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Comparison among Three Prediction Methods for Safety Valves Design in Two-Phase Flow in the case of a Small Valve

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In the case of two- phase flow discharge, pressure safety valves (PSV) design becomes difficult due to complex thermal-fluid dynamic phenomena that occur between the two phases. Currently, there are two main types of prediction models, the Homogeneous Equilibrium Model (HEM) and the Homogeneous Non Equilibrium model (HNE), used for developing methods to calculate the theoretical mass flux G_t; this value has to be corrected by an experimental coefficient k_d, termed as two-phase "discharge coefficient", for obtaining the actual two phase mass flow-rate value W_r.
Generally, for each method a different way of calculating k_d is proposed, but various studies are looking for a general correlation that considers all the two-phase flow aspects. This paper will compare some experimental results obtained with a steam-water system and a small PSV (orifice diameter ϕ_{or}=6 mm) with the predictions of three methods, an HEM, an HNE and a more recent method, called HNE-DS, proposed by the ISO working group on PSV sizing.

1. Introduction

The accurate prediction of the two-phase mass flow rate discharged through a PSV is very difficult due to incomplete knowledge of the complex thermal-fluid dynamic phenomena that occur between the two phases. In particular, the following issues should take into account:

- the close interaction between vapour quality and changes in pressure drop;
- possible thermodynamic non-equilibrium;
- the potential different velocity of the two phases;
- the sound velocity in two-phase flow.

The equation for calculating the dischargeable mass flow rate "W_r" through a PSV having a geometric valve seat area "A" is:

$$W_r = k_d\, G_t\, A \qquad (1)$$

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where G_t is the theoretical max flux through an ideal (isentropic) nozzle and k_d is the two-phase "discharge coefficient". The Homogeneous Models calculate G_t assuming that the two-phase mixture is homogeneous and the liquid and vapour phases run at the same velocity. Consequently, all the physical parameters are defined via averages weighted on the vapour quality (x). The Homogeneous models can be divided into two main groups, the "HEM", Homogeneous Equilibrium Models, and "HNE", Homogeneous Non-Equilibrium Models, depending on whether the thermodynamic equilibrium at the PSV outlet is assumed or not.

In this paper, experimental data have been collected for the mass flow rate and compared with the predictions of three theoretical methods: the first one is based on an HEM developed by Leung (1986)(1990)(1995)(1996); the second one is a calculation method based on an HNE method (Henry et al.,1971, Fauske, 1984); the last one is a recent method, called HNE-DS (Diener et al., 2004), introducing some correction parameters in the HEM hypotheses to consider the boiling delay. Steam-water two-phase flow tests were carried out at the Institute of Thermal-Fluid Dynamic, ENEA, on a commercial PSV (orifice diameter ϕ_{or}= 6 mm) characterized by high single-phase discharge coefficients: k_g=0.80 (gas, certified) and k_l=0.77 (liquid, measured).

2. Sizing Methods in Two-Phase Flow Conditions

HEM method calculate G_t by the following equation:

$$G_t = \frac{\sqrt{-\omega \ln(\eta) - (\omega - 1)(1 - \eta)}}{\omega \cdot (1/\eta - 1) + 1} \cdot \sqrt{\frac{2 p_0}{v_0}} \tag{2}$$

where η is ratio between the inlet and outlet pressures p_{out}/p_0 and ω is a characteristic parameter, function of the inlet conditions only:

$$\omega = \frac{x_0 (v_{g,0} - v_{l,0})}{v_0} + \frac{c_{pl,0} T_0 p_0}{v_0} \cdot \left(\frac{v_{g,0} - v_{l,0}}{\Delta h_{v,0}} \right)^2 \tag{3}$$

here the first term denotes the fluid compressibility at inlet conditions whilst the second one expresses the compressibility depending on the evaporation due to depressurisation. In critical conditions, in eq. (2) the pressure ratio η is replaced by the critical pressure ratio $\eta_c = p_{cr}/p_0$) calculated by

$$\eta_c^2 + (\omega^2 - 2\omega) \cdot (1 - \eta_c)^2 + 2\omega^2 \cdot \ln \eta_c + 2\omega^2 \cdot (1 - \eta_c) = 0 \tag{4}$$

The limits of this model for short valves are already known (Fletcher, 1984, Fauske, 1984, Fisher et al., 1992) even if they refer mainly to tests on tubes and nozzle.

