26th International Congress of Mechanical Engineering
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1264
A SISTEMATIC REVIEW ON TWO-PHASE FLOW THERMOHYDRAULIC MODELS TO CONVECTIVE BOILING
26th COBEM

Gabriel Pereira da Silva Morais
Arthur Kleyton Azevedo de Araújo
Thaís Pirez Alves Ferreira
Universidade Federal de Santa Catarina, Lepten – Boiling
gabriel.pereira.silva@grad.ufsc.br
arthur.kleyton@lepten.ufsc.br
thais.pirez@posgrad.ufsc.br

Júlio César Passos
Universidade Federal de Santa Catarina, Lepten – Boiling, Bloco A3, 2th floor
julio.passos@lepten.ufsc.br

Abstract. *Two-phase flow is present in a wide range of industrial applications, such as solar power, nuclear energy, refrigeration, oil transport pipeline and raw gas transmission. The modelling of such conditions is pivotal to optimal design and operation of two-phase systems. The basic models (homogeneous and separated flow) disagree when the flow pattern is complex, such as annular flow. Thus, the main purpose of this review analysis is to compare experimental results from the open literature to those predicted by models and the pattern-based one, to understand whenever each model should be used and its limitations. The models were implemented in Python and can predict both pressure drop gradient and total pressure loss within the duct length.*

Keywords: *two-phase flow, convective boiling, homogeneous model, separated flow model, two-phase flow boiling*

1. INTRODUCTION

T. Maitra et al. (2017) well detailed the processes with phase changes. The authors explained that a large amount of heat is transported as latent heat, which considerably strengthen the heat transfer, especially in comparison with single-phase processes. They also highlight some of the main applications in which two-phase flow is used, due to its singular performance, such as: thermal generation of electricity, desalination, different metallurgical processes, electronics cooling, food processing, among others.

However, as stated by Wang et al. (2021), even though two phase flow is a significant phenomenon, “the current understanding of the two-phase flow characteristics and the two-phase flow model prediction capability are still very limited.”

Two-phase flow in regimes of vapor-liquid is highly observed in practical situations, such as refrigeration systems, air conditioning systems, chemical processing plants, thermal energy plants, nuclear fusion reactors cooling and fuel cells (Cioncolini and Thome, 2016).

Therefore, its study is of high importance since accurate modeling for projects guarantee reliability, safety, good performance and lower cost of production. Researchers have been developing research and experimental tests in the last 80 years, to improve models of pressure drop for two-phase flow in both horizontal and vertical flows, derived from fundamentals models known as homogeneous and separated flow (Shannak, 2008).

This critical review compares available models for two-phase flow of vapor-liquid, derived from basic models such as homogeneous, separated flow and others; focusing, in particular, over the annular flow.

2. METHODS

In this section it will be presented the tools implemented, listing of the programming language and the packages used to get the fluid properties, data management, and visualization. Then, the method of comparison and its limitations are presented. Finally, the models used for this research are discussed, and their assumptions are highlighted.

The models were implemented in python 3.8, using CoolProp to get the fluid properties, and Numpy, Scipy, Matplotlib, and Pandas packages for data manipulation and visualization. All methods are solved for a 1-D domain, therefore all geometries are discretized over the tube length. The integrals and derivatives were approximated numerically by the trapezoidal rule and the finite differences, respectively.

The pressure drop gradient and the total pressure drop for each vapor quality are compared among the models. Thereafter, it is discussed the assumptions' effect and their implication over the results in depth. To compare them, data from Lima et al. (2008) was used, being the annular quality range chosen. Table 1 lists the inputs for comparison.

Table 1. Data from Lima *et al.* (2008) article.

Properties	**Value**
Fluid	R134a
Mass velocity, G	300 kg/(m^{2}s)
Pressure, P	487 kPa
Tube diameter, D	13.6 mm
Tube length, L	2.12 m
Heat flux, q''	17.6 kW/m^2
Quality, x	0.4 to 0.8
Theta, θ	0 rad

For this study, nine existing models for pressure drop prediction from the literature are compared: four using the homogeneous model, two using the separated flow model, one using an algebraic turbulence model, and one for the frictional term only. Table 2 lists the models used for this research.

