RECOMMENDATIONS ON TWO-PHASE CRITICAL NON-FLASHING FLOWS CALCULATIONS IN ONE-DIMENSIONAL SYSTEM CODE RELAP5

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ABSTRACT

Two-phase critical non-flashing flow might occur, e.g. when a system filled with water and non-condensable gas as air or nitrogen, is emergency released. The common practice in Swedish industry is to employ one-dimensional system codes such as RELAP5 to calculate this type of flow. Such codes have in-build two-phase critical flow models which are intended for flashing steam-water mixture. However, non-flashing flows are different in its nature than flashing flows and because of this the default models might provide non-physical results. This paper aims to validate these models against experimental data and provide recommendations on how to predict non-flashing flows with satisfactory accuracy. Validation was performed against experimental data of [1] – [3] with water stagnation pressure conditions varying from 0.1 to 1.56 MPa, temperature subcooling in the range of 84.7 – 195.6 °C, maximum air mass flux of 383.2 kg/(m^2·sec) and discharge section geometry arranged as an open pipe outlet, converging-diverging nozzle and converging nozzle.

KEYWORDS
nuclear safety analysis, two-phase critical flow, non-flashing mixtures

1. INTRODUCTION

Flashing flow may be observed during blowdown event from the pressure vessel, e.g. during vessel emptying procedure where water is discharged into the environment with lower ambient pressure [4]. Non-flashing flow is another type of two-phase flow where phase change between phases does not take place. This type of flow can be established on a basis of water and non-condensable gas, like air and nitrogen. Such non-flashing flow mixture is relatively common in nuclear energy systems. Sources of non-condensable gases in nuclear system pipelines might be of multiple origins. Their presence in the system might be of no accidental occurrence, like air in containment of PWRs (Pressurized Water Reactors) or nitrogen in the containment of BWRs (Boiling Water Reactors). They might also appear as a consequence of an accidental event, e.g. as nitrogen from hydroaccumulators (ECCS, Emergency Core Cooling System, is stored under nitrogen pressure [5]) due to the failure of isolation valve or nitrogen from a damaged fuel pin. In safety analysis of nuclear facilities, this type of flow should be generally considered in calculations of (1) blowdown, in case of LOCA (Loss of Coolant Accident); (2) a pipeline that is intentionally filled with nitrogen or air; (3) a pipeline that is filled with air due to a leaking valve;

and (4) containment pressure relief system which task is to depressurize a containment of BWR reactor containing nitrogen which prevents hydrogen explosion.

Physical behavior and properties of non-condensable gases differ significantly from condensable mixtures in certain circumstances and conditions, which influence computational results. Non-condensable gases deteriorate condensation heat transfer and cause pressure underestimation if partial pressure of non-condensable is neglected. Increase of the volumetric flow rate of the non-condensable gas decreases rapidly the magnitude of critical flow rate [6]. According to [1] even a very small quantity of air reduces the mass flow rate and during the experiments on air/water flows no initial (minimum) value was observed above which the reduction of flow begins. Reference [5] shows that the flow of mixture can be choked if water is not at saturation condition and when concentration of non-condensable gases is as low as 4%. It was also found that an introduction of even a small quantity of air into water causes a strong fluid-dynamics instabilities resulting in increased error in measurements. Taking this issue into consideration certain databases with air-water flows might provide with misleading results which in turn might affect the validation process.

From the computational perspective, using models validated on steam-water experiments for non-flashing flows might result in non-physical results in the estimation of critical mass flow rate. The main objective of the paper is the validation of RELAP5 two-phase critical flow models with two-phase critical non-flashing flow experiments.

2. ASSESSMENT METHODS

In this Section analytical methods to assess non-flashing critical flow presented in references [1], [2], [6], [7] are evaluated.

2.1. Assessment Method Recommended for Open Pipe-Outlet Arrangements [1]

A method proposed by [1] allows to determine critical mass flux with non-condensable gas, G_c, based on the knowledge of single phase flow magnitude and inlet subcooling at certain conditions. The form of that empirical correlation is:

$$G_c = G_{c0} \cdot exp\left[a\Delta T_{sub} - b\left(\frac{Q_a}{Q_{c0}}\right)^{0.5}\right] \qquad (1)$$

with G_{c0} as reference critical mass flux without non-condensable gas (kg m^2 s^{-1}), coefficients a = $3.61 \cdot 10^{-3}$ and b = 1.55, inlet subcooling ΔT_{sub} and Q_a / Q_{c0} as volumetric flow rates of non-condensable gas and water (m^3 s^{-1}). In order to adopt this formula to determine two-phase critical non-flashing flow, the knowledge of critical mass flux without non-condensable gas (G_{c0}) is necessary. Thus, G_{c0} (and in turn Q_{c0}) needs to be either derived, e.g. from experimental data or computed by other equations or correlations. The formula proposed by [1] is fairly accurate and according to the authors, with accompanying set of reference experimental data, RMS Error = 7.26% and gives best results for non-saturated liquids.

2.2. Assessment Method Recommended for Open Pipe-Outlet Arrangements [6]

In reference [6] an empirical correlation is proposed to estimate two-phase critical non-flashing flow by means of reference mass flow rate and inlet subcooling of water for L/D ≥ 10 with L ≥ 40 mm:

$$G_c = G_{c0}(0.378 + 0.600\exp^{-(\frac{Qa}{Qc0})/0.195}) \qquad (2)$$

The method was derived based on the same experimental data as those available in Ref. [1].

