New prediction methods for CO$_2$ evaporation inside tubes: Part I — A two-phase flow pattern map and a flow pattern based phenomenological model for two-phase flow frictional pressure drops

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Abstract

An updated flow pattern map was developed for CO$_2$ on the basis of the Cheng-Ribatski-Wojtan-Thome CO$_2$ flow pattern map [1] to extend the flow pattern map to a wider range of conditions. A new annular flow to dryout transition (A-D) and a new dryout to mist flow transition (D-M) were proposed. In addition, a bubbly flow region which generally occurs at high mass velocities and low vapor qualities was added to the updated flow pattern map. The updated flow pattern map is applicable to a wider range of conditions: tube diameters from 0.6 to 10 mm, mass velocities from 50 to 1500 kg/m$^2$s, heat fluxes from 1.8 to 46 kW/m$^2$ and saturation temperatures from -28 to +25 °C (reduced pressures from 0.21 to 0.87). The updated flow pattern map was compared to independent experimental data of flow patterns for CO$_2$ in the literature and it predicts the flow patterns well. Then, a database of CO$_2$ two-phase flow pressure drop was set up and the database was compared to the leading empirical pressure drop models: the correlations by Chisholm [2], Friedel [3], Grönnerud [4] and Müller-Steinhagen and Heck [5], a modified Chisholm correlation by Yoon et al. [6] and the flow pattern based model of Moreno Quiben and Thome [7-9]. None of these models was able to predict the CO$_2$ pressure drop data well. Therefore, a new flow pattern based phenomenological model of two-phase flow frictional pressure drop for CO$_2$ was developed by modifying the model of Moreno Quiben and Thome and incorporating the updated flow pattern map in this study. The new CO$_2$ two-phase flow pressure drop model predicts the CO$_2$ pressure drop database much better than the other methods.

Keywords: Model; Flow pattern map; Flow patterns; Phenomenological; Flow boiling; Frictional pressure drop; Macro-channel; Micro-channel; CO$_2$

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1. Introduction

Carbon dioxide 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 in recent years. Compared to other conventional refrigerants, the two-phase flow characteristics of CO$_2$, such as flow pattern, two-phase pressure drop and flow boiling heat transfer, are quite different from those of conventional refrigerants [1, 10]. In order to design evaporators for these systems effectively, it is important to understand and predict the two-phase flow characteristics of CO$_2$ evaporation inside horizontal tubes. In the present study, a two-phase flow pattern map specifically for CO$_2$ and a flow pattern based, phenomenological two-phase flow frictional pressure drop model are presented in Part I, and an updated flow pattern based flow boiling heat transfer model is presented in Part II.

Flow patterns are very important in understanding the very complex two-phase flow phenomena and heat transfer trends in flow boiling. To predict the local flow patterns in a channel, a flow pattern map is used. In fact, successful flow pattern based flow boiling heat transfer and two-phase flow pressure drop models [7-9, 11-13] have been proposed in recent years. Over the past decades, many flow pattern maps have been developed to predict two-phase flow patterns in horizontal tubes, such as those by Baker [14], Taitel and Dukler [15], Hashizume [16], Steiner [17] and so on, just to name a few. Most were developed for adiabatic conditions and then extrapolated by users to diabatic conditions, thereby creating big discrepancies. For this reason, a number of diabatic flow pattern maps related to the corresponding heat transfer mechanisms have been developed [11-13, 18, 19]. However, none of these is applicable to CO$_2$ evaporation in horizontal tubes because the two-phase flow characteristics of CO$_2$ evaporation are greatly affected by the very high pressures and low surface tensions of CO$_2$ [1, 10].

To fill in this void, a new CO$_2$ flow pattern map (the Cheng-Ribatski-Wojtan-Thome CO$_2$ flow pattern map) was recently developed in the Laboratory of Heat and Mass Transfer (LTCM) at Swiss Federal Institute of Technology (EPFL) [1]. This flow pattern map is applicable to a wide range of test conditions for CO$_2$: tube diameters from 0.8 to 10 mm, mass velocities from 170 to 570 kg/m$^2$s, heat fluxes from 5 to 32 kW/m$^2$ and saturation temperatures from -28 to +25 °C (reduced pressures from 0.21 to 0.87). However, this flow pattern map is not validated for the large mass velocities of industrial interest, which can reach 1500 kg/m$^2$s in automobile air-conditioning systems. Therefore, a CO$_2$ flow pattern map covering a wider range of parametric conditions is needed to accurately predict the flow patterns for CO$_2$ evaporation and pressure drops in horizontal tubes.

As the predictions of two-phase flow frictional pressure drops with the leading methods often cause errors of more than 50% [7-9, 20], efforts are increasingly being made to improve the accuracy of two-phase flow pressure drop predictions. In addition, the leading pressure drop prediction methods do not usually contain any flow pattern information, which are intrinsically related to the two-phase frictional pressure drop. As for CO$_2$, the leading prediction 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 tensions characteristic of CO$_2$ at high pressures. Due to these characteristics, normally the two-phase flow pressure drops of CO$_2$ are much lower than those of other refrigerants [1, 10]. Significantly there is no proven, generally applicable two-phase pressure drop prediction method for CO$_2$, although there are a number of studies of CO$_2$ pressure drops in the literature [6, 21-35]. Some researchers have proposed pressure drop correlations for CO$_2$ based on their own experimental data but such methods cannot be extrapolated to other conditions. For example, Yoon et al. [6] proposed a modified Chisholm method to fit their data in a macro-scale channel but it cannot be applied to other conditions.
As opposed to the completely empirical two-phase pressure drop models, a flow pattern based phenomenological model relating the flow patterns to the corresponding two-phase flow pressure drops is a promising method in the two-phase pressure drop predictions. Ould Didi et al. [20] used local flow patterns to analyze 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 recently developed by Moreno Quiben and Thome [7-9]. 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 needs to be modified to predict the present CO$_2$ experimental database put together here.

