Mass flow determination in flashing openings

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ABSTRACT
The output flow characteristics in most of the industrial accidental releases are related to a two-phase flow and their represent a potential hazard to facilities, personnel, equipments and environment. If these releases involve superheated liquid then a flashing process can take place, where a liquid-gas mixture due to the breaking of the metastable state can significantly affect the hazard zone. The calculation of the conditions for the flow after a flashing opening is very relevant in order to understand the mechanisms present after the release opening. Numerical modelling represents an important tool to approach these types of phenomena. However, the accuracy of the obtained results will depend on the realistic values of the flow parameters taken as input information to perform the CFD work. The model proposed here is based on the assumption of the existence of a non reversible work in the system and the use of the thermodynamic jump formulation to model the phase change process in order to predict phase velocity and mass flow. The obtained results have a good agreement with the experimental data available.

Key words: Flashing, CFD, accidental releases

1. INTRODUCTION

The calculation of the flow mass rate of a two-phase jet varies with the conditions of the fluid according to its thermodynamic condition. The mass rate can be estimated as a two-phase mixture in thermodynamic equilibrium or as a liquid-gas flow in non equilibrium according to the thermodynamic behaviour of the whole system [1].

When a liquid at superheated condition is exposed to a lower pressure a phase change takes place. The vapour first appears as individual bubbles by nucleation process. If the nucleation progresses further the liquid breaks into droplet and the gas becomes the continuous phase. The estimation of how many bubbles are created by nucleation inside the liquid core, before it reaches the opening, is not well established in a quantitative manner. The behaviour of the vapour in the stream at the exit of a flashing jet is normally considered as a compressible flow, moreover, it is considered to be in critical condition or at least subsonic. Due to the existence of liquid together with the gas the critical condition of this system differs from the well known sonic condition of a single phase compressible gas.

The classical critical single-flow approach as well as the two-phase models developed based on the assumption of isentropic condition often over predict the discharge velocity of superheated fluid and therefore of the momentum distribution at the exit, even for low quality values. Here is relevant to incorporate the consideration of the presence of non-isentropic condition in the discharge calculation procedure based on the physic relation between the forces acting in the flow and the work done in the process. This fact represents a step forward in the understanding of the discharge process of superheated fluids [2].

2. REVIEW

The critical condition of a compressible flow is achieved when the velocity of flow reaches the speed of sound in the fluid. The speed of sound in gas-liquid mixtures is much lower than those in each individual phase. The velocity of sound in a vapour is often at least one order of magnitude larger that the velocity of the sound in the corresponding liquid [3]. The general expression for the velocity of sound, *c,* within a bubbly flow is a function of the void fraction of the flow, α, and independent of the size of the bubbles [4]. This expression is shown in Eqn **1**.

$$c = \sqrt{\frac{v_l p}{\alpha\left(1-\alpha\right)}} \tag{1}$$

where v_l and p are the pressure and the specific volume of the liquid phase.

The models available to calculate the velocity discharge of a two-phase jet have in common the assumption of an isentropic condition of the fluid; however, there are some differences between them.

The Locally Homogeneous Flow (LHF), also known as Homogeneous Equilibrium Model (HEM), treats the fluid as a mixture of the different fluids, with mean properties based on the individual properties of the fluids and the same velocity, temperature and pressure at each cross section, steady state condition, the one-dimensional approach, the negligible inlet kinetic energy, the no wall friction and no wall heat transfer, and the convergent flow passage. Then, from the energy balance the calculation of the velocity and the mass flow rate is based on the enthalpy difference between the injection and the exit conditions. Whilst the Separated Model (SF) treats the flow as a two-phase, liquid-gas flow, with individual properties, negligible exchange of heat, mass and momentum between them, therefore, the gas content is kept constant at the expansion chamber condition [5].

