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Prediction of two-phase choked-flow through safety valves

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Abstract. Different models of two-phase choked flow through safety valves are applied in order to evaluate their capabilities of prediction in different thermal-hydraulic conditions. Experimental data available in the literature for two-phase fluid and subcooled liquid upstream the safety valve have been compared with the models predictions. Both flashing flows and non-flashing flows of liquid and incondensable gases have been considered. The present paper shows that for flashing flows good predictions are obtained by using the two-phase valve discharge coefficient defined by Lenzing and multiplying it by the critical flow rate in an ideal nozzle evaluated by either Omega Method or the Homogeneous Non-equilibrium Direct Integration. In case of non-flashing flows of water and air, Leung/Darby formulation of the two-phase valve discharge coefficient together with the Omega Method is more suitable to the prediction of flow rate.

1. Introduction

Safety relief valves (SRV) play a fundamental role in many industries, including power plants (both conventional and nuclear), aerospace, automotive, printing industries and multi-purpose plants for the production of fine chemical and pharmaceutical products, where recipes are frequently changed and various processes are carried out; they have to ensure that the operating pressure does not exceed unsafe limits.

The depressurisation rate of a pressure vessel or a plant system is limited by choked flow rates through the safety valve and the prediction of flow rates through it is a crucial issue in the design of both pressure vessels and downstream collecting and handling systems.

It might occur that, due to off-normal or accidental conditions or to a change of recipe in a multi-purpose plant, safety relief valves initially sized for saturated steam or for highly subcooled liquid may be required to discharge a mixture of liquid and vapour or subcooled liquid that flashes along the valve flow path.

Sizing methods and flow models for single-phase flow through safety valves are well established; however, this is not the case for two-phase flow, as complex phenomena occur between the two phases.

In fact, the two phases have different velocities and also their temperatures could differ; therefore momentum and energy exchanges are not merely due to mass transfer. Thermodynamic non-equilibrium phenomena could also occur and the presence of metastable liquid causes vaporisation delays. The sound velocity in two phase flow strongly depends on the fraction of steam and is strongly reduced as soon as vapour appears.

The knowledge about two-phase phenomena in safety valves is still insufficient and the development of a theoretical model able to accurately predict two-phase flow rate through safety



valves is not an easy task even in steady state conditions.

In single-phase choked flow through safety valves (SRV), the flow rate is a function of upstream thermodynamic conditions (pressure, temperature), minimum valve section, and a discharge coefficient, which is defined as the ratio between the actual flow rate and the flow rate through an ideal nozzle operated at the same upstream conditions. During the choked flow the fluid velocity in the minimum section is equal to the sound speed in the fluid. The discharge coefficients for single-phase liquid flow (K_{dL}) and single-phase gas flow (K_{dG}) are determined experimentally and normally are provided by the valve manufacturers.

Most authors [1-5] suggest that two-phase choked flow through safety valves can be evaluated by simplified two-phase flow models whose approach is similar to the one in single-phase: they suggest to multiply the two-phase choked flow rate through an ideal convergent-divergent nozzle and a two-phase discharge coefficient. Even though normally manufacturers provide the discharge coefficient for the liquid and sometimes for gas flow, no such data are provided in two-phase flow.

Several models for the two-phase discharge coefficient have been developed; they evaluate the two-phase valve discharge coefficient as function of K_{dG} , K_{dL} , properties of the two phases and quality or void fraction of the two-phase mixture; each of them applies to a certain ideal nozzle model.

Both theoretical models for safety valves and experimental results have been analysed and some of them have been considered in the present work in order to compare models predictions with experimental results available in the literature and to highlight discrepancies. Experimental/modelling studies of flashing water through small valves have been carried out Boccardi et al. [6-9].

The authors compared the predictions of two-phase flow rate through ideal nozzle by the Homogeneous Equilibrium Model (HEM), the ω method (first developed by Leung [10]), Slip Equilibrium Models (SEM), Homogeneous Non Equilibrium models like the one developed by Henry and Fauske in 1970 (HNE) [11] and afterwards improved by Diener and Schimdt (HNE-DS) [1], Equilibrium Rate Model (ERM) [2], Homogeneous Frozen Models (HFM) [3] or by Homogeneous Direct Integration (HDI) and Homogeneous Non-equilibrium Direct Integration (HNDI) methods [4].