In part I of the present study, first, an updated general flow pattern map for CO$_2$, was developed to meet wider parametric conditions. The updated flow pattern map was compared to the recent flow pattern observations by Gasche [36]. Then, a large database of CO$_2$ two-phase flow pressure drop was set up and compared to the leading two-phase frictional pressure drop models: the correlations by Chisholm [2], Friedel [3], Grönnerud [4], Müller-Steinhagen and Heck [5], a modified Chisholm correlation by Yoon et al. [6] and the flow pattern based model of Moreno Quiben and Thome [7-9]. Finally, based on the updated CO$_2$ flow pattern map, an improved flow pattern based phenomenological model of two-phase flow frictional pressure drop was developed for CO$_2$, which is physically related to the flow patterns defined by the updated CO$_2$ flow pattern map.

2. Updated CO$_2$ flow pattern map

First, an updated CO$_2$ flow pattern map was developed based on the Cheng-Ribatski-Wojtan-Thome CO$_2$ flow pattern map [1] according to new CO$_2$ observations of [36] and sharp changes of trends in flow boiling data that indicate such things as onset of dryout and onset of mist flow. In the present study, the physical properties of CO$_2$ have been obtained from REFPROP of NIST [37].

2.1. Updated flow pattern map for CO$_2$

For non-circular channels, equivalent diameters rather than hydraulic diameters were used in the flow pattern map, as

$$D_{eq} = \frac{4A}{\pi}$$  \hspace{1cm} (1)

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. In the updated CO$_2$ flow pattern map, several new features were developed as compared to the Cheng-Ribatski-Wojtan-Thome flow pattern map [1]:

1. combining with the updated flow boiling heat transfer model for CO$_2$ in Part II, the annular flow to dryout region (A-D) transition boundary was further modified so as to better fit the flow boiling heat transfer characteristics for higher mass velocities;
2. based on experimental heat transfer data, a new criterion for the dryout region to mist flow (D-M) transition was proposed;
3. a bubbly flow occurs at very high mass velocities and very low vapor qualities, bubbly flow pattern boundary was integrated into the map to make it more complete.
With these modifications, the updated flow pattern map for CO\textsubscript{2} is now applicable to much higher mass velocities. Complete flow pattern transition criteria of the updated flow pattern map for CO\textsubscript{2} are described below.

As shown in Fig. 1, the six dimensionless geometrical parameters used in the flow pattern map are defined as [11-13]:

\[ h_{LD} = \frac{h_L}{D} \]  
\[ P_{LD} = \frac{P_L}{D} \]  
\[ P_{TD} = \frac{P_V}{D} \]  
\[ P_{PD} = \frac{P}{D} \]  
\[ A_{LD} = \frac{A_L}{D^2} \]  
\[ A_{TD} = \frac{A_V}{D^2} \]  

where \( D \) is the internal tube diameter, \( P_L \) is the wetted perimeter, \( P_V \) is the dry perimeter in contact with vapor, \( A_L \) and \( A_V \) are the corresponding cross-sectional areas of the liquid and vapor phases, \( P_i \) is the length of the phase interface and \( h_L \) is the height of the liquid phase from the bottom of the tube.

As a practical option and for consistency between the flow pattern map and the flow boiling heat transfer model, an easier to implement version of the flow map was proposed by Thome and El Hajal [38]. The void fraction \( \varepsilon \) is determined with the Rouhani-Axelsson drift flux model [39]:

\[
\varepsilon = \frac{x}{\rho_L} \left[ (1 + 0.12(1-x)) \left( \frac{x}{\rho_L} + \frac{1-x}{\rho_V} \right) \right] \frac{1.18(1-x)}{G \rho_L^{1/2}} \]  

Then, the dimensionless parameters are determined as follows:

\[ A_{LD} = \frac{A(1-\varepsilon)}{D^2} \]  
\[ A_{TD} = \frac{A\varepsilon}{D^2} \]  
\[ h_{LD} = 0.5 \left( 1 - \cos \left( \frac{2\pi - \theta_{out}}{2} \right) \right) \]  
\[ P_{PD} = \sin \left( \frac{2\pi - \theta_{out}}{2} \right) \]

where the stratified angle \( \theta_{out} \) (as shown in Fig. 2) is calculated with the equation proposed by Biberg [40]:

\[
\theta_{out} = 2\pi - 2 \left[ \frac{\pi (1-\varepsilon)}{2} + \left( \frac{3\pi}{2} \right)^{1/3} \left[ 1 - 2(1-\varepsilon) + (1-\varepsilon)^{1/3} - \varepsilon^{1/3} \right] \right] - \frac{1}{200} (1-\varepsilon) \left[ 1 - 2(1-\varepsilon) \right] \left[ 1 + 4(1-\varepsilon)^2 + \varepsilon^2 \right] \]  

Taking into account the modifications in the annular flow to dryout (A-D), dryout to mist flow (D-M) and intermittent flow to bubbly flow (I-B) transition curves, the implementation procedure of the updated flow pattern map for CO\textsubscript{2} is as follows:
The void fraction $\varepsilon$ and dimensionless geometrical parameters $A_{LD}$, $A_{VD}$, $h_{LD}$ and $P_{id}$ are calculated with Eqs. (8) to (12). The stratified-wavy to intermittent and annular flow (SW-I/A) transition boundary is calculated with the Kattan-Thome-Favrat criterion [11-13]:

$$G_{\text{way}} = \left\{ \frac{16A_{id}^3 gD \rho_l \rho_v}{x^2 \pi^2 \left[ 1 - (2h_{id} - 1)^2 \right]^{1/2}} \left[ \frac{\pi^2}{25h_{id}^2} \left( \frac{Fr_L}{We_L} \right) + 1 \right] \right\}^{1/2} + 50$$  (14)

where the liquid Froude number $Fr_L$ and the liquid Weber number $We_L$ are defined as

$$Fr_L = \frac{G^2}{\rho_L^2 gD}$$  (15)

$$We_L = \frac{G^2 D}{\rho \mu}$$  (16)

Then, the stratified-wavy flow region is subdivided into three zones according the criteria by Wojtan et al. [18, 19]:

- $G > G_{\text{way}}(x_{id})$ gives the slug zone;
- $G_{\text{strat}} < G < G_{\text{way}}(x_{id})$ and $x < x_{id}$ give the slug/stratified-wavy zone;
- $x \geq x_{id}$ gives the stratified-wavy zone.