2.3. Assessment Method Related to Nozzles, Orifices, Ruptures and Valves [7]

Another approach to determine non-flashing critical two-phase flow was proposed in [7]. The proposed equation for the critical mass flow rate G_c that passes through nozzles, orifices, rupture discs and PRVs (Pressure Relief Valves) is expressed as the product of discharge coefficient C_d and an equation for the ideal critical mass flow rate $G_{c,id}$:

$$G_c = C_d G_{c,id} \tag{3}$$

The formula for the ideal critical mass flow rate $G_{c,id}$ is a form of modified equation for the ideal gas choking mass flow rate where two-phase flow occurs. This formula takes into consideration existence of a new phase by applying choking condition and including correlation for phase slip:

$$G_{c,id} = \frac{A_t p_o}{B_c^{1/2}} (\gamma / Z_o R T_o)^{1/2} \eta_c^{(\gamma+1)/2\gamma} \tag{4}$$

where two-phase parameter B_c evaluated at throat conditions is determined by the equation:

$$\begin{aligned} B_c = {} & x^2(2k_c + 1 - x)/2k_c) + \frac{x(1-x)\{1+(k_c-1)^2\varphi_c\}\left(2k_c^2 - \frac{x v_{Gc}}{v_{Lo}}\right)}{2k_c^3} \\ & + (1-x)(k_c-1)\varphi_c \left\{\frac{x v_{Gc}}{v_{Lo}} + k_c(1-x)\right\}\left\{x - \frac{k_c(k_c-1)\varphi_c^2}{2(1+\varphi_c)}\right\}/k_c^2 \end{aligned} \tag{5}$$

and entrainment parameter at throat conditions φ is described as:

$$\varphi_c = 1/\left\{(v_{Gc}/v_{Lo})^{1/2} - 1\right\} \tag{6}$$

The expression related to discharge coefficient C_d for nozzles is described by the semi-empirical formula:

$$C_d = 0.75 + 0.25 v_{e*} \tag{7}$$

where v_{e*} is effective specific volume ratio defined by the ratio between effective and homogenous specific volumes evaluated at throat (critical) conditions. Effective specific volume ratio is a function of inlet condition parameters of gas and liquid, mass flowrates M_{Go} and M_{Lo} and specific volumes v_{Go} and v_{Lo}, gas heat ratio capacity γ, and diameter ratio between nozzle and orifice β (= d/D):

$$v_{e*} = f(M_{Go}, M_{Lo}, v_{Go}, v_{Lo}, \gamma, \beta) \tag{8}$$

The analytical expression for the discharge coefficient C_d is:

$$C_d = 0.75 + 0.25 \cdot \{x v_G + k(1-x) v_L\} \cdot \left[x + \frac{(1-x)}{k}\left\{1 + \frac{(k-1)^2}{\left(\frac{v_G}{v_L}\right)^{1/2} - 1}\right\}\right] \tag{9}$$

In order to solve the equation for the critical mass flow rate G_c, the expression for certain parameters is necessary. Quality x is:

$$x = \frac{M_G}{M_G + M_L} \tag{10}$$

Specific volumes of gas and liquid, v_G and v_L, are expressed as:

$$v_G = v_{Go} \eta_c^{-1/\gamma} \tag{11}$$

$$v_L = v_{Lo} \tag{12}$$

Two-phase choking pressure ratio η_c is defined as:

$$\eta_c = \eta_{cs}\{1 - exp(-\alpha x^n)\} \tag{13}$$

where single-phase choking pressure ratio η_{cs} (related to single-phase gas choking flow) is:

$$\eta_{cs} = \{2/(\gamma + 1)\}^{\gamma/(\gamma-1)}(1 - \beta^3)^m \tag{14}$$

Coefficients and exponents α, m and n are defined as:

$$\alpha = 5.65\left(\frac{v_{Go}}{v_{Lo}}\right)^{0.013} \gamma^{0.0561}/(1 - \beta^4)^{0.0322} \tag{15}$$

$$m = -0.117\gamma^{0.693} \tag{16}$$

$$n = 0.717\gamma^{0.299}(1 - \beta^4)^{0.116}/\left(\frac{v_{Go}}{v_{Lo}}\right)^{0.151} \tag{17}$$

Slip ratio k (u_G/u_L) is described using the Chisholm correlation:

$$k = \left\{1 + x\left(\frac{v_G}{v_L} - 1\right)\right\}^{1/2} \tag{18}$$

2.4. Assessment Method Related to Converging-Diverging Nozzles [2]

The estimation method for air-water critical flow is proposed in [2] in the form of:

$$M_L = \frac{M_{LS}}{(1 + C_N Y + Y^2)^{0.5}} \tag{19}$$

where M_L is the two-phase flow mass flow rate (kg s^{-1}), M_{LS} is the mass flow rate of liquid in single-phase flow with two-phase pressure drop and normal liquid-phase coefficient of discharge (kg s^{-1}), C_N is the coefficient of discharge and according to [2] is associated with the orifice diameter, so that for nozzles of 15.9 mm and 25.4 mm. The parameter Y is defined as:

$$Y = \left(\frac{x}{1 - x}\right) \cdot \frac{M_{LN}}{M_{VN}} \tag{20}$$

where x is the quality, and M_{LN} and M_{VN} are mass flow rates of liquid and vapor in single-phase with two-phase pressure drop (kg s^{-1}). Here, similar to the method proposed in [1], the flow rates M_{LN} and M_{VN}, as well before mentioned M_{LS}, need to be provided in order to estimate air-water critical non-flashing flow. These data might be taken from literature or evaluated using, e.g. semi-empirical methods. The equations to estimate these parameters are [2]:

$$M_{LN} = 136 \cdot \frac{\pi}{4} \cdot d^2 \cdot (2 \cdot g \cdot \Delta p \cdot \rho_L)^{0.5} \quad (21)$$

$$M_{LS} = C_N \cdot M_{LN} \quad (22)$$

Reference [2] provides also a modified version of the equation to estimate M_L with the expansion coefficients of the vapor phase:

$$M_L = \frac{1.33 \cdot (Y \cdot F)^{0.79}}{M_{LS}} \quad (23)$$

where the expansion of the vapor phase term F, for the different ratios of downstream to upstream absolute pressures is proposed as:

$$F = 1.695 - 0.695 \cdot r, \text{ for } r > 0.7, \quad (24)$$

$$F = 2.097 - 1.27 \cdot r, \text{ for } r \leq 0.7. \quad (25)$$

3. OVERVIEW OF EXPERIMENTAL CONDITIONS

In the analysis the experimental data on critical non-flashing two-phase flow have been employed from references [1], [2] and [3].