Afterwards the authors considered the models of two phase valve discharge coefficient developed by Lenzing [3], Darby [4], and Leung [5] and combined them with the different models of two-phase choked flow in ideal nozzles, in order to evaluate which couple of the two gives the best prediction of experimental data in different thermal-hydraulic conditions.

2. Two-phase flow through ideal nozzles.

Here the models used for the evaluation of the flow rate through an ideal nozzle are mentioned.

The ω -method is a form of Homogeneous Equilibrium Model that can be applied to choking and non-choking flows, flashing and non-flashing systems and its applicability has been extended to initial subcooled conditions. Firstly developed by Leung [10], it has been revised and modified by other authors and is recommended by known standards, such as API 520 [12].

Different formulations have been proposed for flashing flow of initially saturated and subcooled fluid and for non-flashing flow.

The HNE model, developed by Henry and Fauske in 1970, considers an incompressible liquid phase and describes the vapour phase by a polytropic law with the Tangren's exponent; the model also considers flashing delays when the exit quality is less than 0.05.

The model, reported in [3], can be applied to saturated two-phase mixture at the nozzle inlet.

The HFM model supposes that the quality does not change and the vapour is considered an ideal gas undergoing an isentropic process. Different formulations of this model are available: the Starkman formulation [13] and the Nastoll formulation [3] were used in the present work.

The ERM model [2] was originally developed by Fauske (1985), is valid for saturated and subcooled liquid at the nozzle inlet and cannot be applied to two-phase mixtures. It supposes that thermal equilibrium occurs if the pipe length is greater than 0.1 m. For shorter pipes it takes into account of thermodynamic non-equilibrium phenomena by introducing a non-equilibrium correction factor.

The HDI model [4] evaluates the mass flow rate by integration of Bernoulli's equation using a simple numerical approximation of the fluid properties of the two-phase mixture. It can be applied to saturated mixture and to non-flashing flows.

A modification of the model was developed in order to consider thermodynamic non-equilibrium (Homogeneous Non-Equilibrium Direct Integration Model, HNDIM [14]).

3. Two-phase valve discharge coefficient.

The models by Lenzing, Leung and Darby for the evaluation of the two-phase discharge coefficient are reported.

Lenzing formulation considers a homogeneous flow of the phases; each of them occupies a portion of the flow area and behaves as a single-phase fluid. Lenzing uses the void fraction in the nozzle mouth to evaluate the two-phase discharge coefficient [5]:

$$K_{dTP} = \alpha_e K_{dG} + (1 - \alpha_e) K_{dL} \quad (1)$$

The void fraction α_e at safety valve entrance can be evaluated by the ω method, the HFM by Nastol, HNEM and others.

Leung formulation [5] was developed to be used with ω method, the HFM by Nastol and HNEM and is an extension of the Jobson and Bragg's work on compressible discharge through an orifice to the case of compressible two-phase discharge: it yields the two-phase discharge coefficient as a function of liquid discharge coefficient and the ω parameter. Diagrams are also available.

Darby [4] states that the discharge coefficient is strongly dependent on flow conditions. For choked flow the two-phase coefficient is equal to the gas discharge coefficient, while when the flow is not choked the liquid discharge coefficient is used. This formulation was developed to be used with HDI and HNDI models. The authors suggested the model to be used for the evaluation of flow rate through the ideal nozzles. These ones, together with the discrepancies with respect to the experimental results that they considered, are reported in table 1.

Table 1. Coupling models for choked flow through an ideal nozzle and formulations for the two-phase discharge coefficient

Author	K_{dTP} formulation	Choked flow model	Discrepancy (%)
Lenzing	$K_{dTP} = \alpha_e K_{dG} + (1 - \alpha_e) K_{dL}$	Omega Method, HFM (Nastoll), HNE (Henry-Fauske)	$\pm 10\%$ HNE $\pm 40\%$ HFM/Omega
Leung	Diagrams	Omega Method, HNE (Henry-Fauske)	-
Darby	Choked $\Rightarrow K_{dTP} = K_{dG}$ Not choked $\Rightarrow K_{dTP} = K_{dL}$	HDI, HNDI	-

Table 2. Valves characteristics.