The stratified to stratified-wavy flow (S-SW) transition boundary is calculated with the Kattan-Thome-Favrat criterion [11-13]:

$$G_{\text{strat}} = \frac{226.3^2 A_{id} A_{id}^2 \rho_v \left( \rho_c - \rho_v \right) \mu_c g}{x^2 \left( 1 - x \right) \pi^3}$$  (17)

For the new flow pattern map: $G_{\text{strat}} = G_{\text{strat}}(x_{id})$ at $x < x_{id}$.

The intermittent to annular flow (I-A) transition boundary is calculated with the Cheng-Ribatski-Wojtan-Thome criterion [1]:

$$x_{id} = \left[ 1.8 \frac{0.875}{1.75} \left( \frac{\rho_v}{\rho_l} \right)^{-1/1.75} \left( \frac{\rho_l}{\rho_v} \right)^{-1/7} + 1 \right]^{1/3}$$  (18)

Then, the transition boundary is extended down to its intersection with $G_{\text{strat}}$.

The annular flow to dryout region (A-D) transition boundary is calculated with the new modified criterion in this study:

$$G_{\text{dryut}} = \left\{ \frac{1}{0.236} \ln \left( \frac{0.58}{x} \right) + 0.52 \left( \frac{D}{\rho \sigma} \right)^{0.17} \left[ \frac{1}{gD \rho \left( \rho_c - \rho_v \right)} \right]^{0.17} \left( \frac{\rho_v}{\rho_c} \right)^{0.25} \left( \frac{q}{q_{\text{crit}}} \right)^{0.27} \right\}^{1.471}$$  (19)

which is extracted from the new dryout inception equation in this study:

$$x_d = 0.58 e^{0.52 - 0.25 N_{th}^{-0.17} \left( \rho_c / \rho_v \right)^{0.17} \left( q / q_{\text{crit}} \right)^{0.27}}$$  (20)

where the vapor Weber number $We_v$ and the vapor Froude number $Fr_v$ defined by Mori et al. [41] are calculated as

$$We_v = \frac{G^2 D}{\rho \sigma}$$  (21)

$$Fr_v, \text{Mori} = \frac{G^2}{\rho_v \left( \rho_c - \rho_v \right) gD}$$  (22)

and the critical heat flux $q_{\text{crit}}$ is calculated with the Kutateladze [42] correlation as
\[ q_{\text{crit}} = 0.131 \rho_v^{0.65} h_{\text{tr}} \left[ g \sigma (\rho_L - \rho_v) \right]^{0.25} \]  \hspace{1cm} (23)

The dryout region to mist flow (D-M) transition boundary is calculated with the new criterion developed in this study:

\[ G_M = \left\{ \frac{1}{0.502} \ln \left( \frac{0.61}{x} \right) + 0.57 \left[ \frac{D}{\rho_l \sigma} \right]^{0.16} \left( \frac{1}{gD\rho_l (\rho_L - \rho_v)} \right)^{0.15} \left( \frac{\rho_L}{\rho_v} \right)^{0.09} \left( \frac{q}{q_{\text{crit}}} \right)^{0.72} \right\}^{1.13} \] \hspace{1cm} (24)

which is extracted from the dryout completion equation developed in this study:

\[ x_{\text{crit}} = 0.61 e^{\left( 0.57 - 0.502 \ln \left( \frac{0.61}{x} \right) \right) + 0.57 \left[ \frac{D}{\rho_l \sigma} \right]^{0.16} \left( \frac{1}{gD\rho_l (\rho_L - \rho_v)} \right)^{0.15} \left( \frac{\rho_L}{\rho_v} \right)^{0.09} \left( \frac{q}{q_{\text{crit}}} \right)^{0.72}} \] \hspace{1cm} (25)

The intermittent to bubbly flow (I-B) transition boundary is calculated with the criterion which arises at very high mass velocities and low qualities [11-13]:

\[ G_B = \left\{ \frac{256 A_{\text{eq}} A_{\rho_v}^2 D_{\text{eq}}^{2.5} \rho_l (\rho_L - \rho_v) g}{0.3164 (1 - x)^{0.75} \pi^{0.25} \rho_{l0} \mu_l} \right\}^{1/1.75} \] \hspace{1cm} (26)

If \( G > G_B \) and \( x \leq x_{\text{crit}} \), then the flow is bubbly flow (B).

