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ANALYSIS AND DEVELOPMENT OF A MULTIPHASE FLOW MODEL FOR CHOKE VALVES

Matheus Henrique Pestana de Carvalho
Jorge Luis Baliño
Departamento de Engenharia Mecânica, Escola Politêcnica da Universidade de São Paulo
matheus.pestana.carvalho@usp.br
jlbalino@usp.br

Abstract. *Choke valves are widely used in petroleum production wells with the main goal of controlling the flow rate by maintaining a back pressure upstream the valve. The present work aims to study an additional function of choke valves: flow rate estimation in multiphase flow conditions. To calculate flow rates is necessary to use mathematical models that describe the behavior of the choke valve, knowing the input parameters. There are currently several mathematical models for this purpose, however they are dependent on empirically calculated adjustment factors. The objective of this work is the development of a methodology for estimating the multiphase flow through a choke valve, based on a mathematical model and on the use of information from the characteristic curve of the valve to take into account the deviations of the flow rate from the model in relation to the actual flow rate. The methodology would allow estimating the flow rate knowing only the concentration of the phases, without the need for adjustment parameters of the experimental data. The proposed methodology applied to the experimental data showed a reduction in the mean absolute error, from* 30.1% *to* 19.3%*.*

Keywords: *multiphase flow, choke valves, petroleum production, discharge coefficient, flow coefficient.*

1. INTRODUCTION

Choke valves are designed to create flow restriction at the point where they are installed, which can be either a fixed restriction (positive type) or a variable one (adjustable type). The application of choke valves in oil wells is due to their ability to act as flow control and/or pressure control equipment upstream of the valve, as well as to enable production stabilization from the well.

Additionally, choke valves can be used for estimating the flow rate of oil, water, and gas through mathematical models. However, as highlighted by Buffa (2017), most existing models require adjustment parameters obtained based on experimental data.

The characterization of choke valves is carried out by laboratory surveys of flow coefficient curves. However, these curves are obtained only for single-phase flow of water or air, following a specific procedure standardized by IEC 60534-2-3 norm.

Mathematical analytical models can be used for a diverse range of cases by simply modifying the input parameters, as the equations that describe the physical phenomenon remain identical to the previously studied and simulated equations. On the other hand, in scenarios where CFD (Computational Fluid Dynamics) is applied, the calculation is valid only for that specific case. If there are changes in the parameter conditions or even in the geometric characteristics of the valves, a new study must be conducted.

The present study aims to develop a methodology for estimating multiphase flow rate through choke valves, using the single-phase characterization curves of choke valves to account for deviations between theoretical and actual flow rates. The theoretical model developed by Buffa (2017) is used as a reference, and the model validation is performed using real data obtained from laboratory.

2. Mathematical models

To calculate the flow rate through choke valves, it is necessary to first determine the flow condition in the restriction region. If the flow reaches sonic velocity in the restriction region, it is defined as critical flow, and downstream pressure reductions do not affect the flow rate. In this case, the flow rate is solely determined by the conditions upstream of the valve. On the other hand, subcritical flow is characterized by flow velocity being lower than the sonic velocity, and the flow rate is a function of the pressure differential between the upstream and downstream regions of the valve.

In addition to defining the critical flow point, Buffa (2017) emphasizes in their work the importance of considering slip between phases to reduce systematic errors that underestimate the mass flow rate when using the homogeneous two-phase flow model.

2.1 Multiphase flow model

The model used in this work was developed by Buffa (2017). This model was based on the model by Al-Safran and Kelkar (2009), with the inclusion of the Borda-Carnot flow approach and energy conservation for the downstream section of the restriction. The control volumes employed in the formulation of the theoretical model are illustrated in Figure 1.