Valve	K_{dG}	K_{dL}	Orifice diameter (mm)	Exit area (mm ²)
Crosby 1x2"E"(JLT/JBS).	0.962	0.729	13.5	143.2
ARI DN25/40	0.81	0.81	22.5	397.6
LESER DN25/40 (441)	0.77	0.51	23	415.5

Table 3. Experimental data of mixtures of water and steam.

Valve	p_0 (bar)	T_0 (°C)	x	G_{exp} (kg/m ² s)
LESER DN25/40 (441)	5.4	$T_s(P_0)$	0.012	3750
LESER DN25/40 (441)	5.4	$T_s(P_0)$	0.008	4240
LESER DN25/40 (441)	5.4	$T_s(P_0)$	0.0065	4280
LESER DN25/40 (441)	5.4	$T_s(P_0)$	0.0051	4460
LESER DN25/40 (441)	8	$T_s(P_0)$	0.022	4410
LESER DN25/40 (441)	8	$T_s(P_0)$	0.015	4580
LESER DN25/40 (441)	8	$T_s(P_0)$	0.012	5000
LESER DN25/40 (441)	8	$T_s(P_0)$	0.0046	5960
LESER DN25/40 (441)	10.6	$T_s(P_0)$	0.04	4200
LESER DN25/40 (441)	10.6	$T_s(P_0)$	0.03	4830
LESER DN25/40 (441)	10.6	$T_s(P_0)$	0.025	4900
LESER DN25/40 (441)	10.6	$T_s(P_0)$	0.016	5500
LESER DN25/40 (441)	10.6	$T_s(P_0)$	0.012	6000
LESER DN25/40 (441)	10.6	$T_s(P_0)$	0.007	6700
LESER DN25/40 (441)	10.6	$T_s(P_0)$	0.0028	7300
LESER DN25/40 (441)	10.6	$T_s(P_0)$	0.0011	7900

Table 4. Experimental data of mixtures of water and air.

Valve	p_0 (bar)	T_0 (°C)	x	G_{exp} (kg/m ² s)
LESER DN25/40 (441)	5	25	0.106	2700
LESER DN25/40 (441)	5	25	0.04	4200
LESER DN25/40 (441)	5	25	0.03	5000
LESER DN25/40 (441)	5	25	0.016	6450
LESER DN25/40 (441)	5	25	0.012	7400
LESER DN25/40 (441)	5	25	0.0073	9000
Crosby 1x2"E"(JLT/JBS)	5	25	0.12	3100
Crosby 1x2"E"(JLT/JBS)	5	25	0.021	6500
Crosby 1x2"E"(JLT/JBS)	5	25	0.0078	9500
Crosby 1x2"E"(JLT/JBS)	5	25	0.006	11900
Crosby 1x2"E"(JLT/JBS)	5	25	0.001	19050
ARI DN25/40	5	25	0.15	3000
ARI DN25/40	5	25	0.04	5000
ARI DN25/40	5	25	0.0068	10400
ARI DN25/40	5	25	0.0059	11160
ARI DN25/40	5	25	0.0031	14000
LESER DN25/40 (441)	8	25	0.315	2600
LESER DN25/40 (441)	8	25	0.048	7000
LESER DN25/40 (441)	8	25	0.027	8450
LESER DN25/40 (441)	8	25	0.018	9700
LESER DN25/40 (441)	8	25	0.0092	12400
LESER DN25/40 (441)	8	25	0.006	14000
ARI DN25/40	8	25	0.23	3100
ARI DN25/40	8	25	0.095	5500
ARI DN25/40	8	25	0.028	9600
ARI DN25/40	8	25	0.015	12400
ARI DN25/40	8	25	0.0096	14100
ARI DN25/40	8	25	0.009	15000
ARI DN25/40	8	25	0.0048	18000