A further develop of the equations was made by Solomon, Ruupprecht et al. [5] to cover the cases of complete liquid discharge, critical and non-critical equilibrium gas-liquid discharges, which means that this approach may be applied to both critical and non-critical discharges using different thermodynamic parameters at the exit location for each case. For critical cases, also known as choked flow, the value of pressure at the exit will be the saturation pressure corresponding to the temperature calculated from the equilibrium expression for two phase flow. For non-critical cases, the pressure at the exit is the ambient pressure and the temperature is the saturation temperature at that pressure [6].

The homogenous frozen model (HFM), also assumes that the vapour and the liquid have the same velocity and that the quality of the fluid through the nozzle remains constant. The contribution of the liquid enthalpy is assumed negligible.

The Moody's model assumes that the two phases are in equilibrium but they do not have the same velocity. This difference in velocity is represented by a slip ratio at the exit. The calculation assumes annular flow at the exit.

The Henry and Fauske model is based on a presumption of non equilibrium flow but with liquid and vapour again possessing the same velocity. The critical mass flux is then given by a general expression that involves the relationship between the thermal equilibrium polytrophic exponent, the entropy of the fluid and the quality at the throat of the nozzle. Here the quality is assumed as a function of the flow regimes and the throat pressure gradient. If the quality is equal to the unity, the mass flux is close to the HEM and if the quality is equal to zero, the mass flux is close to HFM.

A different approach involving the investigation of the shock regime in the flow of boiling liquids through a nozzle showed that the gas fraction and the velocity discharge depend on both the nucleation before the nozzle and the pressure drop through the nozzle. The model develop based in this study consist in a two equations model for the two flow regime [7].

The study of phase change present in a two-phase flow as a shock wave allows the application of the jump condition analysis to the discharge of a superheated liquid [8,9]. The jump conditions leaded in the Rayleigh equation and the evaporation adiabatic equation. The point where the Raleigh is tangent to the evaporation adiabatic curve, known as the lower Chapman-Jouguet point, is a unique solution to the jump condition for which the down stream condition is sonic or chocked in relation to the moving wave. However, depending on the initial thermodynamics conditions and the fluid boundary condition the subsonic flow can take place. The formulation involves a quasi one-dimensional steady evaporation wave inside the superheated liquid. The downstream condition has to be in thermal equilibrium, neglecting gravitational effects and the initial liquid condition as stagnation point.

3. MODEL DEVELOPING

The continuity, momentum and energy balances using the jump conditions for a non isentropic case are expressed in Equations **2, 3** and **4**.

$$\left[\frac{w}{v}\right] = 0 \tag{2}$$

$$\left[p + \dot{g}^2 w\right] = F \tag{3}$$

$$\left[\frac{u^* w}{v} + \frac{u^2 w}{2v} + pu\right] = W \tag{4}$$

where $\dot{g} = \frac{w_1}{v_1} = \frac{w_2}{v_2}$ is the mass flow per unit area, $[f]$ represents the jump function, $f_2 - f_1$. The absolute velocities of the flow before the wave, w_1, and after the wave, w_2, are both related to the velocity of the wave, u, as follows in Eqns **5** and **6**:

$$w_1 = u_1 - u_i \tag{5}$$

$$w_2 = u_2 - u_i \tag{6}$$

The term u_i is the velocity of the interface and u_1, u_2 are the relative velocity of the fluid before and after the wave. The pressure p_2 corresponds to the interception of the energy and momentum equations. Where F and W can be interpreted as the momentum and the work done in the system.

The hypothesis proposed in this work is based on the existence of a linear relationship between the total force at the interface and the work done in that location [2]. In this form the process can be assumed as non isentropic. The work done is defined as the force per unit area multiplied by the velocity before the wave as established by Eqn **7**:

$$W = Fw_1 \tag{7}$$

The exit condition can be established based on the jump condition together with the equilibrium condition and the velocity of the sound in the mixture. Assuming that the fluid is at equilibrium condition the properties at any location after the wave involve the quality of the mixture.