Table I. Details on text experiments on air-water flow.

Pressure [MPa]	**Temperature** [° C]	**Quality** [-]	**Max air mass flux** [kg m^{-2} s^{-1}]	**Reference**
0.461 – 1.563	118.87 – 195.58	0 – 0.0295	81.84	[1]
0.131 – 0.711	109.43 – 167.94	0.1985 – 0.4329	120	[2]
0.104 – 0.689	6.67 – 18.33	0 – 0.785	82.87 – 383.15	[3]

The test section of experimental facility described in [1] consists of the vertical pipe with internal diameter of 4.6 mm and length of 1.495 m (length-to-diameter L/D ratio 325). The total numbers of 132 tests were conducted with initial condition parameters:

- Stagnation pressure, p_0: minimum 0.461 MPa, maximum 1.563 MPa.
- Stagnation temperature, T_0: minimum 111.87 °C, maximum 195.58 °C.
- Inlet subcooling ΔT_{sub}: minimum 0.10 °C, maximum 62.59 °C.
- Air mass flux, G_a: up to 81.84 kg/(m^2 s).

The computational model of all experiments consists of boundary conditions and a test section. The boundary conditions were modelled by a time-dependent volume component to model water flow and air mass flow was adjusted to desired value by time-dependent junction component that was connected to the time-dependent volume. Ambient conditions, to which non-condensable-water mixture was discharged, were modeled using time-dependent volume component with standard ambient parameters of 0.1 MPa and 20 °C.

Another series of validation was based on data from [2] experimental study. The test section consists of convergent-divergent nozzle, DeLaval type, which has inlet diameter and throat of 15.9 mm and 25.4 mm, respectively. The total numbers of 39 tests were conducted with initial condition parameters:

- Stagnation pressure, p_0: minimum 0.131 MPa, maximum 0.711 MPa.
- Inlet subcooling ΔT_{sub}: minimum 109.43 °C, maximum 167.94 °C.
- Air mass flux, G_a: up to 120 kg/(m^2 s).

Finally, a validation against an experimental study of [3] has been performed. The experimental set-up consisted of a straight pipe (internal diameter 50.89 mm), converging nozzles (with throat diameter of 15.9 mm, two nozzles with the same diameter of 25.4 mm, and one of 34.9 mm). The total numbers of 422 tests were conducted with initial condition parameters:

- Stagnation pressure, p_0: minimum 0.104 MPa, maximum 0.689 MPa.
- Inlet subcooling ΔT_{sub}: minimum 84.71 °C, maximum 153.69 °C.
- Air mass flux, G_a (max value): 383.15 kg/(m^2•s) (15.9 mm nozzle), 157.70 kg/(m^2•s) (25.4 mm nozzle), 153.82 kg/(m^2•s) (25.4 mm nozzle), and 82.87 kg/(m^2•s) (34.9 mm nozzle).

The test matrix of the experiments [1], [2] and [3] is shown in Fig. 1.

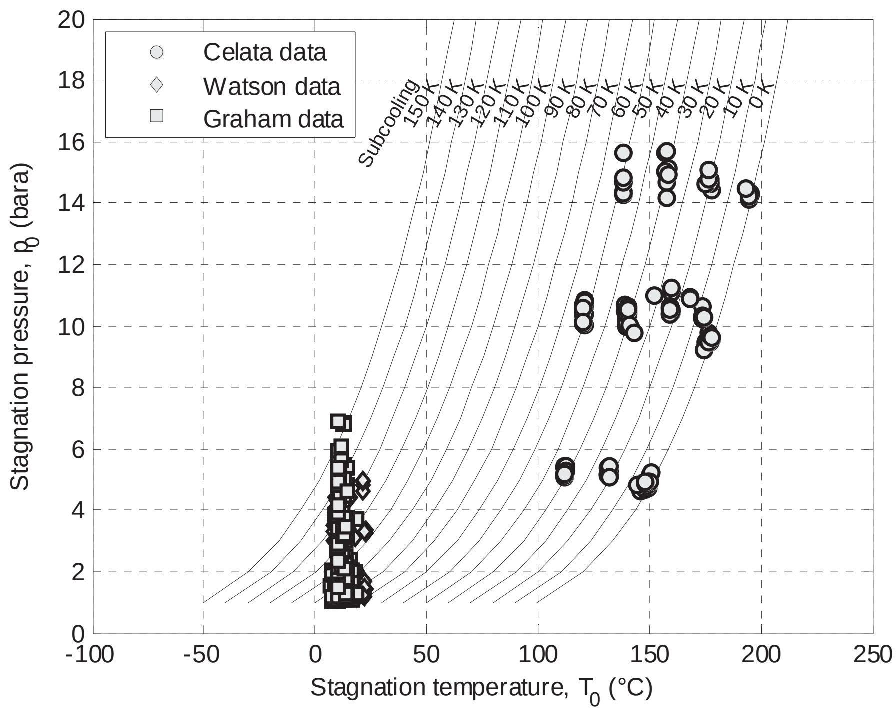


Figure 1. The details of the experiments with information about stagnation temperature T_0, stagnation pressure p_0 and subcooling ΔT_{sub}.