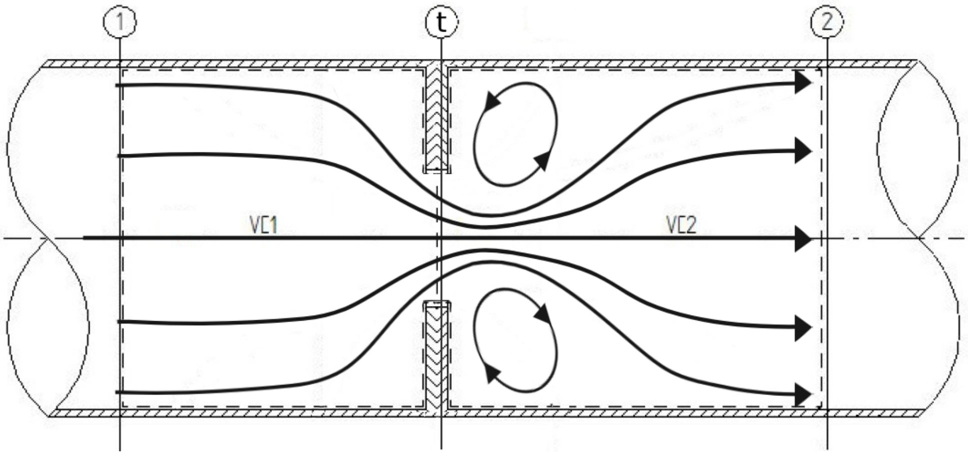

Figure 1. Control Volumes employed in the formulation of the theoretical model.

The mass flux at the restriction (section t), denoted as G_t, is calculated by:

$$G_t = \frac{W_t}{A_t} = \sqrt{\rho_1 \, P_1 \, \Lambda} \tag{1}$$

where ρ_1 and P_1 are the fluid density and the pressure upstream the restriction point, respectively. W_t and A_t are the mass flow rate and the restriction section area, respectively. The nondimensional parameter Λ is defined as:

$$\Lambda = \frac{\frac{2}{x^2}\left[\frac{1-x}{x}\,\omega\, S_{1t}\,(1-y_t) + \frac{n}{n-1}\left(1 - y_t^{\frac{n-1}{n}}\right)\right]}{\left(1 + \frac{1-x}{x\,S_{1t}}\right)\left(y_t^{-\frac{1}{n}} + \frac{1-x}{x}\,\omega\,S_{1t}\right)^2 \left[1 - \beta^4 \left(\frac{1 + \frac{1-x}{x}\,\omega\,S_{1t}}{y_t^{-\frac{1}{n}} + \frac{1-x}{x}\,\omega\,S_{1t}}\right)^2\right]} \tag{2}$$

where x, n and S_{1t} are the mass quality, polytropic exponent and the average slip ratio between the inlet and the restriction point, respectively, y_t is the pressure ratio between the restriction (P_t) and upstream section (P_1) and β is the diameter ratio between the restriction and upstream section respectively. The variable ω is the ration between the density of the gas upstream of the restriction (ρ_{g1}) and density of the liquid (ρ_l):

$$\omega = \frac{\rho_{g1}}{\rho_l} \tag{3}$$

The critical pressure ratio at the restriction, denoted as y_c, is given by:

$$y_c = \left\{ \frac{\frac{1-x}{x}\,\omega\,S_{1c}\,(1-y_c) + \frac{n}{n-1}\left(1 - y_c^{\frac{n-1}{n}}\right)}{\frac{n}{2}\left(1 + \frac{1-x}{x}\,\omega\,S_{1c}\,y_c^{\frac{1}{n}}\right)^2 \left[1 - \beta^4\left(\frac{\frac{1-x}{x}\,\omega\,S_{1c} + 1}{\frac{1-x}{x}\,\omega\,S_{1c} + y_c^{-\frac{1}{n}}}\right)^2\right]} \right\}^{\frac{n}{n-1}} \tag{4}$$

where S_{1c} is the average slip ratio between the inlet and the restriction under critical condition.

In the divergent region (downstream of the restriction), the model considers Borda-Carnot flow, thermal equilibrium between phases, and constant slip. The dimensionless pressure recovery equation is given by:

$$y_2 - y_t = \Lambda\,\sigma^2 \left(\frac{1}{\rho^*_{et}} - \frac{\sigma^2}{\rho^*_{e2}}\right) \tag{5}$$

where y_2 is the pressure ratio between downstream (P_2) and upstream (P_1) sections, σ is the diameter ratio between the restriction and downstream section. The effective densities for the momentum equation ρ_{et} and ρ_{e2} are defined as:

$$\frac{1}{\rho^*_{et}} = \frac{\rho_{g1}}{\rho_{et}} = \left(x + \frac{1-x}{S_t}\right)\left[x\,{y_t}^{-\frac{1}{n}} + (1-x)\,\omega\,S_t\right] \tag{6}$$

$$\frac{1}{\rho^*_{e2}} = \frac{\rho_{g1}}{\rho_{e2}} = \left(x + \frac{1-x}{S_2}\right)\left[x\,\frac{T_2}{T_1}\,{y_2}^{-1} + (1-x)\,\omega\,S_2\right] \tag{7}$$

