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Geometry influence on safety valves sizing in two-phase flow

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Abstract

In the case of two-phase vapour–liquid flow, especially for low vapour quality (<10%), pressure safety valves (PSV) design becomes very difficult due to complex thermal-hydraulic phenomena occurring between the two phases. Currently, there are some calculation methods, based on different simplifying hypotheses, trying to predict the two-phase flow rate through a PSV knowing inlet fluid conditions (pressure, quality or temperature) and the outlet pressure. However, none of them is acknowledged as being reliable for any situation and, therefore, there is still a lacking of standards for PSV design under two-phase conditions. The PSV size is one of the most important parameters used for choosing between the two main prediction models, homogeneous equilibrium model (HEM) and homogeneous non-equilibrium model (HNE).

This paper shows the results of an experimental research carried out with steam-water two-phase flow through two PSVs having the same orifice diameter (10 mm), but different discharge coefficients and inlet geometry. The experimental results are compared with the predictions obtained using a calculation method based on a homogeneous model with non-equilibrium hypotheses and another method proposed in API Recommended Practice 520, developed with equilibrium hypotheses. The results show that the PSV geometry and the discharge conditions are important factors for choosing the more suitable model for the sizing of a little PSV.
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Keywords: Safety valve sizing; Two-phase flow; Homogeneous model; Geometry; Discharge coefficient

1. Introduction

An uncontrolled pressure increase, causing damages to the plant components, is one of the most frequent sources of accidents. A pressure safety valve (PSV) is one of the most commonly used devices for keeping the system pressure below the equipment design value. PSV sizing in single-phase flow is straightforward, while in two-phase flow discharge conditions choosing among the many available correlations and methods, each of them with different starting hypotheses, appears more cumbersome. In this latter case, indeed, the analysis and the mathematical representation of the rapid vaporisation inside a PSV is very difficult owing to the incomplete knowledge of the complex thermal-fluid dynamic phenomena occurring between the two phases. The same difficulty is found in the prediction of the critical flow. This phenomenon occurs when the fluid velocity equals the sound velocity in the fluid and involves reaching of an upper limit in the mass flow-rate, thus resulting in a limitation of the discharge capability. In this situation, a further outlet pressure decrease has no effect on the discharge conditions and, therefore, the mass flow rate will remain constant. Usually, for each set of inlet flow conditions (pressure and vapour quality or temperature for subcooled conditions) it is possible to find the outlet pressure corresponding to the onset of critical flow; the corresponding ratio between outlet and inlet pressure is termed as "critical pressure ratio", and indicated with η_c.

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Nomenclature

C	specific heat capacity (J/kg K)
G	mass flow-rate (kg/h)
h	specific enthalpy (J/kg)
K	discharge coefficient (dimensionless)
k	isentropic expansion exponent (dimensionless)
P	pressure (Pa)
RG	ratio between the model mass flow-rate and the actual one (dimensionless)
T	temperature (°C)
u	velocity (m/s)
v	specific volume (m^3/kg)
x	mass vapour quality (dimensionless)

Greek letters

α	homogeneous void fraction (dimensionless)
η	pressure ratio (dimensionless)
ϕ	diameter (m)
ω	compressible flow parameter (dimensionless)

Subscripts

0	stagnation inlet conditions
c	critical (*choked*) flow conditions
g	gas
in	inlet conditions
l	relative to the liquid phase
lg	difference between vapour and liquid phase
or	orifice
r	actual
s	specific
sat	saturation
t	theoretical
v	valve

In summary, the mass flow-rate calculation under two-phase flow conditions is very complex for the following reasons:

- the close interaction between vapour quality and changes in pressure drop;
- possible thermodynamic non-equilibrium between the liquid and the vapour phases with liquid metastable conditions causing a delay in vaporisation;
- the potential different velocity of the two phases; the slip ratio, defined as the ratio between the gas and the liquid velocity, is a very important parameter being a kinematic non-equilibrium indicator, though its calculation is very uncertain;
- the sound velocity in two-phase flow shows a strong reduction as vapour appears; in the case of water, it changes quickly as reported by Bolle, Downar-Zapolski, Franco, and Seynhaeve (1996) from a high value for subcooled liquid to a value 50 times lower for low vapour quality, which is also markedly less than sound velocity in gas. However, its calculation is still a matter of discussion.

The design of a PSV has to respect some input conditions. Its performance (mass flow capacity) can depend on the fluid and the working and installation conditions, while its intervention is only a result of a component pressure and is therefore affected by any inlet pressure loss and by the back-pressure, especially when the PSV is not balanced. Its sizing is carried out, for the service required, computing the smallest orifice area necessary to discharge the design mass flow rate; afterwards the commercial PSV adopted will be that with the next bigger orifice area. In single-phase flow, the nozzle is assumed to be ideal, the flow adiabatic and isentropic and one-dimensional analysis is applied. The theoretical mass flow-rate G_t, thus computed has to be corrected by an experimental coefficient K_v, termed as "discharge coefficient", to obtain the actual mass flow-rate value

$$G_r = G_t K_v. \tag{1}$$

PSV manufacturers supply and guarantee the discharge coefficient for liquid (K_l) and gas flow (K_g). Their importance is evident when computing the actual mass flow-rate value; at present they are obtained by experimental tests with atmospheric back-pressure.

Although the procedure would be the same for two-phase flow, in this case there is no standard and therefore the designer has to choose among various theoretical calculation methods looking for the most suitable according to the specific design conditions. Moreover, no information is directly available about K_v, its value depending on the flow conditions. The lack of a reference standard represents a serious limit for PSV industrial applications in two-phase flow; in order to overcome it, different agencies are looking for a fairly simple correlation that considers all the two-phase flow aspects. Recently, correlations developed on the basis of the HEM have been considered the most interesting. The American Petroleum Institute, API (2000) has issued a report where a method for PSV sizing in two-phase flow, based on the HEM, is suggested. In another paper, Lenzing, Friedel, Cremers, and Alhusein (1998) proposed a simple correlation that considers the inlet conditions and K_l and K_g, for discharge coefficient computing. On the other hand, the limits of this model for short valve are known—Fletcher (1984), Fauske (1984), and Fisher et al. (1992)—even if they result mainly from tests on tubes and nozzle.

This paper presents the results of a research activity carried out at the Institute of Thermal-Fluid Dynamics of ENEA for studying two-phase flows through safety systems. Tests were carried out on two commercial PSVs

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