The following conditions are applied to the transitions in the high vapor quality range:

- If \( G_{\text{strat}}(x) \geq G_{\text{dryout}}(x) \), then \( G_{\text{dryout}}(x) = G_{\text{strat}}(x) \)
- If \( G_{\text{wavy}}(x) \geq G_{\text{dryout}}(x) \), then \( G_{\text{dryout}}(x) = G_{\text{wavy}}(x) \)
- If \( G_{\text{dryout}}(x) \geq G_{M}(x) \), then \( G_{\text{dryout}}(x) = G_{M}(x) \)

### 2.2 Comparison of the new flow pattern map for CO₂ to experimental data

Gashe [36] recently conducted an experimental study of CO₂ evaporation inside a 0.8 mm hydraulic diameter channel for various mass velocities and observed flow patterns by flow visualization as well. The updated CO₂ flow pattern map was compared to his observations. It should be mentioned here that different names for the same flow patterns are used by different authors. Gasche in particular used the definition of plug flow, which is an intermittent flow in our flow pattern map. The updated CO₂ flow pattern map predicts the observed flow patterns by Gasche very well. Just to show one example, Fig. 3 shows the observed flow patterns of CO₂ by Gasche for \( D_{\text{eq}} = 0.833 \text{ mm} \) (equivalent diameter is used here for the rectangle channel). Fig. 4 shows the observations in Fig. 3 compared to the updated flow pattern map (in the flow pattern map, A is annular flow, D is dryout region, I is intermittent flow, M is mist flow, S is stratified flow and SW is stratified-wavy flow. The stratified to stratified-wavy flow transition is designated as S-SW, the stratified-wavy to intermittent/annular flow transition is designated as SW-I/A, the intermittent to annular flow transition is designated as I-A and so on.). It should be mentioned that the observed slug/annular flow of Gashe is counted as an annular flow in the updated flow pattern map. From the photographs in Fig. 3, it seems that the annular flow is the predominant flow in the slug/annular flow defined by Gashe. The observations (3) and (4) are near their correct regimes, especially by the typical flow pattern map standards.

### 3. CO₂ two-phase pressure drop database and comparison to prediction methods

#### 3.1. Selection of CO₂ two-phase pressure drop data
Five independent experimental studies (1 study is related to macro-scale channel when $D > 3 \, \text{mm}$ and 4 studies are related to micro-scale channels when $D \leq 3 \, \text{mm}$.) from different laboratories have been selected to form the present database for the two-phase pressure drops of CO$_2$. Such a distinction between macro- and micro-scale by the threshold diameter of 3 mm is adopted due to the lack of a well-established theory as pointed out by Cheng et al. [1] and Thome and Ribatski [10]. The database includes the experimental data of Bredesen et al. [21], Pettersen [25], Pettersen [30], Zhao et al. [26, 27] and Yun and Kim [34, 35]. The details of the test conditions covered by the database are summarized in Table 1. The test channels include single circular channels and multi-channels with circular, triangular and rectangular cross-sections and electrical and fluid heated test sections. 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. Experimental data in some papers were discharged or ignored because: i) the same data were in more than one paper by the same authors; ii) some necessary information of the experimental conditions, viz. saturation temperature, vapor quality or tube length was missing; iii) some data showed extremely strange parametric trends; iv) some data were physically unreasonable; v) the uncertainties of some data were very large; and vi) some data were only presented in correlated form and could not be extracted. Just one example is mentioned here to be concise. The pressure drop data of Wu et al. [23] have been excluded because their experimental data are 2 times larger than those of R134a at the same test conditions, which is the opposite of the normal trend. It must be pointed out here that some authors created confusion because they did not cite if two-phase frictional pressure drops or total two-phase pressure drops (that include the momentum pressure drop in evaporation in a horizontal tube) were being reported, and thus their data cannot be utilized. Consequently, for the reasons noted above, not all the data published are suitable to constitute the present database.

3.2. Comparison of existing two-phase pressure drop models to the database

The empirical two-phase frictional pressure drop methods by Chisholm [2], Friedel [3], Grönnerud [4] and Müller-Steinhagen and Heck [5], a modified Chisholm correlation by Yoon et al. [6] and the flow patterned based pressure drop model by Moreno Quiben and Thome [7-9] were selected for comparison to the two-phase pressure drop database in Table 1. Figures 5 to 10 show the comparative results of these two-phase frictional pressure drop methods to the entire CO$_2$ pressure drop database presented in Table 1. Three criteria were used to analyze the accuracy of the pressure drop prediction methods: the standard deviation, the mean error and the percent of data predicted within $\pm$30%. The statistical analysis of the predicted results is summarized in Table 2. Not one of these models is able to predict the CO$_2$ two-phase frictional pressure drop data well (note that all have been extrapolated beyond their original conditions to make this comparison for CO$_2$). Therefore, it is necessary to develop a new model for CO$_2$.

4. Development of a phenomenological two-phase frictional pressure drop model for CO$_2$

A new two-phase frictional pressure drop model for CO$_2$ was made here by modifying the model of Moreno Quiben and Thome [7-9] developed for R-22, R-410a and R-134a and incorporating the updated CO$_2$ flow pattern map, using the CO$_2$ pressure drop database in Table 1. This is a phenomenological two-phase frictional pressure drop model which is intrinsically related to the flow patterns. Therefore, it is different from the other empirical two-phase pressure drop models tested here. 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:
\[ \Delta p_{\text{total}} = \Delta p_{\text{static}} + \Delta p_{m} + \Delta p_{f} \quad (27) \]

For horizontal channels, the static pressure drop equals zero. The momentum pressure drop is calculated as

\[ \Delta p_{m} = G^2 \left[ \left( \frac{1-x}{1-\varepsilon} \right)^2 + \frac{\varepsilon^2}{1-\varepsilon} \right] - \left[ \left( \frac{1-x}{1-\varepsilon} \right)^2 + \frac{\varepsilon^2}{1-\varepsilon} \right] \quad (28) \]

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

4.1. Updated frictional pressure drop model based on updated CO₂ flow pattern map

Several modifications have been implemented to update the Moreno Quiben-Thome two-phase frictional pressure drop model to work better for CO₂:

1) A new two-phase flow friction factor for annular flow \((A)\) has been proposed according to the vapor phase Reynolds number \(Re_v\) and the liquid phase Weber number \(We_L\). Considering the main parameters affecting the flow features in annular flow and the effect of channel sizes (surface tension becomes predominant in micro-channels for CO₂), it is physically reasonable to use these two dimensionless numbers to correlate the two-phase friction factor in annular flow.