The temperature is calculated through energy conservation, resulting:

$$C_p\,(T_2 - T_t) + \frac{(1-x)}{\rho_l}\,(P_2 - P_t) = \frac{1}{2}\,G_t^2\left(\frac{1}{\rho^2_{ct}} - \frac{\sigma^4}{\rho^2_{c2}}\right) \tag{8}$$

where T_2, P_2 and T_t are the temperature and pressure downstream the restriction point and temperature at the restriction point, respectively. The variable ρ_{ct} is the effective density of the mixture for the energy equation at the restriction and ρ_{c2} is the effective density of the mixture for the energy equation downstream of the restriction. The specific heat at constant pressure of the mixture, C_p, is defined as:

$$C_p = x\,C_{pg} + (1-x)\,C_l \tag{9}$$

Slip has a significant impact on the model results. Two correlations were used to calculate slip. For critical flow, the approach proposed by Schüller *et al.* (2003) is utilized:

$$S = \left[1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right]^{1/2}\left[1 + 0.6\,\exp\left(-5.0\,x\right)\right] \tag{10}$$

where S, ρ_l and ρ_g are respectively the slip ratio and the liquid and gas density.

For subcritical flow, the approach proposed by Grolmes and Leung (1985) with the constants proposed by Simpson *et al.* (1983) is utilized:

$$S = a_0\left(\frac{1-x}{x}\right)^{a_1-1}\left(\frac{\rho_l}{\rho_g}\right)^{a_2+1}\left(\frac{\mu_l}{\mu_g}\right)^{a_3} \tag{11}$$

where $a_0 = 1$, $a_1 = 1$, $a_2 = -0.83$ and $a_3 = 0$.

2.2 Model for single-phase compressible flow

For the particular case of single-phase gas flow, the multiphase model is simplified with $x = 1$, resulting in:

$$n = \frac{C_{pg}}{C_{vg}} = \gamma. \tag{12}$$

For the compressible single-phase case, it results:

$$G_t = \frac{W_t}{A_t} = \sqrt{\rho_1\,P_1\,\Lambda_g} \tag{13}$$

where Λ_g is obtained by simplifying Eq. (2) for compressible single-phase flow ($x = 1$):

$$\Lambda_g = \frac{\frac{2\,\gamma}{\gamma - 1}\left(1 - y_t^{\frac{\gamma-1}{\gamma}}\right)}{y_t^{-\frac{2}{\gamma}}\left(1 - \beta^4\, y_t^{\frac{2}{\gamma}}\right)} \tag{14}$$

The critical flow at the restriction, critical pressure ratio, and critical temperature are, respectively:

$$G_c = \frac{W_c}{A_t} = \left(\frac{\gamma\, P_1^2}{R_g\, T_1}\, y_c^{\frac{\gamma+1}{\gamma}}\right)^{\frac{1}{2}} \tag{15}$$

$$y_c = \left[\frac{\frac{2}{\gamma - 1}\left(1 - y_c^{\frac{\gamma-1}{\gamma}}\right)}{1 - \beta^4\, y_c^{\frac{2}{\gamma}}}\right]^{\frac{\gamma}{\gamma-1}} \tag{16}$$

$$T_c = T_1\, y_c^{\frac{\gamma-1}{\gamma}} \tag{17}$$

Considering the divergent section, simplifying Eq. (8), it results:

$$C_{pg}\left(T_2 - T_t\right) = \frac{1}{2}\, G_t^2\, R_g^2\left(\frac{T_t^2}{P_t^2} - \frac{\sigma^4\, T_2^2}{P_2^2}\right) \tag{18}$$

Simplifying Eqs. (5), (6), and (7) for $x = 1$, it is obtained:

$$y_2 - y_t = \Lambda\, \sigma^2\left[y_t^{-\frac{1}{\gamma}} - \sigma^2\left(\frac{T_2}{T_1}\right) y_2^{-1}\right] \Rightarrow \;\; \frac{T_2}{T_1} = \frac{y_2}{\sigma^2}\left[y_t^{-\frac{1}{\gamma}} - \frac{(y_2 - y_t)}{\Lambda\, \sigma^2}\right] \tag{19}$$

2.3 Flow coefficient

The flow coefficient C is a fundamental coefficient that defines the flow capacity of a control valve; it is a function of the geometry of the choke and its opening position. For turbulent and incompressible single-phase flow conditions, it is calculated as:

$$C = \frac{Q}{N_1}\sqrt{\frac{\frac{\rho_1}{\rho_0}}{\Delta P}} \tag{20}$$

where Q, N_1 and ΔP are the volumetric flow rate, numerical constant and the differential pressure between upstream and downstream sections, respectively. ρ_1 and ρ_0 are the density of the fluid and the density of the water, respectively.