4. RESULTS

Results of formulas and equations presented in Section 3 against experimental data of [1], [2] and [3] are presented in this section.

4.1. Experimental data by Celata [1]

The RELAP5 results of Henry-Fauske (GHF) and its frozen form (GFR) are compared with experimental data [1] in Fig. 2. HEM computational results were affected by strong fluid-dynamics instabilities thus no results are shown. In the range of 6.75 – 62.59 °C predictions of Henry-Fauske and frozen model tend to over-estimate experimental results. For the same pressure ranges and temperature subcooling in the range of 0.10 – 6.12 °C the Henry-Fauske and frozen models tend to under-estimate experimental data.

The performance of assessment methods described in details in Section 2 against this experimental data is depicted in Figs. 3-5. Methods proposed by Celata and Park (Eqs. (1)-(2)) provide reasonable estimation accuracy for this experimental data. No significant difference in accuracy is observed for different stagnation pressure regarding these methods. Methods of Morris and Watson (Eqs. (3) and (19)) compute mass flow rate values that achieve maximum for certain experimental pressure for all considered pressure ranges. Modified Watson (Eq. (19) denoted as *Watson/y* on figures, with liquid single-phase flow M_{LN} estimated by the Darcy equation instead of Eq. (21)) provides over-predicted results for higher stagnation pressure (1.0 – 1.5 MPa) and under-predicted for its low value (0.5 MPa). The Watson method over-predicts results to the greatest extent of all methods.

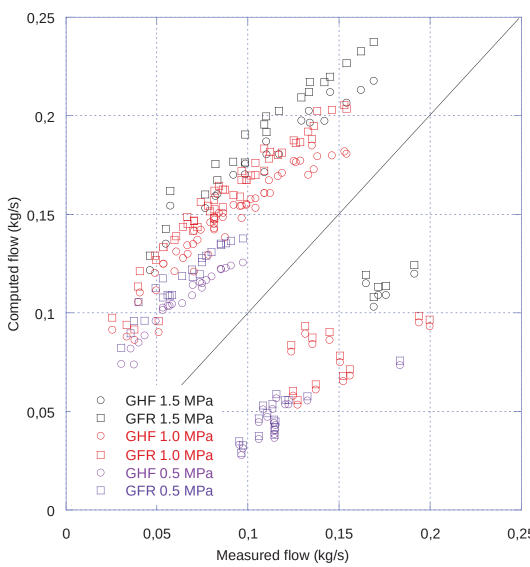


Figure 2. Experimental versus calculated mass flow rate for RELAP5 H-F and “frozen” model.

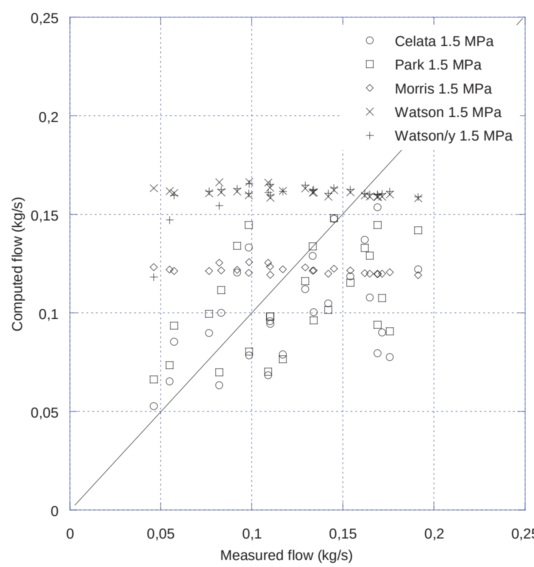


Figure 3. Experimental versus calculated mass flow rate for 1.5 MPa and different assessment methods.

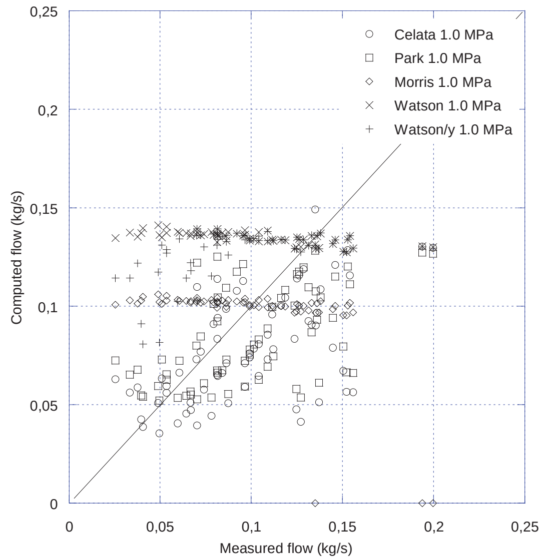


Figure 4. Experimental versus calculated mass flow rate for 1.0 MPa and different assessment methods.

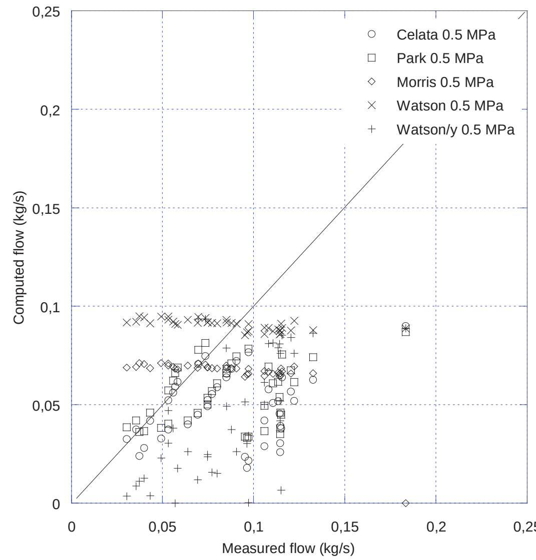


Figure 5. Experimental versus calculated mass flow rate for 0.5 MPa and different assessment methods.