Table 2. Models and its reference.

Model	**Reference Model**
MC Adams *et al.*, (1942)	Homogeneous
Dukler *et al.*, (1964)	Homogeneous
Bettie and Walley, (1982)	Homogeneous
Davidson *et al.*, (1943)	Homogeneous
Zivi *et al.*, (1964)	Separated flow
Lockhart and Martinelli, (1949)	Separated flow
Cioncolini and Thome, (2016)	Surface aerodynamic
Quibén and Thome, (2007)	Frictional pressure drop

As known from literature, the interface between phases in two-phase flows is very complex. There is no model that describes these flow types with accuracy, and the fundamental models homogeneous and separated flow, have the worst results when compared with pattern models, as the first two do not have mathematical adjust for the interface changes between different two-phase flow patterns (Hewitt and Hall-Taylor, 1970).

All models are derived from conservation of mass, momentum and energy, however, each one has different assumptions. The homogeneous and the separated flow are the two main models used to predict the two-phase flow pressure drop, and most of the researchers propose different approaches on both. For example: how to calculate the pseudo properties on the homogeneous, and the two-phase multiplier, and void fraction on the separated flow.

The following equation, Eq. 1, represents the homogeneous model mathematically,

$$-\left(\frac{dp}{dz}\right) = \frac{\frac{2f_{lo}G^2}{D\rho_l}\left[1 + x\left(\frac{\rho_{vl}}{\rho_v}\right)\right] + G^2\rho_{vl}\left(\frac{dx}{dz}\right) + \frac{g\ sin\theta\ \rho_l}{\left[1 + x\left(\frac{\rho_{vl}}{\rho_v}\right)\right]}}{1 - G^2 x\left(\frac{d\rho_v^{-1}}{dz}\right)}, \quad (1)$$

where dp/dz is the total pressure drop gradient, f_{lo} is the friction factor for liquid only, G is the mass velocity, D is the tube diameter, ρ_l is the liquid density, ρ_v is the vapor density, ρ_{vl} is the vaporization density, x is the quality, dx/dz is the quality gradient along the tube length, g is the gravitational acceleration, and θ is the pipe inclination.

The homogeneous model, as exposed in the work of Awad and Muszychka (2008), considers that the liquid and vapor phases are moving with the same velocity (which indicates a slip ratio of 1) and also that the two-phase phenomena can be modeled as a single phase one, whose properties are the average of both the liquid and vapor phases. Collier and Thome (1994) also assumed the thermodynamic equilibrium between phases and applied the denominator as 1.

The pseudo properties obtained for the homogeneous model are the density and the dynamic viscosity. The density is acquired by the condition of homogeneous mixture, which is given by,

$$\frac{1}{\bar{\rho}} = \frac{x}{\rho_v} + \frac{1-x}{\rho_l}. \tag{2}$$

The two-phase dynamic viscosity, μ, is given by the following correlations, which is mostly a weighted function of the viscosity of the liquid, μ_l, and vapor, μ_v, both saturated.

Mc. Adams *et al.* (1942) proposed the following equation to calculate the dynamic viscosity,

$$\frac{1}{\underline{\mu}} = \frac{x}{\mu_v} + \frac{(1-x)}{\mu_l}. \tag{3}$$

Dukler *et al.* (1964) suggested the equation:

$$\underline{\mu} = \left(\frac{x\mu_v}{\rho_v} + \frac{(1-x)\mu_l}{\rho_l}\rho_h\right), \tag{4}$$

where ρ_h is the homogeneous density, a property that combines ρ_l and ρ_h.

Beattie and Walley (1982) given definition for dynamic viscosity is:

$$\underline{\mu} = \mu_v\alpha + \mu_l(1-\alpha)(1-2.5\alpha), \tag{5}$$

being α the void fraction.