For the case of compressible and turbulent single-phase flow, it is calculated as:

$$C = \frac{W}{N_6 Y \sqrt{\Delta P \rho_1}} \tag{21}$$

where W is the mass flow rate, N_6 is a numerical constant and Y is defined as:

$$Y = 1 - \frac{1}{3}\frac{\Delta P}{\Delta P_c} \tag{22}$$

Historically, the flow coefficient is defined as C_v or K_v, depending on the units used. Numerically, C_v represents the number of US gallons of water per minute (gpm) that flow through the valve with a pressure differential of 1 pound-force per square inch (psi), considering the water temperature within the range of 4 to 38 degrees Celsius. On the other hand, K_v represents the flow rate in cubic meters per hour (m^3/h) of water that flows through the valve with a pressure differential of 1 bar, considering the water temperature between 5 and 40 degrees Celsius (IEC 60534-1).

Eqs. (20) and (21) can result in either C_v or K_v depending on the values of the constants N_1 and N_6 chosen, as established in the standard IEC 60534-2-1.

2.4 Discharge coefficient

In general, discharge coefficients are experimentally determined to calibrate a specific model. These coefficients can be predefined based on the model, as in the cases of Sachdeva *et al.* (1986) and Perkins (1993), or they can be obtained through a correlation of the specific data set.

The discharge coefficient can be defined in terms of volumetric flow rate (typically used for incompressible flows):

$$C_{DQ} = \frac{Q_r}{Q_{th}} \tag{23}$$

where Q_r is the actual volumetric flow rate and Q_{th} is the volumetric flow rate predicted by the mathematical model. In terms of the mass flow rate:

$$C_{DW} = \frac{W_r}{W_{th}} \tag{24}$$

where W_r is the actual mass flow rate and W_{th} is the mass flow rate predicted by the mathematical model.

3. Methodology

3.1 Derivation of discharge coefficient for compressible single-phase flow

The proposed discharge coefficient is obtained by incorporating the theoretical model (Eq. 13) and the equation for compressible fluids presented in the standard (Eq. 21) into discharge coefficient equation (Eq. 24). Isolating the mass flow rate from the theoretical model of single-phase gas flow, Eq. (13), it is obtained:

$$W_{th} = A_t (P_1\, \rho_1\, \Lambda_g)^{\frac{1}{2}} = A_1\, \beta^2 (P_1\, \rho_1\, \Lambda_g)^{\frac{1}{2}} \tag{25}$$

where:

$$\rho_1 = \frac{P_1}{R_g\, T_1} \tag{26}$$

Isolating the flow rate in Eq. (21), it results:

$$W_r = C\, N_6\, Y \sqrt{\Delta P\, \rho_1} \tag{27}$$

Substituting Eq. (25) from the theoretical model of single-phase gas flow and Eq. (27) of the flow coefficient for compressible fluids into Eq. (24), it results:

$$C_{DW} = C\, \frac{N_6}{A_1}\, Y\, \frac{1}{\beta^2} \left(\frac{1 - y_2}{\Lambda_g} \right)^{1/2} \tag{28}$$

For compressible flow, the discharge coefficient deduced in Eq. (28) depends on the flow conditions (through y_2 and Y) as well as the position of the choke, represented by the variables β, A_1, and C.

3.2 Derivation of the discharge coefficient for multiphase flow with compressible gas

For multiphase flow with compressible gas phase, the same methodology for compressible single-phase flow detailed in section 3.1 is utilized. The main difference lies in the calculation of the Y factor and the calculation of the parameter Λ_g', as detailed below.