4.2. Experimental data by Watson [2]

The RELAP5 results of Henry-Fauske and its frozen form are compared with experimental data [2] in Fig. 6. The frozen form of Henry-Fauske model over-predicts data, while unmodified form of H-F model under-predicts it. This observation is similar with respect to experimental data of [1]. The performance of assessment methods described in details in Section 2 against this experimental data is depicted in Fig. 7. The Park method is the most accurate of all methods for this experimental data, which tend to slightly under-predict results for higher experimental flows. The Celata method strongly under-estimates for all experimental data whereas methods of Morris, Watson and modified Watson tend to compute over-predicted results. The Morris method over-predicts results to the greatest extent of all methods.

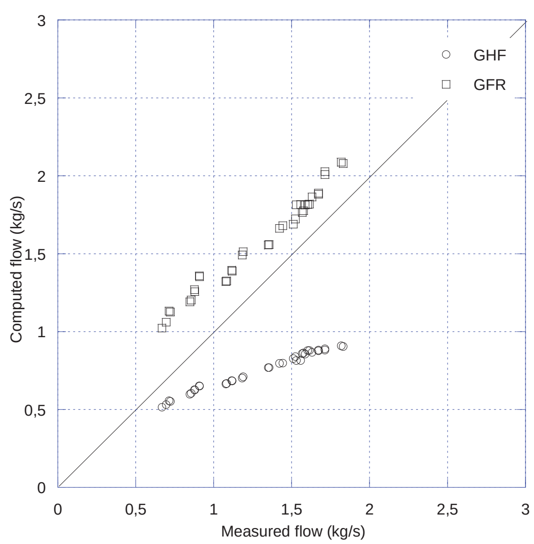


Figure 6. Experimental versus calculated mass flow rate for RELAP5 H-F and "frozen" model.

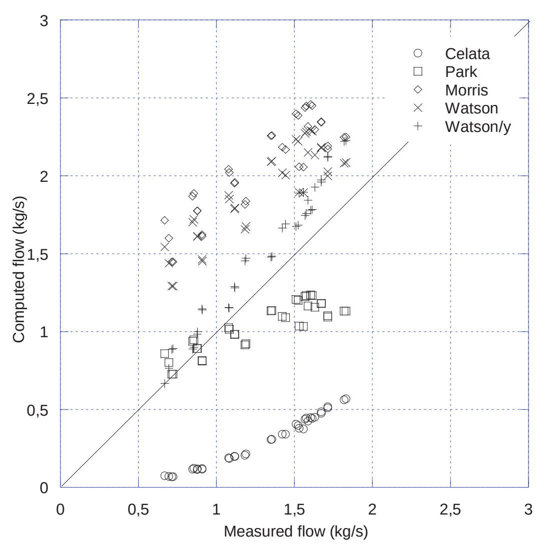


Figure 7. Experimental versus calculated mass flow rate data for the examined nozzle.

4.3. Experimental data by Graham [3]

The experiments by Graham in Ref. [3] consist of different series of tests that correspond to different diverging nozzles of varied throat diameters (one nozzle with 15.9 mm, two nozzles with the same diameter of 25.4 mm, and one of 34.9 mm) and length-to-diameter (L/D) ratios.

4.3.3.1 Nozzle D = 15.9 mm with ratio L/D ratio of 0.605

The RELAP5 results of Henry-Fauske and its frozen form are compared with experimental data [3] for nozzle with D = 15.9 mm and L/D ratio of 0.605 in Fig 8. Both forms of equation strongly under-predict experimental results.

The performance of assessment methods described in details in Section 2 against this experimental data is depicted in Fig. 9. The Celata and Park methods provide fairly accurate estimation for this experimental data. The Park method tends to over-predict data for lower experimental flow rate (< 2 kg/sec) and under-estimate for greater values. Methods of Morris, Watson and modified Watson generally over-predict results in the whole range of experimental flow.

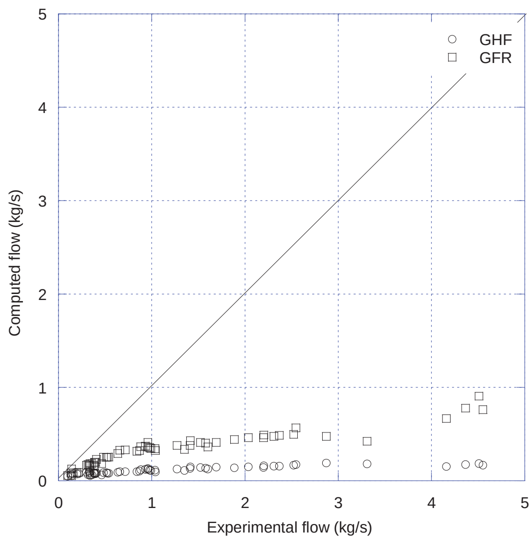


Figure 8. Experimental versus calculated mass flow rate (Henry-Fauske, "frozen") for the examined nozzle.

