatic two phase frictional pressure drop.

Data used for comparison	**Data points**	**Percentage of predicted points within ±30 %**	**Mean error** $\left|\bar{\xi}\right|$	**Standard deviation σ**
All new data points [23-26]	463	40.8%	53.4%	64.2%
All new data points without the dryout and mist flow data [23-26]	287	62.7%	27.3%	34.2%
New dryout and mist flow data points [23-26]	176	4.6%	96.4%	43%
All data points including new data points and in previous data	850	56.2%	45.5 %	66 %
All data points without the dryout and mist flow data	599	68.9%	25.3%	30.1%
All dryout and mist flow data points including previous data	251	25.6%	82.4 %	35.6%

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\xi_i - \bar{\xi}\right)^2}\ ;\ \left|\bar{\xi}\right| = \frac{1}{N}\sum_{i=1}^{N}\left|\xi_i\right|\ ;\ \xi_i = \frac{Predicted - Measured}{Measured}$$

In this study, the Cheng et al. CO_2 two phase pressure drop model has been evaluated with the new experimental data after 2007. A total of 463 new diabatic two phase frictional pressure drop data from [23-26] were digitized and used to compare to the predicted two phase pressure drop by the Cheng et al. [7] two phase pressure drop model.

Table 1 shows the statistical analysis of the predicted two phase pressure drop data by the Cheng et al. [7] model. For all new experimental data, the model predicts 40.8 % of all the new data within ±30%, 62.7% of the data without dryout and mist flow data within ±30% and only 4.6% of the dryout and mist flow data within ±30%. It should be realized that the Cheng et al. model has been extrapolated to its original conditions. In particular, it does not capture the dryout and mist flow data.

Furthermore, the whole data points including all the new data points and previous data used in their model, it predicts 56.2% % of the whole data within ±30%, 68.9% of those without dryout and mist flow data within ±30% and 25.7% of all the dryout and mist flow data within ±30%. Therefore, it is essential to improve the model by using the current experimental data in table 8. It should be mentioned that the Cheng et al. model is diabatic model and adiabatic pressure drop model together with adiabatic flow pattern map should also be developed.

4. Conclusion

According to the comparative results and analysis, the Cheng et al. [7] CO_2 two-phase frictional pressure drop model predicts the CO_2 pressure drop database better than the existing methods in their original study. Due to the limited and less accurate experimental data in micro-scale channels available in the literature, the CO_2 pressure drop model does not predict these data satisfactorily. With the new database, several microchannel experimental studies are included. The test conditions are beyond the applicable ranges of the original model of Cheng et al. The model does not predict the database properly. According to the segmented data before and after dryout regimes, it seems that the model is able to predict the database while it does not predict those in dryout and mist flow regimes. The main reason is that the Cheng et al. flow pattern map does not predict the dryout occurrence and completion properly for the new database. Also, it does not capture the mist flow data due to the same reason. The Cheng model should be improved based on the new database, which will be the research in the next stage. It is also needed to develop adiabatic flow map and corresponding pressure drop model for CO_2 two phase flow as the Cheng et al. flow map and pressure drop model are diabetic. It is also suggested that additional, more accurate experimental CO_2 pressure drop data be obtained through well designed measurement facilities to further test or improve the model under a wide range of test conditions in the future.

References

[1] Bansal, P., A review - status of CO_2 as a low temperature refrigerant: Fundamentals and R&D opportunities. *Appl. Therm. Eng*. 2012, *vol*. 41, 18-29.

[2] Thome, J. R.; Ribatski, G. State-of-the-art of two-phase flow and flow boiling heat transfer and pressure drop of CO_2 in macro- and micro-channels. *Int. J. Refrig*. 2005, *vol*. 28, 1149-1168.

[3] Mastrullo, R., Mauro, A.W., Viscito, L., Flow boiling of carbon dioxide: Heat transfer for smooth and enhanced geometries and effect of oil. state of the art review. *Int. J. Refrig*. 2019, *vol*. 108, 311 – 335.

[4] Cheng, L., Ribatski, G., Thome, J. R. Analysis of supercritical CO_2 cooling in macro- and micro-channels. *In. J. Refrig*. 2008, *vol*. 31, 1301-1316.

[5] Cheng, L., Xia, G., Li, Q. CO_2 Evaporation Process Modeling: Fundamentals and Engineering Applications, *Heat Transfer Eng*. DOI: 10.1080/01457632.2021.190529, 2021, 1-21.

[6] Cheng, L.; Ribatski, G.; Wojtan, L.; Thome, J. R. New flow boiling heat transfer model and flow pattern map for carbon dioxide evaporating inside horizontal tubes. *Int. J. Heat Mass Transfer*. 2006, *vol*. 49, 4082-4094.

[7] Cheng, L.; Ribatski, G.; Moreno Quibén, J.; Thome, J. R. New prediction methods for CO_2 evaporation inside tubes: Part I - A general two-phase flow pattern map and development of a phenomenological model of two-phase flow frictional pressure drop. *Int. J. Heat Mass Transfer*. 2008, *vol*. 51, 111-124.

[8] Cheng, L.; Ribatski, G.; Thome, J. R. New prediction methods for CO_2 evaporation inside tubes: Part II - A general flow boiling heat transfer model based on flow patterns. *Int. J. Heat Mass Transfer*. 2008, *vol*. 51, 125-135.

[9] Cheng, L.; Thome, J. R. Cooling of microprocessors using flow boiling of CO_2 in micro-evaporators: Preliminary analysis and performance comparison. *Appl. Therm. Eng.* 2009, *vol. 29,* 2426-2432.