From the mass conservation equation it is clear that the mass flow per unit area is constant. As expressed by Eqn **8**.

$$\frac{w_1}{v_1} = \frac{w_2}{v_2} \tag{8}$$

Considering that the first point in the jump equations coincides with the stagnation point, $u_1 = 0$ then the relative velocity of the fluid at that point corresponding a that point is only the interface velocity, $w_1 = u_i$. For a position in the flow after the wave, the velocity must be different to above condition. In fact this velocity is proposed to be the velocity of the sound in that mixture.

Based on the combination of the velocity can be expressed a relation between both velocities before and after the wave shown in Eqn **9**.

$$w_2 = u_2 + w_1 \tag{9}$$

Combining these equations with the mass conservation, the expression of velocity after the wave becomes a function of the void fraction after the wave and the wave velocity, as expressed by Eqn **10**.

$$u_2 = \left(\frac{\rho_{2,l} + \alpha\rho_{2,fg} - \rho_1}{\rho_{2,l} + \alpha\rho_{2,fg}} \right) w_1 \tag{10}$$

On the other hand, the velocity after the wave is expressed as the speed of sound in the flow, as shown by Eqn **11**.

$$u_2 = \sqrt{\frac{p_2}{\rho_{2,l}\alpha(1-\alpha)}} \tag{11}$$

Using the relation between forces per unit of area and the work done by the fluid from Eqns **3** and **4**, it is possible to rewrite an implicit relationship for the characteristics of the flow after the wave as a function of the void fraction, as Eqn **12** establishes:

$$\begin{aligned} &\rho_1 \frac{\rho_{2,l} + \alpha\rho_{2,fg}}{\rho_{2,l} + \alpha\rho_{2,fg} - \rho_1} \frac{p_2}{\rho_{2,l}\alpha(1-\alpha)} + p_2 - p_1 - \rho_1(\mathrm{U}_2 - \mathrm{U}_1) - \\ &\frac{1}{2} \frac{p_2}{\rho_{2,l}\alpha(1-\alpha)} - p_2 \sqrt{\frac{p_2}{\rho_2\ \alpha(1-\alpha)}} \left(\frac{\rho_{2,l} + \alpha\rho_{2,fg} - \rho_1}{\rho_{2,l} + \alpha\rho_{2,fg}} \right) = 0 \end{aligned} \tag{12}$$

With the void fraction known, the velocity at the exit is directly computed by Eqn **11,** the velocity of the wave is then computed from Eqn **9**. Finally the momentum and work done in the system by the transition between these two locations are computed from the momentum and energy conservation equations.

The total mass flow discharge by the system will be estimated by the velocity and the density established by the jump condition at the nozzle (see Eqn 13) and the proportion of the gas and the liquid mass flow correspond to the void fraction of the mixture as shown by Eqns **14** and **15**.

$$\dot{m} = \rho_2 u_2 A \quad (13)$$

$$\dot{m}_l = (1-\alpha)\,\dot{m} = (1-\alpha)\,\rho_l uA \quad (14)$$

$$\dot{m}_v = \alpha\dot{m} = \alpha\rho_g uA \quad (15)$$

4. RESULTS

The results shown in this section correspond to the application of the proposed model to an experimental case performed by Allen J.L. [10], using propane as working fluid. The major interest in this case obeys to the existence of previous studies using different approaches for calculating velocity discharge and mass flow rate applied to this case. Velocity discharge and mass flow information for the different sources is presented in Table 1.

Table 1 Comparison of the result obtained for a experimental case with initial temperature of 232 K and 10132 Pa corresponding to a nozzle diameter of 4 mm using propane as working fluid

	Experiment	TRAUMA (liq)	TRAUMA (HEM)	Proposed model
Velocity [m/s]	~(32	59.42	130.23	29.00
Mass flow rate [kg/s]	0.11	0.110	0.059	0.126
Source	[9]	[11,12]	[6,11,12]	[2]

5. DISCUSSION

Due to the coexistence of liquid and vapour phases at the flashing jet, the exit of a flashing jet, which is related with the critical condition, is characterized for a speed of sound in a mixture rather than the speed of the sound in every individual phase. The discharge velocity computed by the proposed model for the test case, shown in Table 1, differs from the velocities calculated using the non equilibrium condition models described by Kelsey [11,12] named Moody's model and Homogeneous Equilibrium Model (HEM) model. The velocity of the real discharge is closer to the velocity of sound in the corresponding two-phase mixture.