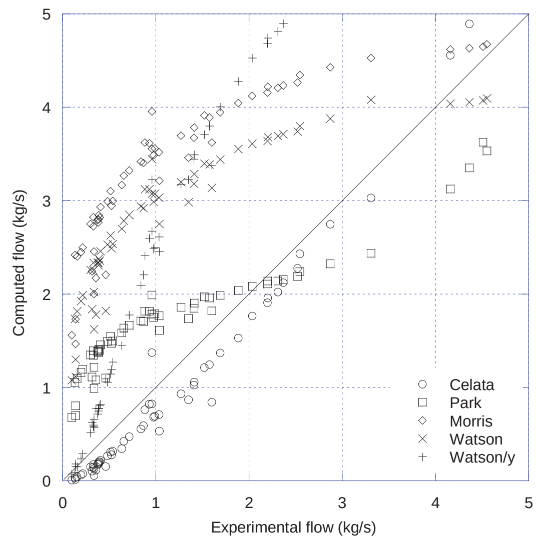
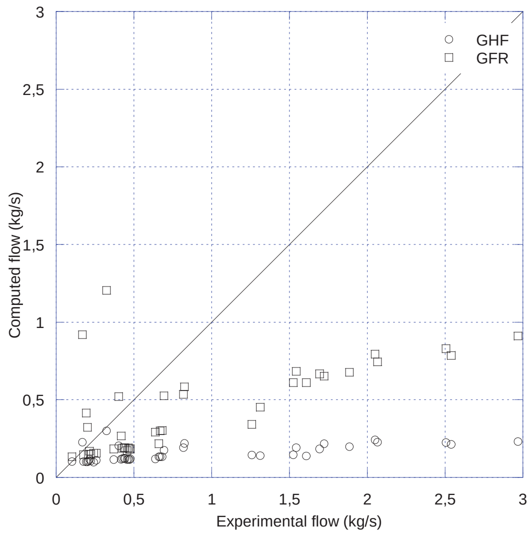


Figure 9. Experimental versus calculated mass flow rate for the examined nozzle.

4.3.3.2 Nozzle D = 25.4 mm with ratio L/D ratio of 0.604

The RELAP5 results of Henry-Fauske and its frozen form are compared with experimental data [3] for nozzle with D = 25.4 mm and L/D ratio of 0.604 in Fig. 10. Both forms of equations strongly under-predict experimental results.

The performance of assessment methods described in details in Section 2 against this experimental data is depicted in Fig. 11. The Celata method provides strongly under-predicted results for all flow rates. The Park method results are generally slightly under-estimated and methods of Morris, Watson and modified Watson tend to over-predict results for all mass flows. The Morris method over-predicts results to the greatest extent of all methods.



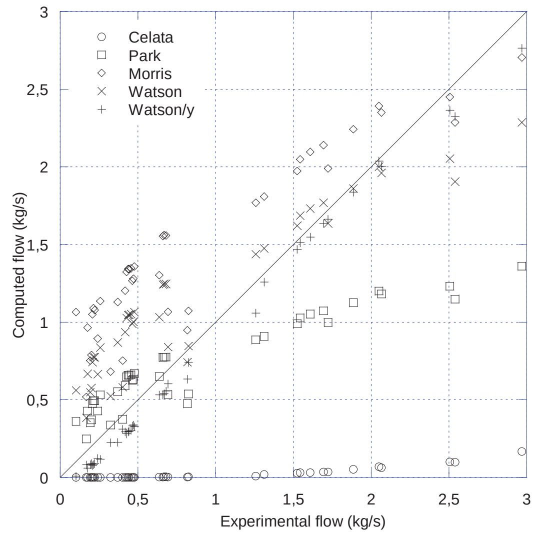
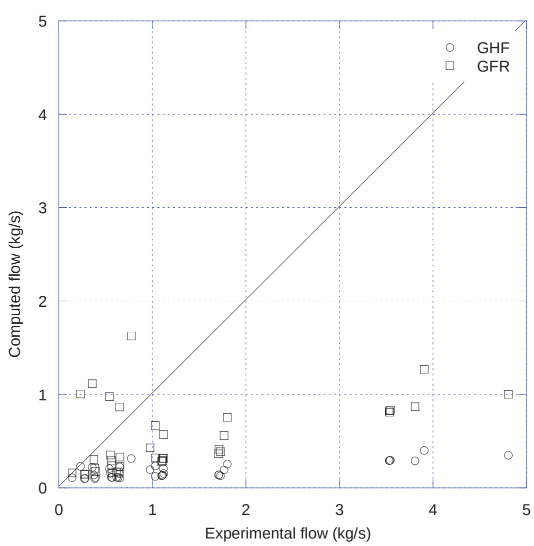


Figure 10. Experimental versus calculated mass flow rate (Henry-Fauske, "frozen") for the examined nozzle.

Figure 11. Experimental versus calculated mass flow rate for the examined nozzle.

4.3.3.3 Nozzle D = 25.4 mm with ratio L/D ratio of 0.454

The RELAP5 results of Henry-Fauske and its frozen form are compared with experimental data [3] for nozzle with D = 25.4 mm and L/D ratio of 0.454 in Fig. 12. Both forms of equations strongly under-predict experimental results. The performance of assessment methods described in details in Section 2 against this experimental data is depicted in Fig. 13. For this data with smallest nozzle's L/D ratio all assessment methods under-predict results. The Celata method provides strongly under-predicted results for all flow rates. Regarding methods of Park, Morris, Watson and modified Watson, they tend to under-predict results for greater mass flows.



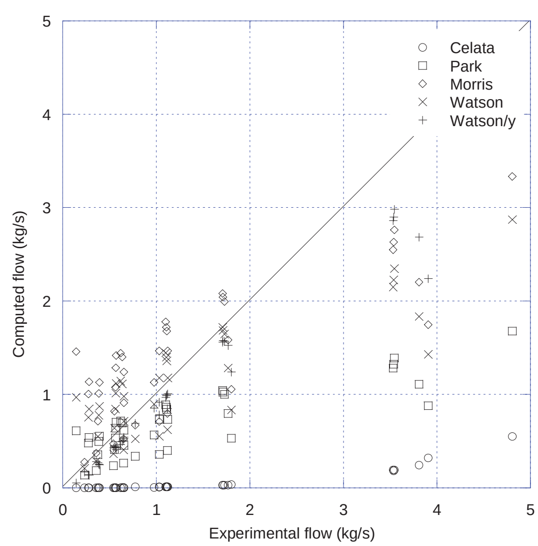


Figure 12. Experimental versus calculated mass flow rate (Henry-Fauske, "frozen") for the examined nozzle.