2) A new method for slug and intermittent flow \((\text{Slug+I})\) has been proposed to avoid any jump in the pressure drops between these two flow patterns.

3) A modified two-phase flow friction factor for stratified-wavy flow \((\text{SW})\) has been implemented to best fit the CO₂ experimental data.

4) A new method for slug-stratified wavy \((\text{Slug+SW})\) flow has been proposed to avoid any jump in the pressure drops between these two flow patterns.

5) A new frictional pressure drop method for mist flow \((\text{M})\) has been developed according to the experimental data.

6) Corresponding to the modifications in annular flow \((A)\) and mist flow \((M)\), the frictional pressure drop in the dryout region \((D)\) is automatically modified.

7) A new frictional pressure drop method for stratified flow \((\text{S})\) has been proposed to maintain consistency with the other methods for CO₂.

8) A frictional pressure drop method has been proposed for bubbly flow \((\text{B})\) consistent with the frictional pressure drops in the neighboring regimes.

The details of the updated two-phase flow frictional pressure drop model for CO₂ are as follows (For non-circular channels, the hydraulic diameter \(D_h\) should be used in the pressure drop model):

1) CO₂ frictional pressure drop model for annular flow \((A)\). The basic equation is:

\[ \Delta p_{A} = 4f_A \left( \frac{L}{D_h} \right) \frac{\rho_v u_v^2}{2} \quad (29) \]

where the two-phase flow friction factor of annular flow \(f_A\) and the mean velocity of the vapor phase \(u_v\) are respectively calculated as

\[ f_A = 3.128 \frac{Re_v^{-0.454} \ We_L^{-0.0308}}{2} \quad (30) \]

\[ u_v = \frac{Gx}{\rho_v \varepsilon} \quad (31) \]

The vapor phase Reynolds number \(Re_v\) and the liquid phase Weber number \(We_L\) based on the mean liquid phase velocity \(u_L\) are calculated as...
\[ Re_v = \frac{G_x D}{\mu_v e} \]  
\[ We_v = \frac{\rho_v u_v^2 D}{\sigma} \]  
\[ u_v = \frac{G(1-x)}{\rho_v (1-e)} \]

2) CO\(_2\) frictional pressure drop model for slug and intermittent flow (Slug+I). A proration is proposed as follows:

\[ \Delta P_{\text{SLUG-I}} = \Delta P_{\text{LO}} \left( 1 - \frac{e}{e_{\text{lt}}} \right) + \Delta P_A \left( \frac{e}{e_{\text{lt}}} \right) \]  
where \( \Delta P_A \) is calculated with Eq. (29) and the single phase frictional pressure drop considering the total vapor-liquid two-phase flow as liquid flow \( \Delta P_{LO} \) is calculated as

\[ \Delta P_{LO} = 4 f_{LO} \left( \frac{L}{D} \right) \left( \frac{G^2}{2 \rho_L} \right) \]  
The friction factor is calculated with the Blasius equation as

\[ f_{LO} = \frac{0.079}{Re_{LO}^{0.25}} \]  
\[ Re_{LO} = \frac{GD}{\mu_L} \]  

3) CO\(_2\) frictional pressure drop model for stratified-wavy flow (SW). Its equation is:

\[ \Delta P_{\text{SW}} = 4 f_{SW} \left( \frac{L \rho_v u_v^2}{2D} \right) \]  
where the two-phase friction factor of stratified-wavy flow \( f_{SW} \) is calculated as

\[ f_{SW} = \theta_{\text{dry}}^{0.02} f_v + (1 - \theta_{\text{dry}}^{0.02}) f_A \]  
and the dimensionless dry angle \( \theta_{\text{dry}}^{*} \) is defined as

\[ \theta_{\text{dry}}^{*} = \frac{\theta_{\text{dry}}}{2\pi} \]  
where \( \theta_{\text{dry}} \) is the dry angle. The dry angle \( \theta_{\text{dry}} \) defines the flow structure and the ratio of the tube perimeter in contact with vapor. For the stratified-wavy regime (SW), the following equation is proposed:

\[ \theta_{\text{dry}} = \theta_{\text{swat}} \left( \frac{G_{\text{wavy}} - G}{G_{\text{wavy}} - G_{\text{swat}}} \right)^{0.61} \]  
The single-phase friction factor of the vapor phase \( f_v \) is calculated as

\[ f_v = \frac{0.079}{Re_v^{0.25}} \]  
where the vapor Reynolds number is calculated with Eq. (32).

4) CO\(_2\) frictional pressure drop model for slug-stratified wavy flow (Slug+SW). The following proration is used:

\[ \Delta P_{\text{SLUG-SW}} = \Delta P_{\text{LO}} \left( 1 - \frac{e}{e_{\text{lt}}} \right) + \Delta P_{SW} \left( \frac{e}{e_{\text{lt}}} \right) \]  
where \( \Delta P_{LO} \) and \( \Delta P_{SW} \) are calculated with Eqs. (36) and (39), respectively.
5) \( \text{CO}_2 \) frictional pressure drop model for mist flow (M). The expression used is:

\[
\Delta p_M = 4f_M \left( \frac{L}{D} \right) \left( \frac{G^2}{2 \rho_H} \right)
\]  

(45)

The homogenous density \( \rho_H \) is defined as

\[
\rho_H = \rho_v (1 - \varepsilon_H) + \rho_l \varepsilon_H
\]

(46)

where the homogenous void fraction \( \varepsilon_H \) is calculated as

\[
\varepsilon_H = \left[ 1 + \left( \frac{1-x}{x} \right) \frac{\rho_v}{\rho_l} \right]^{-1} \quad (47)
\]

and the friction factor of mist flow \( f_M \) was correlated according to the experimental data, as

\[
f_M = \frac{91.2}{\text{Re}_M^{0.932}}
\]  

(48)

\[
\text{Re}_M = \frac{GD}{\mu_H}
\]

(49)

where the homogenous dynamic viscosity is calculated as proposed by Ciccitti et al. [43]

\[
\mu_H = \mu_v (1-x) + \mu_l x
\]  

(50)

The constants in Eq. (48) are quite different from those in the Blasius equation. The reason is possibly because there are limited experimental data in mist flow in the database and also perhaps a lower accuracy of these experimental data. Therefore more accurate experimental data are needed in mist flow to further verify this correlation or modify it if necessary in the future.