The over predicted value of the velocity obtained for both HEM and Moody's model can be explained in the assumption of that the initial stagnation point corresponds to liquid condition and the generation of vapour takes place under saturation or equilibrium conditions during the expansion process. This situation does not represent the bubble generation in a metastable liquid. In fact the phase change occurs under a rapid acceleration or pressure changes generating a flashing vapour-liquid mixture, which can be modelled as a shock wave moving through a multiphase medium [13]. This is especially true when the pressure change is large when compared to the ambient pressure, or any of the driving potentials are large relative to their reference values. So, in neither of these cases the modelling hypothesis are not the most realistic for the physics involved in a flashing discharge.

The introduction of new consideration shown by Eqn **7** covers the fact that there is a work done against or in the system, W, and this work is related to the momentum of the fluid by the parameter, F, highlighting a way to assume the process of a flashing discharge as a non isentropic process.

The expression shown by Eqn **12** include all, the possibility of the critic condition for an actual two-phase mixture, a non isentropic process, and the modeling of the phase change as a wave with a discontinuity if the properties, therefore the computed velocity discharge and the mass flow are better than the calculated using previous models.

6. CONCLUSIONS

The consideration of a non-isentropic flow plus the treatment under jump conditions approach allows a more realistic calculation of the liquid and gas mass flow as well as the velocity discharge of a flashing jet. So, this procedure is a big step forward in the understanding, physical modelling and calculation of a flashing jet. The results obtained by the application of the proposed model have a very good agreement with the experimental data.

7. REFERENCES

1. Khajehnajafi, L. and Shinde J. Prediction of discharge rate from pressurized vessel blowdown through sheared pipe. 1994. Process Safety Progress 2: 75–82.
2. Polanco, G. C. Phase change within flows from breaches of liquefied gas pipelines. PhD Thesis. Coventry University, 2009.
3. Gudmundsson, J. S. and H. K. Celius. Gas-liquid metering using pressure-pulse technology. SPE Annual Technical Conference and Exhibition, Houston, Texas. 1999.
4. Young, F. R. Cavitation. London, Imperial College Press. 1998.
5. Solomon C. Ruupprecht, Chen Faeth. Flow and atomization in flashing injectors. 1985. Atomization Spray Technology 1: 53–76.
6. Wheatley, C. J. A theoretical study of NH3 concentration in moist air arising from accidental releases of liquefied NH3, using the computer code TRAUMA. Health and Safety Executive. Report number: SRD/HSE/R 393. 1987.
7. Skripov, V. P., Sinitsyn E. N. et al. Thermophysical properties of liquids in metaestable (superheated) state. Amsterdan.Gordon and Breach Science Publisher. 1988.
8. Simoes-Moreira, J. R. Oblique evaporation waves. 2000. Shock Waves 10: 229–234.
9. Simoes-Moreira, J. R. and C. W. Bullard. Pressure drop and flashing mechanisms in refrigerant expansion devices. 2003. International Journal of Refrigeration 26: 840–848.
10. Allen, J. T. Laser-based droplet size measurements in two-phase, flashing propane jets. Health and Safety Laboratory. 1996.
11. Kelsey, A. CFD modelling of two phase flashing jets: Simulation of evaporating sprays to inform modelling of flashing jet. Health and safety laboratory: Report number: 56. 1999
12. Kelsey, A. CFD modelling of two phase flashing jets: Simulation of flashing Propane jets. Health & Safety Laboratory Report: 61. 2001.
13. Yang, L., Zhang C. Two-fluid model of refrigerant two-phase flow through short tube orifice. 2005. *International Journal of Refrigeration* 28: 419–427