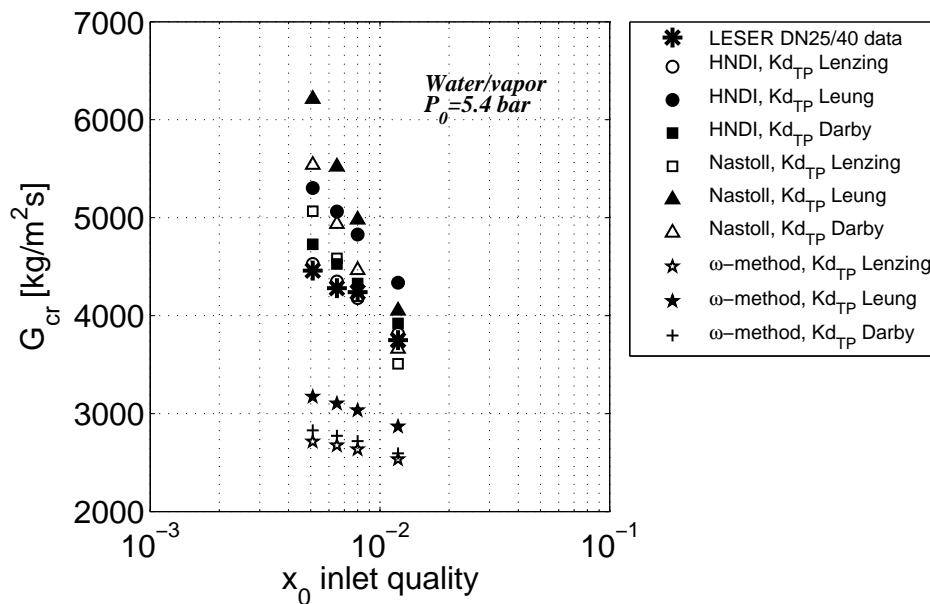


Figure 1. Comparison of the prediction of HNDIM, Nastoll HFM and ω -method coupled with Lenzing's, Leung's and Darby's formulations of discharge coefficients with the flow rate of water/vapour discharged through a LESER DN25/40 valve at 5.4 bar.

4. Experimental data on safety valves.

Experimental data on spring safety valves have been taken from the scientific literature. Different valves have been used in the experimental studies available at present [4, 6-9].

As far as discharge of saturated mixture in the stagnation section is concerned, we considered experimental data obtained with the LESER DN25/40 (441) valve. Experimental data of non-flashing choked flow through three different valves (LESER DN25/40 (441), ARI DN25/40 and Crosby 1x2"E"(JLT/JBS)) are considered. Their characteristics [4] are reported in table 2.

Table 3 reports test conditions and the values of the mass flow rate obtained experimentally with mixture of water and steam. Table 4 refers to the experimental tests with water and air.

5. Models predictions.

We applied the formulations of discharge coefficient proposed by Lenzing, Leung and Darby to several choke models for ideal nozzle, in order to find out which couple of models best predicts the flow rate.

The HEM, ω -method and HDIM provided approximately the same predicted flow rate; therefore only the values predicted by the ω -method are reported here.

The flow rate predictions of two-phase mixture at the stagnation point are reported in figures 1, 2,3 relatively to stagnation pressures of 5.4 bar, 8 bar and 10.6 bar respectively.

The discrepancies, in terms of relative error, between predicted and experimental values are highlighted in table 5, which reports the minimum and the maximum percentage error (respectively in the first and second line of each cell of the table) for each couple of models.

The ω -method always underestimates the flow rate, while the HNE model strongly overestimates it. The best prediction is given by the HNDI model coupled with the Lenzing two-phase discharge coefficient.