The equation for the discharge coefficient in compressible single-phase flow (Eq. 28) is rewritten as follows:

$$C_{DW} = C\, \frac{N_6}{A_1}\, Y\, \frac{1}{\beta^2} \left(\frac{1 - y_2}{\Lambda_g'} \right)^{1/2} \tag{29}$$

To calculate the factor Y, given by Eq. (22), it is proposed to use the theoretical model to estimate the critical pressure differential of the mixture. The critical pressure differential is calculated by:

$$\Delta P_c = P_1 \left(1 - y_{2c}\right) \tag{30}$$

The pressure ratio y_{2c} can be calculated using Eq. (5) for the critical point:

$$y_{2c} = y_c + \Lambda_c \, \sigma^2 \left(\frac{1}{\rho^*_{et}} - \frac{\sigma^2}{\rho^*_{e2}} \right) \tag{31}$$

where y_c is given by Eq. (4).

To calculate Λ'_g, a γ_e based on a pseudo-fluid is proposed. Its derivation considers the adiabatic evolution of the mixture in the converging section.

$$P_1 \, \rho_1^{-\gamma_e} = P_t \, \rho_t^{-\gamma_e} \quad \Rightarrow \quad \frac{P_t}{P_1} = \left(\frac{\rho_t}{\rho_1} \right)^{\gamma_e} = \left(\frac{\dfrac{x}{\rho_{g1}} + \dfrac{1-x}{\rho_l}}{\dfrac{x}{\rho_{gt}} + \dfrac{1-x}{\rho_l}} \right)^{\gamma_e} \tag{32}$$

A polytropic evolution is assumed for the gas phase:

$$P_1 \, \rho_{g1}^{-n} = P_t \, \rho_{gt}^{-n} \quad \Rightarrow \quad \frac{P_t}{P_1} = \left(\frac{\rho_{gt}}{\rho_{g1}} \right)^n \tag{33}$$

By combining and nondimensionalizing the above equations, it results:

$$\gamma_e = \frac{\ln y_t}{\ln \left[\dfrac{x + (1-x)\,\omega}{x \, y_t^{-1/n} + (1-x)\,\omega} \right]} \tag{34}$$

$$\Lambda'_g = \left[\frac{2 \, \dfrac{\gamma_e}{\gamma_e - 1} \left(1 - y_t^{\frac{\gamma_e - 1}{\gamma_e}} \right)}{y_t^{-\frac{2}{\gamma_e}} \left(1 - \beta^4 \, y_t^{\frac{2}{\gamma_e}} \right)} \right] \tag{35}$$

For multiphase flow with compressible gas phase, the discharge coefficient depends on the flow conditions (through y_2 and Y), as well as the position of the choke represented by the variables β, A_1, and C, similar to the compressible single-phase case. However, it is also affected by the composition of the phases incorporated in Λ'_g (through x).

4. Results

This section has been divided into two parts. The first part provides details on the laboratory data used for the validation of this study, as well as the calculation of the flow coefficient for the specific valve. The second part evaluates the performance of the proposed discharge coefficient for multiphase flows with compressible gas phase.

4.1 Experimental data and calculation of the discharge coefficient

The methodology was applied to estimate the experimental data published by Schüller *et al.* (2003, 2006). The experiments were conducted using an orifice-type choke with a restriction diameter of $11mm$ for multiphase flows (oil, gas, and water) as well as single-phase gas and water flows.

The experimental data provided by Schüller *et al.* (2003, 2006) include 80 data points obtained through an 11mm diameter orifice. Among these data points, 9 correspond to single-phase water flow and 4 correspond to single-phase gas flow. Based on the data points related to single-phase water flow and Eq. (20), an average discharge coefficient $\overline{C}$ was calculated for this configuration, with a value of 3.58 and a standard deviation of 0.09.

Table 1. Data Schüller *et al.* (2003, 2006) - water.

Test Identifier	P_1 (bar)	T_1 $(°C)$	x_g $(-)$	x_o $(-)$	x_w $(-)$	$P_1 - P_2$ (bar)	W (kg/s)	Q (m/h)	C $(-)$
W-OR-11-01	8.36	49.9	0	0	1	0.85	0.77	2.77	3.475
W·OR-11-02	9.74	50.9	0	0	1	2.27	1.29	4.64	3.563
W·OR-11-03	12.4	50.9	0	0	1	4.88	1.91	6.88	3.598
W-OR-11-04	15.8	50.9	0	0	1	8.42	2.3	8.28	3.298
C2-W-OR-11-251	15.89	43.9	0	0	1	5.98	2.1	7.56	3.574
C2-W-OR-11-252	23.54	47.9	0	0	1	13.08	3.13	11.27	3.601
C2-W-OR-11-253	27.39	53.9	0	0	1	16.58	3.58	12.89	3.659
C2-W-OR-11-254	31.39	58.9	0	0	1	20.23	4	14.40	3.701
C2-W-OR-11-255	35.32	66.9	0	0	1	23.71	4.41	15.88	3.769

Alternatively, the discharge coefficient can be calculated using experimental data from single-phase gas flow by applying Eq. (21). The results are presented in Table 2.