Davidson *et al.* (1943) equation for dynamic viscosity is:

$$\underline{\mu} = \mu_l(1 + x\frac{\rho_{vl}}{\rho_v}). \tag{6}$$

Second model implemented was Separated Flow Model, seen below in Eq. 7

$$-\left(\frac{dp}{dz}\right) = \frac{\frac{2f_{lo}G^2}{D\rho_l}\phi_{lo}^2 + G^2\frac{dx}{dz}\left\{\left[\frac{2x}{\alpha\rho_v} - \frac{2(1-x)}{\rho_l(1-\alpha)}\right] + \left(\frac{d\alpha}{dx}\right)_P\left[\frac{(1-x)^2}{\rho_l(1-\alpha)^2} - \frac{x^2}{\alpha^2\rho_v}\right]\right\} + g\,sin\theta\,[\alpha\rho_v - (1+\alpha)\rho_l]}{1 - G^2\left\{\frac{x^2}{\alpha} + \left(\frac{d\rho_v{}^{-1}}{dP}\right)_x\left[\frac{(1-x)^2}{\rho_l(1-\alpha)^2} - \frac{x^2}{\alpha^2\rho_v}\right]\right\}}, \tag{7}$$

where ϕ_{lo} is the two-phase multiplier for liquid only.

The separate flow model, also known as two-fluid model, as explained by Ishii and Hibiki (2006), considers each phase individually. The authors details that in this formulation, “the transfer processes of each phase are expressed by their own balance equations; thus, it is anticipated that the model can predict more detailed changes and phase interactions”. Another point highlighted by Ishii and Hibiki (2006) is that this model is relevant because it can also appraise the dynamic and non-equilibrium interaction between the phases, which is achieved by the application of the momentum equations for both phases, two independent velocity fields and two energy equations in its formulation.

This model is built using the following assumptions on every reference: empirical correlations for friction multiplier and void fraction, constant ρ across the channel, constant velocity for each phase but not necessarily equal, thermodynamic equilibrium between phases, use of the denominator as 1 (Collier and Thome, 1994).

Butterworth (1974) identified similarity between five void fraction equations, from different studies. Then suggested a unique equation as function of B_B, n_1, n_2, and n_3 that correlates these three models as,

$$\alpha = \left[1 + B_B\left(\frac{1-x}{x}\right)^{n_1}\left(\frac{\rho_v}{\rho_l}\right)^{n_2}\left(\frac{\mu_l}{\mu_v}\right)^{n_3}\right]^{-1}. \tag{8}$$

Thus, the coefficients B_B, n_1, n_2, and n_3 for the models used in this systematic review are shown in table 3.

Table 3. Butterworth correlation coefficients for each model analyzed.

Model	B_B	n_1	n_2	n_3
Zivi *et al.*, (1964)	1	1	0.67	0
Lockhart and Martinelli, (1949)	0.28	0.64	0.36	0.07
Homogeneous	1	1	1	0

Third model implemented is from the work of Cioncolini and Thome (2016) in pressure drop for annular flow, presented below in Eq. 9:

$$-\left(\frac{df}{dz}\right) = \frac{2f_{TP}\rho_m V_m^2}{D} + G^2\frac{d\rho_m^{-1}}{dz} + \rho_{avg} g sin(\theta), \quad (9)$$

where f_{TP} is the two-phase fanning friction factor, ρ_m is the momentum based density, V_m is the momentum velocity, ρ_{avg} is the average cross-sectional density.

This model has better results for annular flows, since it is considering the aerodynamic interaction between the liquid film and the vapor core (captured by the momentum Weber number) and the asymmetries in the liquid film induced by gravity (captured by the momentum Froude number).The authors plotted, in log scale, the Weber and Froude momentum numbers against the fanning friction factor and found high correlation between them for vertical and horizontal flows.

The last implemented model was flow pattern-based model for horizontal tubes (Quibén and Thome, 2007), for the annular region equation, seen below in Eq. 10:

$$(\Delta p)_{annular} = 4(f_i)_{annular}\left(\frac{L}{D}\right)\frac{\rho_G u_G^2}{2}, \quad (10)$$

being ρ_G the gas density, u_G the gas velocity and f_i the interfacial friction factor.

This model derives from the pattern flow model (Collier and Thome, 1994), its friction factor model was developed under a phenomenological approach, based on interfacial characteristics from two-phase flow, using Wojtan et al. (2005) flow pattern map.