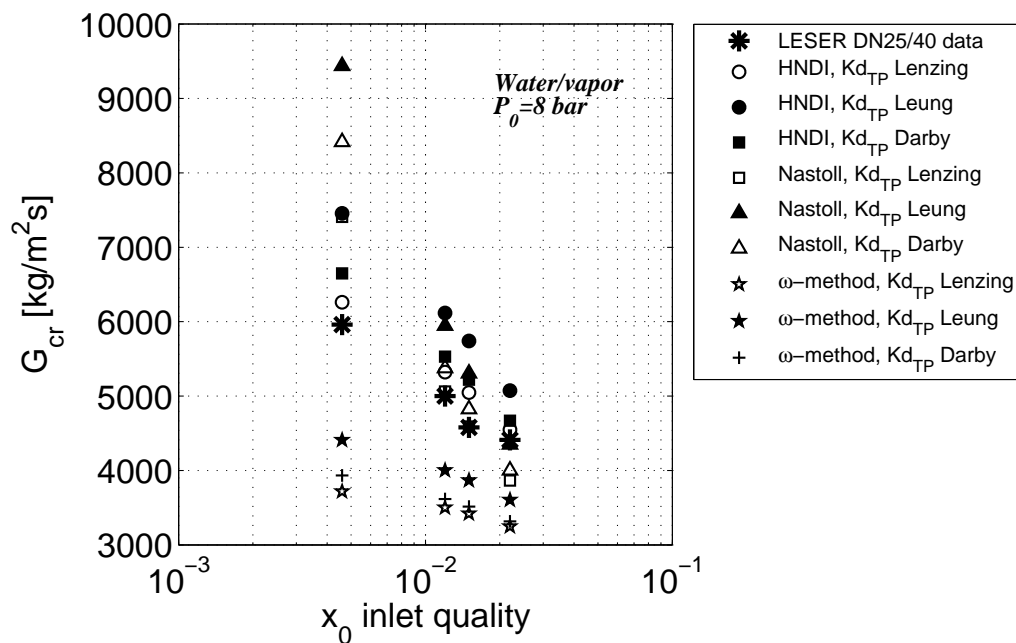


Figure 2. Comparison of the prediction of HNDIM, Nastoll HFM and ω -method coupled with Lenzing's, Leung's and Darby's formulations of discharge coefficients with the flow rate of water/vapour discharged through a LESER DN25/40 valve at 8 bar.