Table 2. Data Schüller *et al.* (2003, 2006) - gas.

Identificador Teste	ΔP (bar)	ρ_{g1} (kg/m)	W (kg/s)	Y $(-)$	C $(-)$
G-OR-11-01	0.850	6.331	0.050	0.923	3.079
G·OR-11-02	2.430	7.497	0.090	0.814	3.416
G-OR-11-03	4.680	9.118	0.130	0.707	3.714
G·OR 11-04	6.580	10.421	0.160	0.667	3.822

The average value obtained is 3.51 with a standard deviation of 0.26. This means that the average value is very close to the value obtained from single-phase water experiments, despite the higher standard deviation. In this case, there are greater sources of uncertainty due to the need for software (PVTSim®) for estimating γ_g and the use of the theoretical model for calculating the critical pressure differential, as there is no available information in the works of Schüller *et al.* (2003, 2006).

To standardize the analysis of the discharge coefficient, the flow coefficient calculated for incompressible water flow, $C = 3.58$, was used since the obtained values had a lower standard deviation.

4.2 Evaluation of the proposed discharge coefficient

Figure 2 shows the actual discharge coefficients of the multifluid flow data compared to the theoretical model proposed in this study, obtained using Eq. (24).

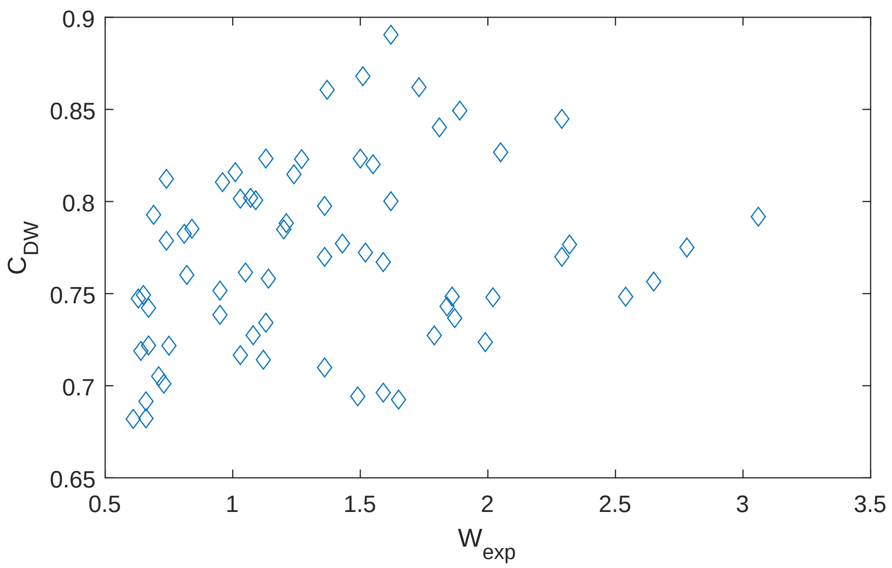

Figure 2. Discharge coefficients calculated from the experimental data and model.

A significant variation in the actual value of the discharge coefficient, C_{DW}, is observed, ranging between 0.65 and 0.9 (Figure 2). There are several proposed values for the discharge coefficient depending on the model used. Sachdeva *et al.* (1986) propose values between 0.75 and 0.85, Perkins (1993) suggests a fixed value of 0.826, while Al-Safran and Kelkar (2009) propose values between 0.7 and 0.75. These models assume a single discharge coefficient value for the entire set of experimental data, which is shown to be incorrect. None of these proposals cover the entire range observed in the experimental data in question. Additionally, except for Perkins (1993) model, experiments are necessary to adjust the models.