As compared to HEM model, the HNE-DS method introduces, the parameter "N" correlated to the boiling delay and depending on η_c and x_0. This parameter, that multiplies the second term of eq. (3) is calculated by:

$$N = \left(x_0 + c_{pl,0} T_0 p_0 \cdot \frac{v_{g,0} - v_{l,0}}{\Delta h^2_{v,0}} ln(1/\eta_{cr}) \right)^{0.4} \tag{5}$$

The range of variability for N is $0<N\leq 1$; for high values the method tends to the HEM (for N=1 the equations become the same) whilst for low values the non equilibrium hypothesis prevails.
The HNE methods are mainly used in the case of short nozzles (less than 10 cm) where the fluid residence time could be too short for a significant vaporisation. In the HNE method used in this paper, implemented as proposed by Fischer et al. (1992), the possibility of an intermediate situation between equilibrium and non equilibrium is taken in account; to this aim, a specific parameter N has been introduced.

3. Experimental Set-up And Test Matrix

The VASIB facility (for details see Boccardi et al., 2008) allows to test various devices (commercial safety valves up to ϕmax = 10 mm, or different reference geometries such as convergent, divergent, or straight nozzles, etc) in two-phase flow, with a back-pressure different from atmospheric. Moreover, its thermal-hydraulic characteristics allow to maintain the test conditions without time restriction obtaining more stable and reliable measurements. Usually, the tests have been carried out setting an inlet pressure and a mass flow-rate and changing the inlet vapour quality. Experimental data characterized by pressure loss (Δp) through the valve less than 10 kPa and those with inlet vapour quality less than 0.5% have not been considered to avoid using data affected by large instrumentation errors. Table 1 shows the performed test matrix.

Table 1 Test Matrix

Pin MPa	Tests	Mass flow rate kg/s					Quality %						
		0.08	*0.11*	*0.14*	*0.19*	*0.25*	*1*	*2*	*3*	*4*	*5*	*7.5*	*10*
0.5	*4*	3	1	-	-	-	2	1	1	-	-	-	-
0.75	*10*	6	3	1	-	-	3	2	2	1	2	-	-
1	*17*	5	7	5	-	-	2	4	2	3	4	2	-
1.25	*20*	7	7	5	1	-	3	4	3	3	3	2	2
1.5	*28*	8	8	7	4	1	5	4	4	4	3	4	4
1.75	*28*	7	7	7	6	1	5	4	5	5	3	3	3
Total	*107*	36	33	25	11	2	20	19	17	16	15	11	9

4. The Discharge Coefficient

The "discharge coefficient" k_d (eq.1) is an experimental coefficient that considers the differences between ideal and real valves. PSV manufactures provide and guarantee the coefficients, obtained by experimental tests, for liquid (k_l) and gas flow (k_g); in the case of two-phase flow there are no standards for k_d estimation.
Leung (2004) and Darby (2004) have proposed general methods for k_d calculation. Leung estimates k_d as a function of the compressibility coefficient ω, obtaining values between k_g and 1. According to Darby, k_d equals h k_l for subcritical flow and k_g for critical flow. Lenzing et al. (1998) propose to calculate k_d as a function of the void fraction at inlet conditions, α_0, knowing k_l and k_g:

$k_d=\alpha_0 k_g+(1-\alpha_0)k_l$ (6)

Under this hypothesis, k_d varies between k_l and k_g; in our test conditions, it moves rapidly to k_g for increasing vapour quality. For the HNE-DS (Diener et al. 2004), the authors suggest to modify eq. (6) introducing a different value of the void fraction calculated in the narrowest cross section of the valve (usually the orifice):