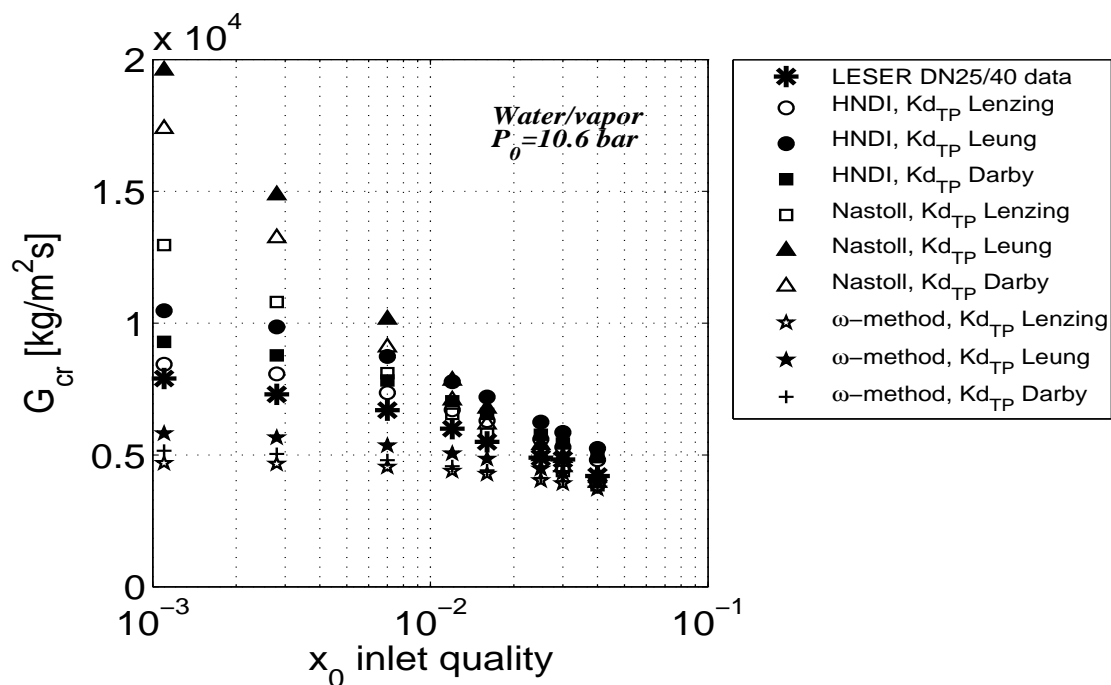
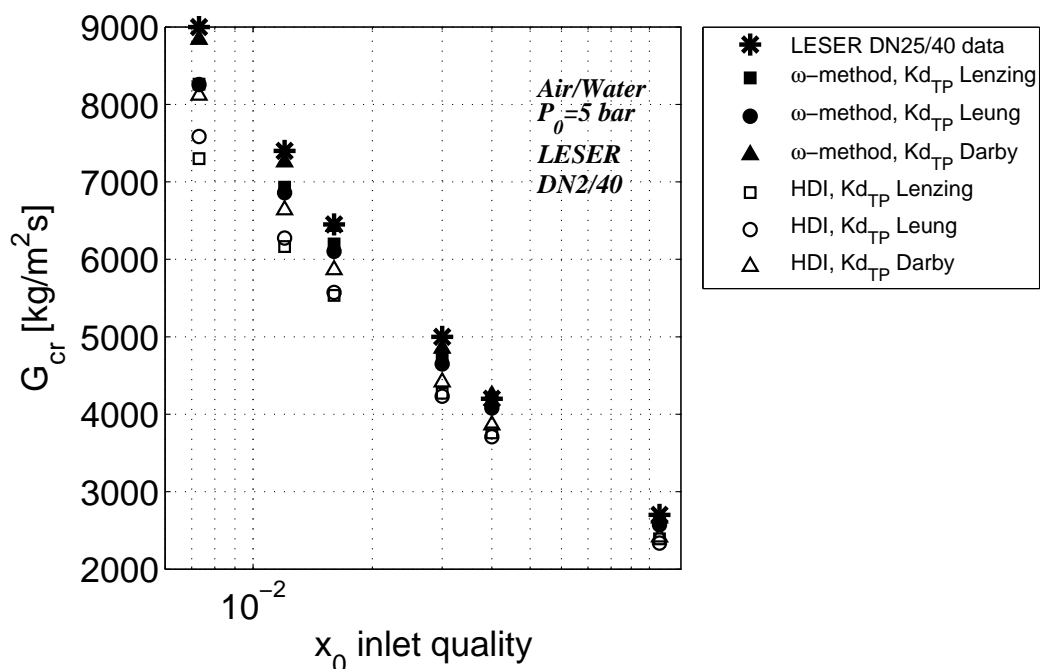


Figure 3. Comparison of the prediction of HNDIM, Nastoll HFM and ω -method coupled with Lenzing's, Leung's and Darby's formulations of discharge coefficients with the flow rate of water/vapour discharged through a LESER DN25/40 valve at 10.6 bar.

Table 5. Discrepancies between predicted and experimental flow rate of water/vapour mixture through a LESER valve (expressed as % error).

Model		Lenzing	Leung	Darby	Lenzing	Leung	Darby	Lenzing	Leung	Darby
	P_0 (bar)	5.4	5.4	5.4	8	8	8	10.6	10.6	10.6
Omega	Error	-32.5%	-23.5%	-30.8%	-25.3%	-15.6%	-23.2%	-11.6%	-4.3%	-10.3%
	range	-39.2%	-28.9%	-36.6%	-37.6%	-26.0%	-34.0%	-40.7%	-26.4%	-34.7%
HNDI	Error	-1.4%	13.9%	+2.1%	+3.1%	15.1%	+5.9%	+6.9%	+21.3%	12.6%
	range	+1.7%	18.9%	+6.0%	+10.2%	25.4%	14.0%	+14.7%	+35.1%	20.3%
HFM Nastoll	Error	-6.5%	+8.0%	-2.3%	-12.4%	-1.4%	-9.3%	-9.0%	+0.4%	-5.9%
	range	+13.6%	39.3%	24.2%	+24.3%	58.3%	41.2%	+64.1%	148.0%	+120%
HNE	Error	+5.7%	+25%	13.1%	-0.2%	14.6%	+5.4%	+2.4%	+16.4%	+8.1%
	range	+16.7%	49.4%	33.2%	+20.0%	61.1%	43.7%	+37.9%	117.3%	92.7%
HFM Starkman	Error	+29.6%	50.8%	36.4%	+25.4%	41.1%	29.8%	-20.5%	+20.2%	+6.6%
	range	+34.8%	65.4%	47.5%	+36.5%	62.8%	45.2%	+38.7%	+62.6%	47.1%