Figure 3 presents the ratio between the values calculated using the theoretical model without discharge coefficient applied, with discharge coefficient applied, and by using Eq. (21) with an average fluid density, all divided by the actual mass flow rate. As it can be observed, treating multi phase flows with single phase equations, as utilized in the standard, leads to significant errors as the gas mass ratio in the mixture increases.

The theoretical model provides more accurate results than a homogeneous model for flows with a higher gas content, as observed in Figure 3, where the average absolute error of the theoretical model is 30.1%.

By applying the proposed discharge coefficient, there is a reduction in the average absolute error from 30.1% to 19.3%, indicating a significant improvement in the accuracy of the theoretical model.

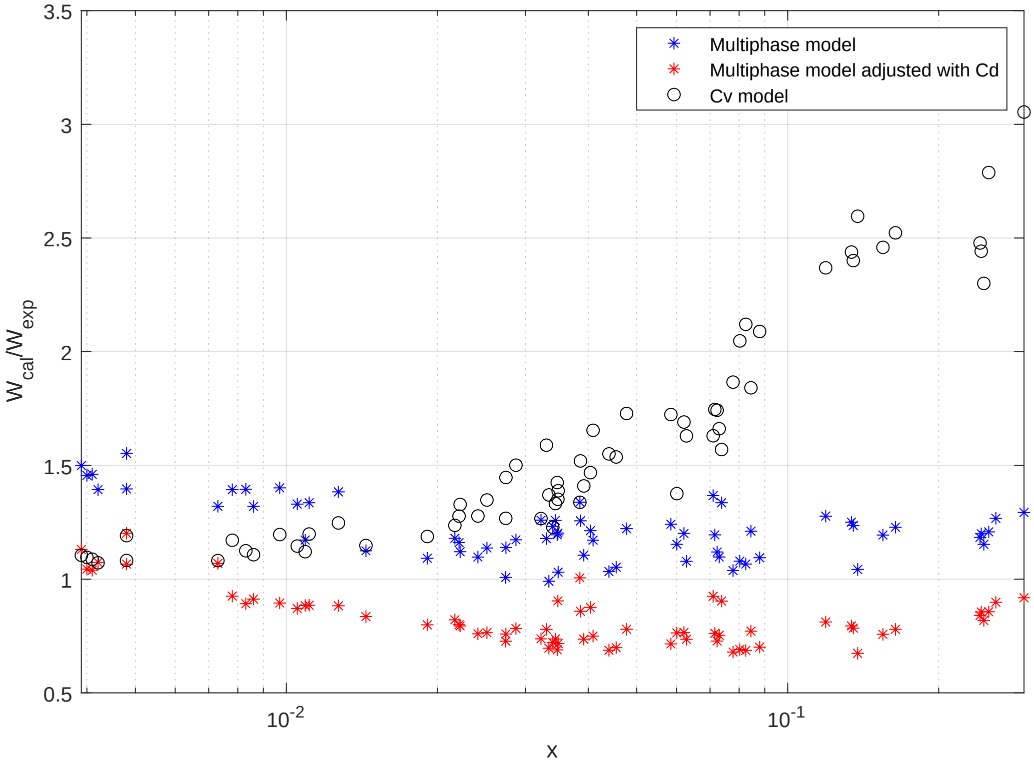

Figure 3. Comparison among the evaluated models.

5. Conclusions

Firstly, it is important to highlight the excellent agreement regarding the calculation of the flow coefficient using compressible and incompressible single-phase flow data. The obtained values for the flow coefficient show minimal difference (2%) when considering all uncertainties in the calculation using compressible flow data.

In multiphase flow scenarios, it is not advisable to use a constant discharge coefficient as it fails to reproduce the observed variations shown in Figure 2. For such cases, it is necessary to consider the different scenarios of concentration, slip, and specific masses of each experimental point. This justifies the effort to expand the methodology to correlate multiphase data.

The application of the proposed methodology to the experimental data showed a significant reduction in the mean absolute error, from 30.1% to 19.3%. It is important to note that the proposed methodology does not require the execution of additional experimental data for model adjustment.

Finally, it is emphasized that the discharge coefficient is calculated based on the flow coefficient provided by choke manufacturers and flow information. The inclusion of flow data in the model is crucial to capture the variations in compressible flow. Without considering the flow variables, the discharge coefficient would result in a constant value for each choke valve position, which is very different from what is observed in Figure 2.

6. ACKNOWLEDGEMENTS

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