3. RESULTS AND DISCUSSION

This section shows the results for each model separated by the terms of friction, acceleration and gravity pressure gradients and total pressure drop when using data from Table 1 as input. Characteristics of each result is analyzed to highlight its differences and reasoning of occurrence.

Figure 1 shows plots of all 9 friction pressure gradient models, as the order of magnitude from Homogeneous void fraction, Zivi *et al*. (1964) and Lockhart and Martinelli (1949) is lower than other models, it is plotted on a different graph, so its visualization is favored. All the models have a tendency of increasing the pressure drop gradient with quality. This happens due to the vapor acceleration and liquid film slendering for the annular flow.

In Figure 1 it is possible to see that Davidson *et al.* (1943) has the higher friction pressure gradient, since its linear function starts at a higher point and has a bigger angle of inclination, which indicates that the model should not be applied to high quality conditions.

Figure 1. Friction component of pressure gradient for all models, plotted in two graphs to adjust for different order of magnitude.

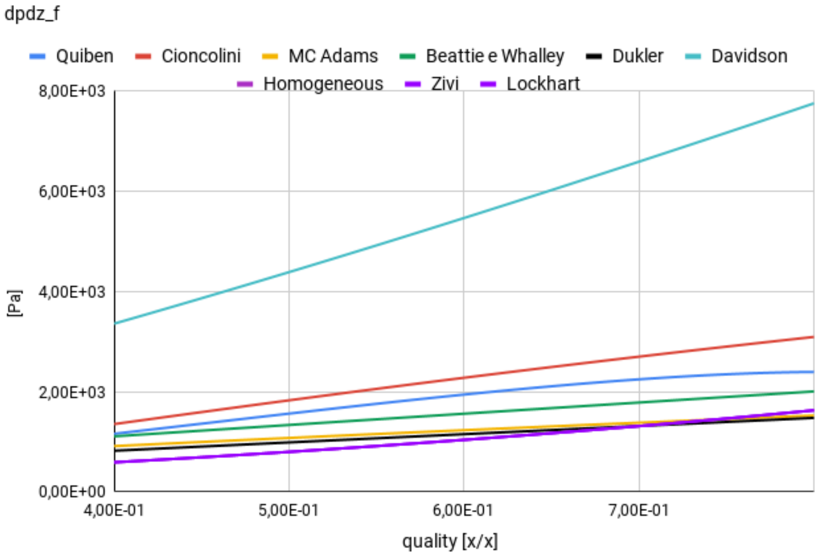

Figure 2 presents results from the acceleration pressure gradient from the eight models that considers this characteristic. As it is seen, models derived from homogeneous have the same results, which happens because the acceleration component is dependent only on the vaporization density, mass velocity and quality gradient along tube length, and none of these variables are dependent from two-phase dynamic viscosity or quality. For the other models the pressure drop gradient increases with vapor quality.

Figure 2. Plots of acceleration component of pressure gradient, except for Quibén (2007) since their model in the studied article stands just for friction pressure loss.

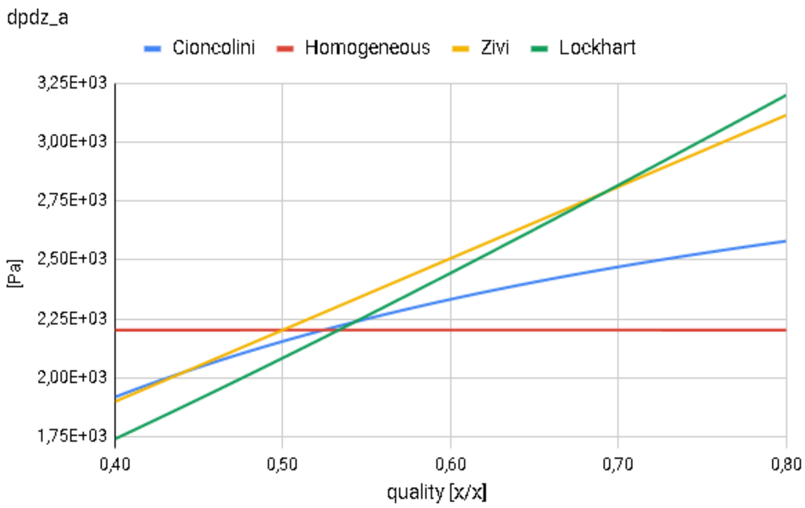

Table 4. Presents the total pressure loss from each model.