**Figure 4.** Comparison of the prediction of HNDIM, Nastoll HFM and ω -method coupled with Lenzing's, Leung's and Darby's formulations of discharge coefficients with the flow rate of water/air at 5 bar through a LESER valve.

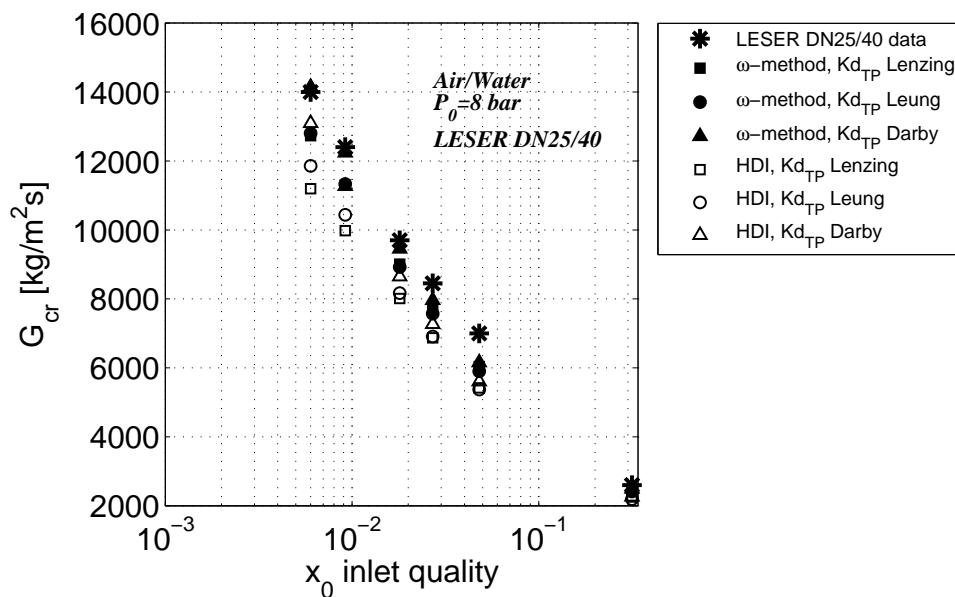


Figure 5. Comparison of the prediction of HNDIM, Nastol HFM and ω -method coupled with Lenzing's, Leung's and Darby's formulations of discharge coefficients with the flow rate of water/air at 8 bar through a LESER valve.

Table 6. Discrepancies between predicted and experimental flow rate of water/air mixture through the LESER DN25/40 (441) valve (expressed as % error).

Model		Lenzing	Leung	Darby	Lenzing	Leung	Darby
	p_0 (bar)	5	5	5	8	8	8
Omega	Error	-0,45%	-2.84%	-2.90%	-4.30%	-7.10%	-12.00%
	range	-8.20%	-8.25%	1.09%	-13.80%	-15.70%	1.06%
HDI	Error	-10.47%	-11.65%	-8.10%	-13.40%	-15.31%	-6.44%
	range	-18.90%	-15.73%	-11.70%	-22.60%	-23.30%	-19.94%
HFM Starkman	Error	-7.20%	-3.78%	3.00%	-30.14%	-25.50%	-17.67%
	range	52.80%	49.02%	54.11%	52.50%	48.30%	53.10%
HFM Nastoll	Error	-34.68%	-34.08%	-29.42%	-31.00%	-30.50%	-23.20%
	range	-37.69%	-38.11%	-35.42%	-42.81%	-43.50%	-41.00%

Boccardi et al. [6-9] compared experimental results on commercial valves with 10 mm orifice diameter with ω -method, HNE and found that the geometry of the valve strongly influences flow rate and therefore the accuracy of the prediction method. In particular it was found that the ω -method always underpredicts the flow rate of water and steam. The HNE model gave better results, but overpredicted the flow rate at low inlet quality in valves with slightly convergent-divergent nozzle.