Figure 13. Experimental versus calculated mass flow rate for the examined nozzle.

4.3.3.4 Nozzle D = 34.9 mm with ratio L/D ratio of 0.604

The RELAP5 results of Henry-Fauske and its frozen form are compared with experimental data [3] for nozzle with D = 34.9 mm and L/D ratio of 0.604 in Fig. 14. Both forms of equations generally under-predict experimental results. The performance of assessment methods described in details in Section 2 against this experimental data is depicted in Fig. 15. All methods under-estimate experimental result in which the Celata method provides strongly under-predicted results and the Morris method under-predicts results to the least extent of all methods.

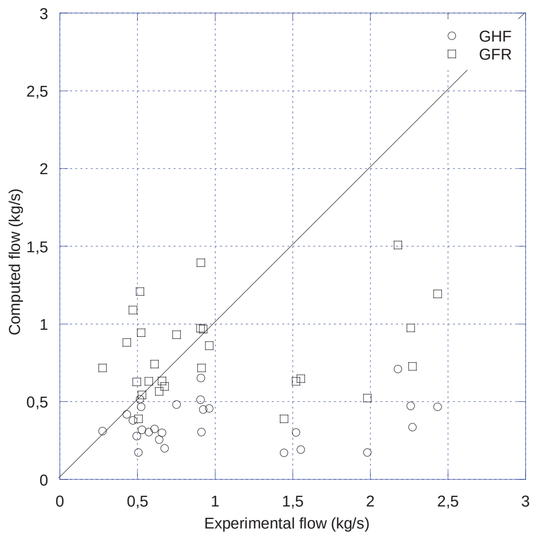


Figure 14. Experimental versus calculated mass flow rate (Henry-Fauske, "frozen") for the examined nozzle.

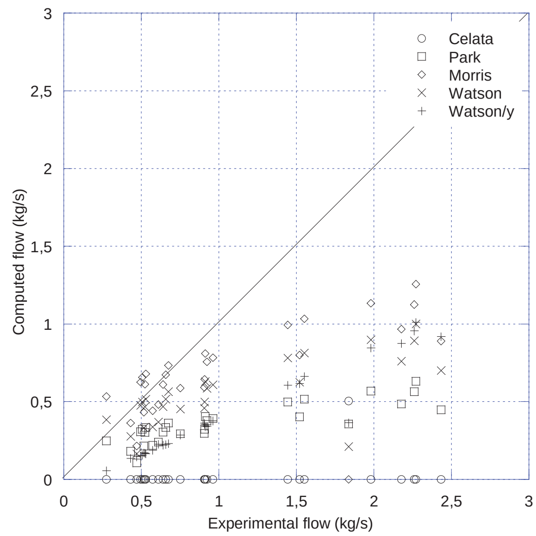


Figure 15. Experimental versus calculated mass flow rate for the examined nozzle.

5. CONCLUSIONS

The validation of H-F two-phase critical models implemented in one-dimensional thermal-hydraulic system code RELAP5 has been conducted for non-flashing flow experiments of [1], [2] and [3].

For simple test section geometries (open pipe outlet) of reference [1], Henry-Fauske and its frozen form tend to over-predict the majority of data for stagnation conditions in all pressure ranges of 0.5 MPa, 1.0 MPa and 1.5 MPa. For more complex geometries of converging-diverging and diverging nozzles, which were performed based on experimental data from Refs. [2] and [3], in most cases predictions of RELAP5 code were generally slightly to fairly under-estimated. Regarding prediction of data [2] Henry-Fauske model provided under-predicted results while its frozen form slightly over-predicted results. The analytical methods of [1] and [6] provide satisfactory results for simple test section geometries and large L/D ratio. For more complex geometries from Refs. [2] and [3] they generally under-estimate experimental data. Analytical methods that have been derived based on experiments on converging-diverging and diverging nozzles of Refs. [2], [3], and [7], vary in solution accuracy with respect to nozzle diameter and L/D ratio.

Future work will be devoted to enlarge validation database with new experiments on converging-diverging and converging nozzles and to derive and propose methods to assess two-phase critical non-flashing flow for transient conditions.

NOMENCLATURE

A	flow area (m^2)
a	experimental parameter from equation (2)
b	experimental parameter from equation (2)
C_d	discharge coefficient
C_N	flow coefficient for nozzles
F	expansion of the vapor phase
G	mass flux (kg m^2 s^{-1})
g	gravity constant (m s^{-2})
H, h	enthalpy (kJ kg^{-1})
k	phase slip ratio (= u_G/u_L)
M	mass flow rate (kg s^{-1})
m	exponent in equation for two-phase choking pressure ratio ηc
n	polytropic exponent
P, p	pressure (Pa)
Q	volumetric flow rate (m^3 s^{-1})
r	ratio of downstream to upstream absolute pressure
s	entropy (kJ kg^{-1} K^{-1})
T	temperature (K)
ΔT	inlet subcooling (K)
v	specific volume (m^3 kg^{-1})
x	quality , $W_g/(W_g + W_l)$
Y	void fraction
α	void fraction
β	diameter ratio d/D
γ	isentropic exponent
η	critical pressure ratio, P_t/P_0
ρ	density (kg m^{-3})