Model	**Total pressure loss**
MC Adams *et al.*, (1942)	7.27 kPa
Dukler *et al.*, (1964)	7.11 kPa
Bettie and Walley, (1982)	7.97 kPa
Davidson *et al.*, (1943)	16.3 kPa
Zivi *et al.*, (1964)	7.56 kPa
Lockhart and Martinelli, (1949)	7.44 kPa
Homogeneous alpha	6.91 kPa
Cioncolini and Thome, (2016)	9.68 kPa
Quibén and Thome, (2007)	0.756 kPa

As seen in the section, results can vary from each model in each one of the three components, and the main reason for these differences are how the momentum equilibrium differential equation is manipulated and approximated by each author to obtain a solution that could fit the real data.

Table 4 lists the total pressure drop for each model. The difference between the homogeneous models is derived from the friction term only since the acceleration pressure drop gradients are the same for all of them, this happens because the friction term is dependent from $\underline{\mu}$, that is a result from each researcher's research and different on each model. The Quibén and Thome (2007) model estimates results with just friction losses, so it's lower total pressure loss.

The models from Quibén et al. and Davidson et al. diverge from the mean by 90.4% and 106.6%, respectively. The separated flow models and Cioncolini give closer results with minimum variance between them, with the maximum divergence from the mean being less than 25%. When opposed to the uncertainty of these models on predicting the two-phase pressure drop (~30%) (Cioncolini and Thome, 2017) this difference is satisfactory.

In the next topic conclusions and an overview from the exposed are presented.

4. CONCLUSIONS

This work evaluated the main models used to predict two-phase pressure drop for annular flow. The several models studied have results with standard deviation (STD) of 3.99 kPa, that happens mainly in homogeneous models, where STD is around 4.44 kPa. Sophisticated models have similar results of the simplest ones, indicating possible overfitting of the complex ones.

Specific models for annular flow, as Cioncolini (2016) and Quibén (2007), have more physical characteristics of the situation modeled, so it's results usually are more trustworthy. For example, the separated flow models friction component should be preferred when evaluating annular flow, that is because despite the liquid entrainment in the vapor, their phases are well separated.

The acceleration components of the models are directly proportional to the void fraction and liquid entrainment in vapor phase. Homogeneous models, in turn, don't consider surface slipping between the phases, that is why it's results in Figure 2 are combined, it doesn't depend on the liquid and vapor velocities. And as the same of friction pressure gradient, separated flow models should be preferred for acceleration pressure drop in annular flow, since it considers vapor core acceleration.

In general, models provide similar results for the gradient of pressure drop and total pressure loss for annular flow, but as it is seen homogeneous models are underfitting the situation, since they don't consider the slip between the surface of the flows neither the acceleration of vapor core, so separated models and Quibén (2007) are preferred for annular flow pressure loss estimation.

5. ACKNOWLEDGEMENTS

Gratefully acknowledgements to Agência Nacional de Petróleo, Gás Natural e Biocombustíveis (ANP) which has been financially supporting this project through Programa de Formação de Recursos Humanos (PRH), project number 201706829.

6. REFERENCES

AWAD, M. M.; MUZYCHKA, Y. S. Effective property models for homogeneous two-phase flows. **Experimental Thermal and Fluid Science.** [S.L.], v. 33, n. 1, p. 106-113, 2008.

BEATTIE, D.R.H.; WHALLEY, P.B.. A simple two-phase frictional pressure drop calculation method. **International Journal Of Multiphase Flow**, [S.L.], v. 8, n. 1, p. 83-87, fev. 1982. Elsevier BV. http://dx.doi.org/10.1016/0301-9322(82)90009-x.