The underprediction of the ω -method is due to the fact that it is not able to take into account thermodynamic non-equilibrium effects occurring through safety valves, which causes an increase of flow rate with respect to thermodynamic equilibrium conditions.

The flow rate of water/air mixtures have been compared with the experimental values through the LESER valve, the Crosby valve and the ARI valves reported in table 2. Figures 4 and 5 show the comparison with experimental flow rates through a LESER valve at 5 and 8 bar respectively.

The discrepancies, in terms of relative error, between predicted and experimental values are highlighted in table 6,7 and 8, which report the minimum and the maximum percentage error (respectively in the first and second line of each cell of the table) for each couple of models applied to the LESER, Crosby and ARI valves.

It can be seen that all models tend to underestimate the flow rate. The best predictions are reported in the table in bold characters.

The model that globally best predicts the flow rate of non-flashing mixtures of water and air is the ω -method, coupled with the Darby's discharge coefficient.

The presence of an incondensable gas influences seems to influence the discharge capability of the safety valve and the discharge coefficient tends to the value for gas flow.

Table 7. Discrepancies between predicted and experimental flow rate of water/air mixture through the Crosby 1x2 E JLT/JBS valve (expressed as % error).

Model		Lenzing	Leung	Darby
	p_0 (bar)	5	5	5
		8.29%	4.95%	-0.19%
Omega	Error range	-10.18%	-9.02%	13.36%
		-3.12%	-3.66%	4.06%
HDI	Error range	-18.62%	-15.55%	-8.39%
		-64.76%	-61.90%	-56.70%
HFM Starkman	Error range	57.70%	46.18%	58.60%
		-24.40%	-25.00%	-16.10%
HFM Nastoll	Error range	-33.09%	-37.80%	-32.54%

Table 8. Discrepancies between predicted and experimental flow rate of water/air mixture through the ARI DN25/40 valve (expressed as % error).

Model		Lenzing	Leung	Darby	Lenzing	Leung	Darby
	p_0 (bar)	5	5	5	8	8	8
Omega	Error	-11.77%	-11.18%	-8.16%	-1.51%	-2.23%	-1.27%
	range	-21.50%	-22.03%	-21.27%	-19.47%	-17.20%	-14.50%
HDI	Error	-20.10%	-17.10%	-15.60%	-10.90%	-11.30%	-10.42%
	range	-29.00%	-29.30%	-28.56%	-28.28%	-23.35%	-22.40%
HFM	Error	-42.35%	-37.50%	-33.40%	43.63%	-38.90%	-34.70%
Starkman	range	28.70%	29.21%	31.14%	-55.70%	54.80%	56.40%
HFM	Error	-39.21%	-35.80%	-31.50%	-31.36%	-31.74%	-31.06%
Nastoll	range	-47.10%	-47.40%	-46.90%	-43.72%	-43.52%	-42.08%

6. Conclusions

A thorough analysis of the models available in the literature has been carried out.

The authors compared the predictions of two-phase flow rate through ideal nozzle by several models (HEM, ω -method, SEMs, Henry-Fauske's Homogeneous Non Equilibrium, ERM, HFM, HDI, HNDI) and used the models developed by Lenzing, Darby, and Leung for the two phase valve discharge coefficient.

The results show that for flashing flows good predictions are obtained by multiplying the Lenzing's formulation of the two-phase valve discharge coefficient and the critical flow rate obtained by the Homogeneous Non-equilibrium Direct Integration.

On the other hand, Leung/Darby formulation of the two-phase valve discharge coefficient together with Omega Method is the most suitable to the prediction of flow rate in case of non-flashing flows of air and water.

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