6) \( \text{CO}_2 \) frictional pressure drop model for dryout region (D). The linear interpolating expression proposed is:

\[
\Delta p_{dryout} = \Delta p_v(x_{di}) - \frac{x-x_{di}}{x_{de} - x_{di}} \left[ \Delta p_v(x_{di}) - \Delta p_M(x_{de}) \right]
\]  

(51)

where \( \Delta p_{dryout} \) is the frictional pressure drop at the dryout inception quality \( x_{di} \) and is calculated with Eq. (29) for annular flow or with Eq. (39) for stratified-wavy flow, and \( \Delta p_M(x_{de}) \) is the frictional pressure drop at the completion quality \( x_{de} \) and is calculated with Eq. (45).

7) \( \text{CO}_2 \) frictional pressure drop model for stratified flow (S). No data fell into this flow regime but for completeness, the method is as follows:

For \( x \geq x_{IA} \):

\[
\Delta p_{strat(x \geq x_{IA})} = 4f_{strat(x \geq x_{IA})} \frac{L \rho_v u^2}{2D}
\]  

(52)

where the mean velocity of the vapor phase \( u_v \) is calculated with Eq. (31) and the two-phase friction factor of stratified flow \( f_{strat(x \geq x_{IA})} \) is calculated as

\[
f_{strat(x \geq x_{IA})} = \theta_{strat}^* f_v + (1 - \theta_{strat}^*) f_A
\]  

(53)

The single-phase friction factor of the vapor phase \( f_v \) and the two-phase friction factor of annular flow \( f_A \) are calculated with Eqs. (43) and (30), respectively, and the dimensionless stratified angle \( \theta_{strat}^* \) is defined as

\[
\theta_{strat}^* = \frac{\theta_{strat}}{2\pi}
\]  

(54)

where the stratified angle \( \theta_{strat} \) is calculated with Eq. (13).

For \( x < x_{IA} \):

For \( x \geq x_{IA} \):
\[ \Delta p_{\text{strat}(x<z_{lo})} = \Delta p_{lo} \left( 1 - \frac{\varepsilon}{\varepsilon_{11}} \right) + \Delta p_{\text{strat}(x>z_{lo})} \left( \frac{\varepsilon}{\varepsilon_{11}} \right) \]  
\hfill (55)

where \( \Delta p_{lo} \) and \( \Delta p_{\text{strat}(x>z_{lo})} \) are calculated with Eqs. (36) and (52), respectively.

8) \( \text{CO}_2 \) frictional pressure drop model for bubbly flow (B). No data are available for this regime but following the same format as the others without creating a jump at the transition, the following expression is used:

\[ \Delta p_{b} = \Delta p_{lo} \left( 1 - \frac{\varepsilon}{\varepsilon_{11}} \right) + \Delta p_{d} \left( \frac{\varepsilon}{\varepsilon_{11}} \right) \]  
\hfill (56)

where \( \Delta p_{lo} \) and \( \Delta p_{d} \) are calculated with Eqs. (36) and (29), respectively.

4.2. Comparisons of the updated pressure drop model to the database

The new updated \( \text{CO}_2 \) two-phase frictional pressure drop model was compared to the \( \text{CO}_2 \) two-phase pressure drop database in Table 1. Fig. 11 (a) show the comparison of the new model to experimental data of Bredesen et al. [21] and Fig. 11 (b) shows the corresponding flow pattern map at the same experimental condition as in Fig. 11 (a). The new model predicts the experimental data very well. Fig. 12 shows the comparative results of the predictions by the new \( \text{CO}_2 \) pressure drop model to the entire two-phase pressure drop database in Table 1. The statistical analysis is summarized in Table 3. The new \( \text{CO}_2 \) two-phase frictional pressure drop model predicts the \( \text{CO}_2 \) pressure drop data better than other existing empirical methods. The detailed breakdown of the statistical analysis for the new pressure drop model is summarized in Table 4. Most of the experimental data points (75.5%) are in annular flow and 75.7% of experimental data in annular flow are predicted within \( \pm 30\% \). However, the predictions in some regions such as S-Slug and SW are not satisfactory. 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 ranges of test parameters. Especially, there are few experimental data for micro-scale channels and these have low accuracies in some flow regimes. Therefore, additional experimental \( \text{CO}_2 \) pressure drop data are needed to further improve the \( \text{CO}_2 \) pressure drop model.

5. Conclusions

An updated flow pattern map was developed for \( \text{CO}_2 \) to extend the previous Cheng-Ribatski-Wojtan-Thome \( \text{CO}_2 \) flow pattern map [1] to a wider range of conditions. The updated map was compared to the new flow pattern observations for \( \text{CO}_2 \) available in the literature and good agreement was obtained. The updated map is applicable to a wider range of conditions: tube diameters from 0.6 to 10 mm, mass velocities from 50 to 1500 kg/m\(^2\)s, heat fluxes from 1.8 to 46 kW/m\(^2\) and saturation temperatures from -28 to +25 °C (reduced pressures from 0.21 to 0.87). Then, a database of \( \text{CO}_2 \) two-phase pressure drop was set up and compared to the leading empirical pressure drop models: the correlations by Chisholm [2], Friedel [3], Grönnerud [4] and Müller-Steinhagen and Heck [5], a modified Chisholm correlation by Yoon et al. [6] and the flow pattern based model of Moreno Quiben and Thome [7-9]. None of these models was able to predict the \( \text{CO}_2 \) pressure drop data well. Therefore, a new flow pattern based phenomenological model of two-phase frictional pressure drop for \( \text{CO}_2 \) was developed. The new \( \text{CO}_2 \) two-phase flow pressure drop model predicts the \( \text{CO}_2 \) pressure drop database better than the existing methods. It is suggested that additional experimental \( \text{CO}_2 \) pressure drop data be obtained to further test the \( \text{CO}_2 \) two-phase frictional pressure drop model in the future.
Acknowledgements