BUTTERWORTH, D.. A comparison of some void-fraction relationships for co-current gas-liquid flow. **International Journal Of Multiphase Flow**, [S.L.], v. 1, n. 6, p. 845-850, abr. 1975. Elsevier BV. http://dx.doi.org/10.1016/0301-9322(75)90038-5.

CIONCOLINI, Andrea; THOME, John R.; LOMBARDI, Carlo. Unified macro-to-microscale method to predict two-phase frictional pressure drops of annular flows. **International Journal Of Multiphase Flow**, [S.L.], v. 35, n. 12, p. 1138-1148, dez. 2009. Elsevier BV. http://dx.doi.org/10.1016/j.ijmultiphaseflow.2009.07.005.

CIONCOLINI, Andrea; THOME, John R.. Pressure drop prediction in annular two-phase flow in macroscale tubes and channels. **International Journal Of Multiphase Flow**, [S.L.], v. 89, p. 321-330, mar. 2017. Elsevier BV. http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.11.003.

COLLIER, John G.; THOME, John R.. **Convective Boiling and Condensation**. 3. ed. Midsomer Norton: Oxford University Press, 1994. 596 p.

DAVIDSON, W.F. *et al*. Studies of heat transmission through boiler tubing at pressures from 500 to 3300 pounds. **Transactions Of ASME**, [S.L.], v. 65, p. 553-591, 1943.

DUKLER, A. E.; WICKS, Moye; CLEVELAND, R. G.. Frictional pressure drop in two-phase flow: b. an approach through similarity analysis. **Aiche Journal**, [S.L.], v. 10, n. 1, p. 44-51, jan. 1964. Wiley. http://dx.doi.org/10.1002/aic.690100118.

HEWITT, G. F.; HALL-TAYLOR, N. S.. **Annular Two-Phase Flow**. Oxford: Pergamon Press Ltd., 1970. 310 p.

ISHII, H.; HIBIKI, T. **Thermo-fluid Dynamics of Two-phase Flow**. New York: Springer, 2006. 462 p.

LIMA, Ricardo J. da Silva; QUIBÉN, Jesús Moreno; THOME, John R.. **Flow boiling in horizontal smooth tubes: new heat transfer results for r-134a at three saturation temperatures**. Applied Thermal Engineering, [S.L.], v. 29, n. 7, p. 1289-1298, maio 2009. Elsevier BV. http://dx.doi.org/10.1016/j.applthermaleng.2008.06.021.

LOCKHART, R.W.; MARTINELLI, R.C.. Proposed correlation of data for isothermal two-phase two-component flow in pipes. **Chemical Engineering Progress**, [S.L.], v. 45, p. 39-48, 1949.

MAITRA T., ZHANG S., TIWARI M.K. **Thermal Transport in Micro and Nanoscale Systems**. In: Kulacki F. (eds) Handbook of Thermal Science and Engineering. [S.L.], Springer, Cham. https://doi.org/10.1007/978-3-319-32003-8_1-1, 2017.

MCADAMS, W. H.; WOODS, W. K.; HEROMAN, L. C.. Vaporization inside horizontal tubes - II: Benzene-oil mixture. **Transactions Of Asme**, [S.L.], v. 64, p. 193-200, jan. 1942.

QUIBÉN, Jesús Moreno; THOME, John R.. Flow pattern based two-phase frictional pressure drop model for horizontal tubes, Part II: new phenomenological model. **International Journal Of Heat And Fluid Flow**, [S.L.], v. 28, n. 5, p. 1060-1072, out. 2007. Elsevier BV. http://dx.doi.org/10.1016/j.ijheatfluidflow.2007.01.004.

SHANNAK, Benbella A.. Frictional pressure drop of gas liquid two-phase flow in pipes. **Nuclear Engineering And Design**, [S.L.], v. 238, n. 12, p. 3277-3284, dez. 2008. Elsevier BV. http://dx.doi.org/10.1016/j.nucengdes.2008.08.015.

WANG, Dewei et al. **Investigation of air-water two-phase flow characteristics in a 25.4 mm diameter circular pipe. Progress in Nuclear Energy.** [S.L.], p. 103813, 2021.

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.