$\alpha_{seat}=1-\{v_{l,o}/v_o[\omega(1/\eta-1)+1]\}$ (7)

Finally, if k_g is unknown or a conservative design is required, k_l is used instead of k_d. Fig. 1 shows the k_d values calculated according to the three suggestions of Leung (2004), Lenzing et al. (1994) (k_d values are slightly higher using α_{seat}) and Darby (2004). In order to compare the three method without other uncertainty sources (different k_d choices), correlation (6) has been adopted in every cases, since it does not require ω (HNE is not a "ω method") and takes in account inlet conditions (Darby's k_d is constant).

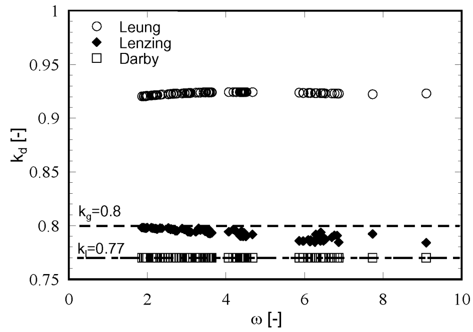

Fig. 1 Test discharge coefficient calculated by Leung, Lenzing et Darby

5. Results and Discussion

In order to evaluate the prediction accuracies of the methods, two parameters have been introduced: RG, i.e. the ratio between the mass flow rate predicted by the method, calculated by eq. (1), and the actual mass flow rate; the second one (Boccardi et al, 2008), Δupc, is defined as

$\Delta upc= (u_{out}-u_{in})/u_{in}$ (8)

u_{in} and u_{out} are the velocities calculated at orifice area under equilibrium hypothesis, at the inlet and outlet conditions, respectively, and it can be correlated to expansion phenomena in the PSV.

5.1 Comparison between HNE-DS and HEM

Fig. 2 shows RG values for HNE-DS and HEM; the markers denote different values of Δupc. It can observed that the differences between the two methods become larger as

Δupc increases. The HNE-DS method presents a better performance and slightly overestimates for a few high values of Δupc.

In fig. 3, the ratio between the mass flow rate calculated (named RGM) by HNE-DS and HEM methods is reported as function of Δupc, while the markers denote the precision of HNE-DS method predictions. RGM values are greater than 1 for all the points because HEM method calculations are always lower; the HEM method underestimations are almost between 2 and 40%. RGM increases with Δupc but the HNE-DS method's precision remains good: that means that this method becomes more reliable than the other one more and more Δupc increases.

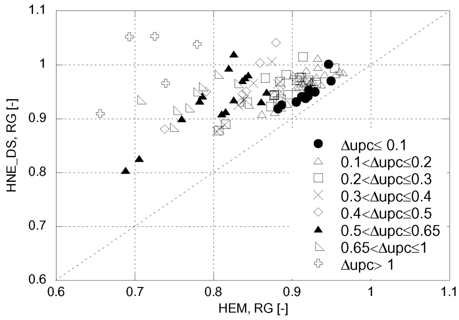

Figure 2. HNE-DS RG as a function of HEM RG. Parameter Δupc

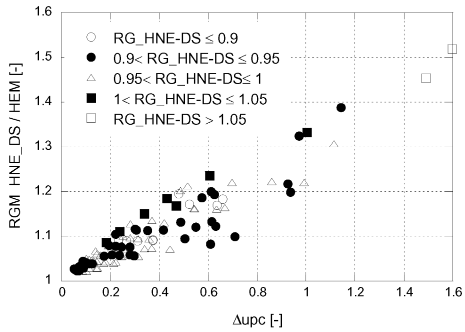

Figure 3: RGM HNE-DS/HEM as function of Δupc. Parameter RG_HNE-DS

5.2 Comparison between HNE-DS and HNE

Fig. 4 shows that all HNE predictions are higher than those of HNE-DS; the differences decrease with Δupc decreasing. Moreover, the points overestimated by HNE are more than HNE-DS and they cannot be connected to particular Δupc values.