The Laboratory of Heat and Mass Transfer (LTCM) at École Polytechnique Fédérale de Lausanne (EPFL) wishes to thank Valeo Engine Cooling in France for its financial and technical support on this CO\(2\) heat transfer and flow project. The constructive discussion and suggestions with Mr. Lorenzo Consolini of LTCM in the development of the CO\(2\) two-phase frictional pressure drop model are greatly appreciated. The authors wish to thank Prof. Gasche of the Universidade Estadual Paulista (UNESP) in Brazil for providing his experimental flow pattern data and photographs.

Nomenclature

\(A\) cross-sectional area of flow channel, m\(^2\);
\(A_L\) cross-sectional area occupied by liquid-phase, m\(^2\);
\(A_{LD}\) dimensionless cross-sectional area occupied by liquid-phase;\n\(A_V\) cross-sectional area occupied by vapor phase, m\(^2\);
\(A_{VD}\) dimensionless cross-sectional area occupied by vapor phase;\n\(D\) internal tube diameter, m;
\(Fr_L\) liquid Froude number \([G^2/\left(\rho_L^2gD\right)]\);
\(Fr_{V,Mori}\) vapor Froude number \([G^2/\left(\rho_v(\rho_L-\rho_v)gD\right)]\) defined by Mori et al. [41];\n\(f\) friction factor;\n\(G\) total vapor and liquid two-phase mass flux, kg/m\(^2\)s;\n\(g\) gravitational acceleration, 9.81 m/s\(^2\);\n\(h_L\) vertical height of liquid, m;\n\(h_{LD}\) dimensionless vertical height of liquid;\n\(h_{LV}\) latent heat of vaporization, J/kg;\n\(L\) tube length, m;\n\(N\) number of data points;\n\(P_i\) perimeter of interface, m;\n\(P_{ID}\) dimensionless perimeter of interface;\n\(P_L\) perimeter of tube wetted by liquid, m;\n\(P_{LD}\) dimensionless perimeter of tube wetted by liquid;\n\(P_V\) perimeter of tube in contact with vapor, m;\n\(P_{VD}\) dimensionless perimeter of tube in contact with vapor;\n\(p\) pressure, bar;\n\(p_r\) reduced pressure \([p/p_{eva}]\);\n\(q\) heat flux, W/m\(^2\);\n\(Re_{LO}\) Reynolds number considering the total vapor-liquid flow as liquid flow \([GD/\left(\mu_L\right)]\);\n\(Re_M\) Reynolds number \([GD/\left(\mu_0\right)]\) defined in mist flow;\n\(Re_V\) vapor phase Reynolds number \([GxD/\left(\mu_v\sigma\right)]\);\n\(T_{sat}\) saturation temperature, °C;\n\(u\) mean average velocity, m/s;\n\(We_L\) liquid Weber number \([G^2D/\left(\rho_L\sigma\right)]\) defined by Eq. (16); \([\rho_L u_c^2D/\sigma]\) defined by Eq. (33);\n\(We_V\) vapor Weber number \([G^2D/\left(\rho_v\sigma\right)]\).
Greek symbols

\( \Delta p \) pressure drop, Pa
\( \varepsilon \) cross-sectional vapor void fraction
\( \varepsilon_i \) relative error
\( \varepsilon_{IA} \) vapor void fraction at \( x = x_{IA} \)
\( \bar{\varepsilon} \) average error, \%
\( |\bar{\varepsilon}| \) mean error, \%
\( \mu \) dynamic viscosity, Ns/m\(^2\)
\( \theta_{dry} \) dry angle of tube perimeter, rad
\( \theta'_{dry} \) dimensionless dry angle \( [\theta_{dry}/(2\pi)] \)
\( \theta_{strat} \) stratified flow angle of tube perimeter, rad
\( \theta'_{strat} \) dimensionless stratified flow angle \( [\theta_{strat}/(2\pi)] \)
\( \theta_{wet} \) wet angle of the tube perimeter, rad
\( \rho \) density, kg/m\(^3\)
\( \sigma \) surface tension, N/m
\( \sigma \) standard deviation, \%

Subscripts

A annular flow
B bubbly flow
crit critical
de dryout completion
di dryout inception
dry dry
dryout dryout region
eq equivalent
f frictional
H homogeneous
h hydraulic
I intermittent flow
IA intermittent flow to annular flow transition
L liquid
LD liquid in cross section of the tube
LO considering the total vapor-liquid flow as liquid flow
LV liquid-vapor vapor quality
\( M \) mist flow
\( m \) momentum; mean
\( out \) tube outlet
\( Slug \) slug flow
\( SW \) stratified-wavy flow
\( static \) static
\( strat \) stratified flow
\( strat(x \geq x_{IA}) \) stratified flow at \( x \geq x_{IA} \)
\( strat(x < x_{IA}) \) stratified flow at \( x < x_{IA} \)
\( total \) total
\( tp \) two-phase flow
\( V \) vapor
\( VD \) vapor in cross section of the tube
\( wavy \) wavy flow
\( wet \) wet perimeter
\( \delta \) liquid film thickness

References


[37] REFPROP. NIST Refrigerant Properties Database 23, Gaithersburg, MD, 1998, Version 6.01


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Fig. 4. The experimental data of the observed flow patterns in Fig. 3 shown in the updated CO$_2$ flow pattern map where (1), (2), (3) and (4) — plug flow; (5) — slug/annular flow; (6) — annular flow.