[10] Cheng, L.; Xia, G.; Thome, J. R. Flow boiling heat transfer and two-phase flow phenomena of co_2 in macro- and micro-channel evaporators: fundamentals, applications and engineering design. *Appl. Therm. Eng*. 2021, article 117070.

[11] Karayiannis, T.G., Mahmooud M.M. Flow boiling in microchannels: Fundamentals and applications, *Appl. Therm. Eng*. 2017, *vol*. 115, 1372-1397.

[12] Cheng, L.; Xia, G. Fundamental issues, mechanisms and models of flow boiling heat transfer in microscale channels, *Int. J. Heat Mass Transfer.* 2017, *vol.* 108 (Part A), 97-127.

[13] Cheng, L. Fundamental issues of critical heat flux phenomena during flow boiling in microscale-channels and nucleate pool boiling in confined spaces. *Heat Transfer Eng.* 2013, *vol.* 34, *issue* 13, 1011-1043.

[14] Kandlikar, S.G., Grande, W.J. Evolution of microchannel flow passages - Thermohydraulic performance and fabrication technology. *Heat Transfer Eng*. 2003, vol. 24 (1), 3-17,

[15] Kandlikar, S. G. Fundamental issues related to flow boiling in minichannels and microchannels. *Exp. Therm. Fluid Sci*. 2002, *vol*. 26, 389-407.

[16] Cheng, L.; Mewes, D. Review of two-phase flow and flow boiling of mixtures in small and mini channels. *Int. J. Multiphase Flow*. 2006, *vol*. 32**,** 183-207.

[17] Ould-Didi, M. B.; Kattan, N.; Thome, J. R. Prediction of two-phase pressure gradients of refrigerants in horizontal tubes. *Int. J. Refrig*. 2002, *vol*. 25, 935-947.

[18] Moreno Quibén, J.; Thome, J. R. Flow pattern based two-phase frictional pressure drop model for horizontal tubes, Part I: diabatic and adiabatic experimental study. *Int. J. Heat Fluid Flow*. 2007, *vol*. 28, 1049-1059.

[19] Moreno Quibén, J.; Thome, J. R. Flow pattern based two-phase frictional pressure drop model for horizontal tubes, Part II: new phenomenological model. *Int. J. Heat Fluid Flow*. 2007, *vol*. 28, 1060-1072.

[20] Moreno Quibén, J.; Cheng, L.; da Silva Lima, R. J.; Thome, J. R. Flow boiling in horizontal flattened tubes: Part I — Two-phase frictional pressure drop results and model, *Int. J. Heat Mass Transfer*. 2009, *vol.* 52, 3634-3644.

[21] Moreno Quibén, J.; Cheng, L.; da Silva Lima, R. J.; Thome, J. R Flow boiling in horizontal flattened tubes: Part II — Flow boiling heat transfer results and model, *Int. J. Heat Mass Transfer*. 2009, *vol.* 52, 3645-3653.

[22] Bredesen, A.; Hafner, A.; Pettersen, J.; Neksa, P.; Aflekt, K. Heat transfer and pressure drop for in-tube evaporation of CO_2. In: *Proceedings of the International Conference on Heat Transfer Issues in Natural Refrigerants*, University of Maryland, USA, 1997, pp. 1-15.

[23] R. Mastrullo , A.W. Mauro, G.P. Vanoli, Carbon dioxide heat transfer coefficients and pressure drops during flow boiling: Assessment of prediction methods, *Int. J. Refrig*. 2010, *vol*. 33, 1068–1085.

[24] Wu, J., Koettig, T., Franke, Ch., Helmer, D., Eisel, T., Haug, F., Bremer, J. Investigation of heat transfer and pressure drop of CO_2 two-phase flow in a horizontal minichannel. *Int. J. Heat Mass Transfer*. 2011,*vol.* 54, Issues 9–10, 154-2162.

[25] Ducoulombier, M., Colasson, S., Bonjour, J., Haberschill, P. Carbon dioxide flow boiling in a single microchannel – Part I: Pressure drop. *Exp. Therm. Fluid Sci*. 2011, *vol.* 35, 581–596.

[26] Zhang, L., Jiang, L., Liu, J., Yuan, Y., Zhang, J. Research on pressure drop characteristics of CO_2 flow boiling based on flow pattern in horizontal minichannel. *Heat Mass Transfer*, 2020, *vol*. 56, 2939–2952.

Nomenclature

D	internal tube diameter, m
f	friction factor
G	total vapor and liquid two-phase mass flux, kg/m^{2}s
L	channel length, m
N	number of data points
p	pressure, pa
Re_M	Reynolds number [$GD_{eq}/(\mu_H)$] defined in mist flow
Re_V	vapor phase Reynolds number [$GxD_{eq}/(\mu_V \varepsilon)$]
u	mean velocity, m/s
We_L	liquid Weber number [$\rho_L u_L^2 D_{eq}/\sigma$]

Greek symbols

Δp	pressure drop, Pa
ε	cross-sectional vapor void fraction
μ	dynamic viscosity, Ns/m^2
ρ	density, kg/m^3
σ	surface tension, N/m; standard deviation, %
ξ_i	relative error, %
$\bar{\xi}$	average error, %

$\left\|\bar{\xi}\right\|$	mean error, %

Subscripts

A	annular flow
$dryout$	dryout region
eq	equivalent
f	frictional
g	gas
in	tube inlet
L	liquid
m	momentum
out	tube outlet
$static$	static
$total$	total
tp	two-phase flow
V	vapor