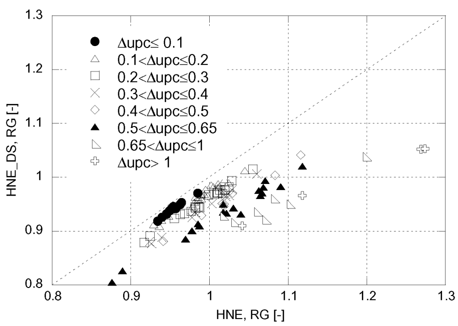

Figure 4. HNE-DS RG as a function of HNE RG. Parameter Δupc

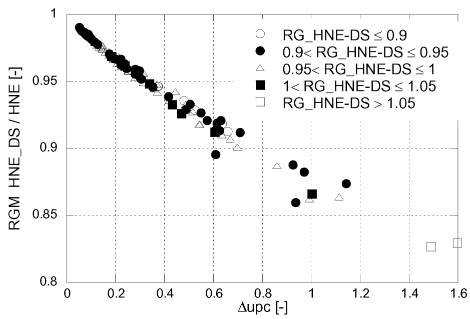

Figure 5: RGM HNE-DS/HNE as function of Δupc. Parameter RG_HNE-DS

RGM between HNE-DS and HNE, Fig 5, is always less than 1 because HNE predictions are higher than HNE-DS ones; the trend decreases almost linearly showing an increasing difference between the two methods as Δupc increases. The comparison does not highlight any clear indications on Δupc useful to understand when a method is better than the other.

5.3 Statistical evaluations

The accuracy of the methods can also be evaluated by statistical parameters (Diener et al., 2005). Table 3, where $X_{i,ln}=\ln G_{i,exp}/G_{i,calc}$ and $X_{i,abs}=G_{i,exp}-G_{i,calc,}$ summarizes the numerical values of statistical quantities of interest.

Table 3 Statistical reproductive accuracy of the sizing methods

			HEM	*HNE-DS*	*HNE*
Variance of logarit. deviations	$S_{\ln} = \exp\sqrt{\frac{\sum_{i=1}^{n} X^2_{i,\ln}}{n-f-1}} - 1$	S_{ln} (%)	*18.6*	*6.9*	*5.8*
Mean logarit. deviation	$X_{\ln} = \exp\left(\frac{1}{n}\right)\sum_{i=1}^{n} X_{i.\ln} - 1$	X_{ln} (%)	*16.2*	*5.3*	*-0.25*
Variance of absolute deviations	$S_{abs} = \sqrt{\frac{\sum_{i=1}^{n} X^2_{i,abs}}{n-f-1}}$	S_{abs} (kg/s)	*0.02*	*0.006*	*0.01*

Overall, all three methods show good values. The negative value of HNE mean logarithmic deviation indicates a tendency to overestimate the calculated mass flow rate; its maximum deviation for the tests overestimated amounts to 27.4%. HNE-DS method has a positive value of the mean logarithmic deviation (i.e. it underestimates on the average), but occasionally overestimates up to a maximum deviation of 5.2%. HEM method presents no overestimation.

6. Conclusions

The performance of the methods seems to depend on their adaptability to different geometries and thermal-fluid dynamic conditions (Boccardi et al., 2008) as well as on the choice of the method to calculate the discharge coefficient. In the present work, the discharge coefficients calculated as proposed by Lenzing have been used for the comparison with experimental data.

The HNE-DS method shows the best predictive aptitude having fewer and lower overestimations and good values of the statistical parameters. HNE method is not conservative because overestimates too many tests while the HEM method is always conservative, but has a lower precision.