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Fig. 12. Comparison of the predicted frictional pressure gradients by the new model to the entire database (74.7% of the data are predicted within ±30%).
Table 1. Database of CO\textsubscript{2} pressure drops in evaporation

<table>
<thead>
<tr>
<th>Data source</th>
<th>Channel configuration and material</th>
<th>Hydraulic diameter (D_h) (mm)</th>
<th>Saturation temperature (T_{sat}) (°C)</th>
<th>Reduced pressure (p_r)</th>
<th>Mass flux (G) (kg/m\textsuperscript{2}s)</th>
<th>Heat flux (q) (kW/m\textsuperscript{2})</th>
<th>Data points</th>
<th>Heating method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bredesen et al. [21]</td>
<td>Single circular tube, stainless steel</td>
<td>7</td>
<td>-25</td>
<td>0.21</td>
<td>200, 300, 400</td>
<td>3, 6, 9</td>
<td>319</td>
<td>Electrical heating</td>
</tr>
<tr>
<td>Pettersen [25]</td>
<td>Multi-channel with 25 circular channels, aluminium</td>
<td>0.8</td>
<td>0</td>
<td>0.47</td>
<td>190, 280, 380,</td>
<td>10</td>
<td>24</td>
<td>Heated by water</td>
</tr>
<tr>
<td>Pettersen [30]</td>
<td>Multi-channel with 25 circular channels, aluminium</td>
<td>0.8</td>
<td>0</td>
<td>0.47</td>
<td>200, 300, 400,</td>
<td>10</td>
<td>20</td>
<td>Heated by water</td>
</tr>
<tr>
<td>Zhao et al. [26, 27]</td>
<td>Multi channel triangle, stainless steel</td>
<td>0.86</td>
<td>10</td>
<td>0.61</td>
<td>300</td>
<td>11</td>
<td>9</td>
<td>Electrical heating</td>
</tr>
<tr>
<td>Yun and Kim [34, 35]</td>
<td>Single circular tube, multi rectangle channels</td>
<td>2.0, 0.98, 1.53 (1.74)\textsuperscript{\textastern}, 1.14 (1.52)\textsuperscript{\textastern}, 1.34 (1.53)\textsuperscript{\textastern}</td>
<td>0, 5, 10</td>
<td>0.47, 0.54, 0.61</td>
<td>200, 300, 400, 1000, 1500, 2000,</td>
<td>15, 20, 15</td>
<td>15</td>
<td>Electrical heating</td>
</tr>
</tbody>
</table>

\* The values in the brackets are equivalent diameters, for circular channels, the equivalent diameters equal the hydraulic diameters.
Table 2. Statistical analysis of the two-phase frictional pressure drop predictions

| Models and data used for comparison | Data points | Percentage of predicted points within ±30 % | Mean error $|\bar{e}|$ | Standard deviation $\sigma$ |
|------------------------------------|------------|---------------------------------------------|----------------|-----------------------------|
| Chisholm model [2] for all data points | 387 | 56.1 % | 48.6 % | 73.8 % |
| Friedel model [3] for all data points | 387 | 71.1 % | 30.9 % | 55.8 % |
| Grönnerud model [4] and all data points | 387 | 30.2 % | 75 % | 113.1 % |
| Müller-Steinhagen and Heck model [5] for all data points | 387 | 55.8 % | 33.3 % | 44.3 % |
| Modified Chisholm by Yoon et al. model [6] for all data points | 387 | 47 % | 34.7 % | 93.7 % |
| Moreno Quiben and Thome model [7-9] for all data points | 387 | 42.4 % | 50.1 % | 90.6 % |

\[
\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (e_i - \bar{e})^2}; \quad |\bar{e}| = \frac{1}{N} \sum_{i=1}^{N} |e_i|; \quad e_i = \frac{\text{Predicted} - \text{Measured}}{\text{Measured}}
\]
Table 3. Statistical analysis of the predicted two-phase frictional pressure drops

<table>
<thead>
<tr>
<th>Models and data used for comparison</th>
<th>Data points</th>
<th>Percentage of predicted points within ±30 %</th>
<th>Mean error $\bar{e}$</th>
<th>Standard deviation $\sigma$</th>
</tr>
</thead>
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<tr>
<td>The new model for all data points</td>
<td>387</td>
<td>74.7 %</td>
<td>28.6%</td>
<td>44.3%</td>
</tr>
<tr>
<td>Friedel model [3] for all data points</td>
<td>387</td>
<td>71.1 %</td>
<td>30.9%</td>
<td>55.8%</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Flow Pattern</th>
<th>Percentage of predicted points within ±30 %</th>
<th>Predicted data points</th>
<th>Total data points</th>
<th>Flow pattern data Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-SLUG</td>
<td>0%</td>
<td>0</td>
<td>2</td>
<td>0.52%</td>
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<tr>
<td>I-SLUG</td>
<td>83.3%</td>
<td>5</td>
<td>6</td>
<td>1.55%</td>
</tr>
<tr>
<td>SW</td>
<td>58.3%</td>
<td>7</td>
<td>12</td>
<td>3.1%</td>
</tr>
<tr>
<td>Annular</td>
<td>75.7%</td>
<td>221</td>
<td>292</td>
<td>75.5%</td>
</tr>
<tr>
<td>Dryout</td>
<td>74.6%</td>
<td>50</td>
<td>67</td>
<td>17.3%</td>
</tr>
<tr>
<td>Mist flow</td>
<td>75%</td>
<td>6</td>
<td>8</td>
<td>2.07%</td>
</tr>
<tr>
<td>Total</td>
<td>74.7%</td>
<td>289</td>
<td>387</td>
<td>100%</td>
</tr>
</tbody>
</table>
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