Subscripts

0	stagnation conditions and reference conditions in equation (2)
a	air properties
c	critical condition
e*	effective
G, g	vapor phase
id	ideal
L,l	liquid phase
L	related to flowrate of liquid component in two-phase flow
LN	related to mass flowrate of liquid in single-phase flow with two-phase pressure drop and normal and unit coefficient of discharge
LS	related to mass flowrate of liquid in single-phase flow with two-phase pressure drop and normal liquid-phase coefficient of discharge
s	single phase
sub	subcooling
t	throat
VN	related to flowrate of vapor in single-phase flow with two-phase pressure drop and unit coefficient of discharge

REFERENCES

1. G.P. Celata, M. Cumo, F. D'Annibale, G.E. Farello, "The Influence of Non-Condensible Gas on Two-Phase Critical Flow", *International Journal of Multiphase Flow* **14**(2), pp. 175-187 (1988).
2. G.G. Watson, V.E. Vaughan, M.W. McFarlande, "Two-Phase Pressure Drop with a Sharp-Edged Orifice", National Engineering Laboratory NEL, 1967.
3. E.J. Graham, "The Flow of Air-Water Mixtures Through Nozzles", National Engineering Laboratory NEL, 1967.
4. L. Sokolowski, T. Kozlowski, "Assessment of Two-Phase Critical Flow Models Performance in RELAP5 and TRACE Against Marviken Critical Flow Tests", NUREG/IA-0401, International Agreement Report, U.S. Nuclear Regulatory Commission, 2012.
5. R.J. Simoneau, "Depressurization and Two-Phase Flow of Water Containing High Levels of Dissolved Nitrogen Gas", NASA Technical Paper 1839, Cleveland, Ohio, 1981.
6. H.-S. Park et al. , "Experimental Study on a Two-Phase Critical Flow with a Non-Condensable Gas at High Pressure Conditions", *International Journal of Multiphase Flow* **33**, pp. 1222-1236 (1997).
7. S.D. Morris, "Discharge Coefficients for Chocked Gas-Liquid Flow Through Nozzles and Orifices and Applications to Safety Devices", *Journal of Loss Prevention in the Process Industries* **3**, pp. 303-310 (1990).
8. S.C. Jamerson, H.G. Fisher, "Using Constant Slip Ratios to Model Non-Flashing (Frozen) Two-Phase Flow Through Nozzles", *Process Safety Progress* **18**, pp. 89-98 (1999).
9. R.E. Henry, H.K. Fauske, "The Two-Phase Critical Flow of One-Component Mixtures in Nozzles, Orifices, and Short Tubes", *Journal of Heat Transfer* **93**, pp. 179-187 (1971).
10. J. Lenclund, J.E.S. Venart, "Single and Two-Phase Discharge from a Pressurized Vessel", *Revue Générale de Thermique* **35**, pp. 503-516 (1995).
11. H. Städtke, "Gasdynamic Aspects of Two-Phase Flow", Wiley-VCH Verlag GmbH&Co. KGaA, Weinheim, 2006.
12. J.C. Leung, "Similarity between Flashing and Nonflashing Two-Phase Flows", *American Institute of Chemical Engineering Journal* **36**, pp. 797-800 (1990).
13. J.C. Leung, M.A. Epstein, "A Generalized Correlation for Two-Phase Nonflashing Homogeneous Chocked Flow", *Journal of Heat Transfer* **112**, pp. 528-530 (1990).
14. J.C. Leung, "Two-Phase Flow Discharge in Nozzles and Pipes – A Unified Approach", *Journal of Loss Prevention in the Process Industries* **3**, pp. 27-32 (1990).
15. A. Beune, J.G.M. Kuerten, J. Schmidt, "Numerical Calculation and Experimental Validation of Safety Valve Flows at Pressures up to 600 bar", *American Institute of Chemical Engineering Journal* **57**, pp. 3285-3298 (2011).
16. G. Boccardi, R. Bubbico, G.P. Celata, B. Mazzarotta, "Two-Phase Flow Through Pressure Safety Valves. Experimental Investigation and Model Prediction", *Chemical Engineering Science* **60**, pp. 5284-5293 (2005).
17. R. Darby, "On Two-Phase Frozen and Flashing Flows in Safety Relief Values. Recommended Calculation Method and the Proper Use of the Discharge Coefficient", *Journal of Loss Prevention in the Process Industries* **17**, pp. 255-259 (2004).
18. T. Lenzing, L. Friedel, J. Cremers, M. Alhusein, , "Prediction of the Maximum Full Lift Safety Valve Two-Phase Flow Capacity", *Journal of Loss of Prevention in the Process Industries* **11**, pp. 307-321 (1998).
19. J. Liu, J. Chen, Z. Chen, "Critical Flashing Flow in Convergent-Divergent Nozzles with Initially Subcooled Liquid", *International Journal of Thermal Sciences* **47**, pp. 1069-1076 (1998).
20. F. Mayinger, "Two-Phase Flow Phenomena with Depressurization – Consequences for the Design and Layout of Safety and Pressure Relief Valves", *Journal of Chemical Engineering and Processing: Process Intensification* **23**, pp. 1-11 (1988).
21. D. Moncalvo, L. Friedel, , "Critical Air/Water Blow-Down in Safety Valves at Low Qualities", *Journal of Hazardous Materials* **186**, pp. 2162-2165 (2011).

22. RELAP5/MOD3.3 Code Manual, 2006, Nuclear Safety Analysis Division, Information Systems Laboratories, Inc.
23. G. Polanco, A.E. Holdø, G. Munday, "General Review of Flashing Jet Studies", *Journal of Hazardous Materials* **173**, pp. 2-18 (2010).