The PSV tested has discharge coefficients for gas and liquid very close each other, therefore the k_d calculated by the methods proposed by Lenzing and Darby (fig. 1) are similar, with the latter slightly lower. This involves a calculated mass flow rate lower and more suitable to be used with overestimating methods (HNE and, even if for only a few points , HNE-DS, see Fig. 4). The method proposed by Leung implies a higher k_d , corresponding to about 10% of mass flow rate increment; this is certainly unacceptable for HNE and HNE-DS methods (too overestimated points) and would involve excessive overestimations in HEM predictions as far as a maximum deviation of 11.4 %.

By using α_{seat} instead of α_0, k_d is slightly higher but the differences are negligible. Considering the valve geometry, its small dimensions would have suggested to use

HNE models (Lees, 1996); if we compare HNE and HEM predictions, this is true for the variance of absolute deviations but we have to consider the conservative aspect too (HNE overestimates). In conclusion, the difficulty to find a theoretical model adapted to sizing a PSV in two-phase conditions has been demonstrated again; in fact the more accurate method, HNE-DS, is a HEM method that uses a semi empirical approach (N calculation) to consider non equilibrium phenomena.

References

Boccardi G., Bubbico R., Celata G.P., Di Tosto F. (2008), Geometry influence on safety valves sizing in two-phase flow, *Journal of Loss Prevention in the Process Industries*, volume 21 (2008) pp. 66–73

Bolle, L., Downar-Zapolski, P., Franco, J., Seynhaeve, J.M., (1996). Experimental and theoretical analysis of flashing water through a safety valve, *Journal of Hazardous Materials*, Volume 46, Issue 2-3, pp105-116

Darby R. (2004), On two phase frozen and flashing flows in safety relief values Recommended calculation method and proper use of discharge coefficient Ge, *Journal of Loss Prevention in the Process Industries*, vol. 17 (2004) pp. 255–259

Diener, R., Schmidt, J., (2004) Sizing of Throttling Device for Gas/Liquid Two-Phase Flow Part 1: Safety Valves, *Process Safety Progress*, Vol.23, No.4, pp. 335-344.

Diener, R., Schmidt, J., (2005) Sizing of Throttling Device for Gas/Liquid Two-Phase Flow Part 2: Control Valves, orifices and nozzles, *Process Safety Progress*, Vol.24, No.1, pp. 29-37.

Fauske, H.K., (1984) Scale up for safety relief runaway reactions. *Plan/Operations Prog*, 3, 7

Fisher, H. G., Forrest, H.S., Grossel, S. S., Huff J.E., Muller A. R., Noronha J.A., Shaw D.A., Tilley B.J., (1992). Emergency relief system design using DIERS technology. *The DIERS Project Manual*, AIChE, New York

Fletcher ,B, (1984). Flashing flow through orifices and pipes. *CEP*, pp.76-81

Henry, R.E., Fauske, H.K., (1971). The two-phase critical flow of one-component mixtures in nozzles, orifices, and short tubes. *Journal of Heat Transfer*, 93, pp.179-187.

Lees, F. P. (1996). Loss prevention in the process industries. Oxford/Boston, USA: Butterworth Heinemann.

Lenzing, T., Friedel, L., Cremers, J., Alhusein, M., (1998). Prediction of the maximum full lift safety valve two-phase flow capacity. *Journal of Loss Prevention in the Process Industries,* Vol.11, pp. 307-32

Leung, J. C., (1986). A generalized correlation for one-component Homogeneus Equilibrium flashing choked flow, , *AIChE Journal,* vol.32, 1622

Leung, J. C., (1990). Two-phase flow discharge in nozzles and pipes – A Unified Approach, *Journal Loss Prevention Process Industrial*, vol 3, pp. 27-32

Leung J.C., (1995). The omega method for discharge rate evaluation. *International Symposium on Runaway Reactions and Pressure Relief Design*, Boston, 367-393.

Leung, J.C., (1996). Easily size relief devices and piping for two-phase flow. *Chemical Engineering Progress*, 92 (12), 28-50

Leung, J. C., (2004). A theory on the discharge coefficient for safety relief valve, *Journal Loss Prevention Process Industrial*, vol 17, (2004) pp. 301-313