Two phase pressure drop in a rupture disc/ safety valve unit

Lutz Friedel

Techn. Prüfung, Hoechst AG, D-6230 Frankfurt/M. 80 Hanns-Michael Kissner, Dechema, D-6000 Frankfurt/M. 97, FRG

For straightforward engineering design purposes, the pressure drop of a rupture disc/safety valve unit is related by means of experimentally determined relative discharge reduction coefficients to the flow resistance of the safety valve in the unit. In the case of single phase flow the pressure drop can be calculated on the basis of the liquid or gas/vapour flow discharge coefficients available from the respective suppliers' catalogues. For two phase flow conditions reference must be made to the fitting correlations of S. D. Morris or H. C. Simpson *et al.*, which are presently the most accurate methods available.

(Keywords: design principles pressure system design; two phase flow)

Pressurized reactors in the chemical industry have recently been increasingly protected against an undesired pressure rise using combined units consisting of a rupture disc and a pressure relief valve. This trend results from the demand for absolute security (tightness) or for long-time protection of the safety valve against aggressive or fouling promoting fluids. However, the current hydraulic design of these units is based only on a few experimental values of the relative discharge reduction coefficient, deduced from specific single phase pressure drop measurements in narrow parameter ranges. From experience, a reliable design using this data, especially for two phase flow conditions, will not be possible. On the other hand, a tentatively calculated value for the unit flow resistance as the sum of both individual pressure drops leads to unnecessarily oversized minimum flow cross areas and thus the safety design problem is only transferred to another plant area, since a larger than necessary total pressure drop is assumed. Thus, an adequate and reliable fluid-dynamic design is required.

Therefore, experiments for the determination of the discharge reduction coefficient have been carried out. In this respect, the irreversible pressure drop across a combined unit, consisting of a bursted metal foil rupture disc with vacuum support and a full lift safety valve, as well as across both components alone for comparison have been determined. As model fluids air/water, air/water–ethanol and air/water–glycerine mixtures were used. The basic concept is then to relate the unit pressure drop to the easier accessible flow resistance of the safety valve in the unit. It in turn, in the case of single phase flow can be calculated using the liquid or gas/vapour discharge coefficients included in the respective suppliers' catalogues. For two phase flow design, the fitting correlations of S. D. Morris[1] or H. C. Simpson *et al.*[2] are recommended.

Analytical studies

The pressure profile along a discharge line with practically fully established single phase or two phase flow upstream of the device is shown in *Figure 1*. Directly across the open rupture disc/safety valve unit there develops a pressure differential, which is subsequently partially recovered in the downflow direction due to a reverse transformation of kinetic energy into pressure energy, and which finally changes to a net pressure drop characteristic for the safety device. This pressure difference, determined if necessary by extrapolation of the pressure courses with and without the unit, is related to the combined fitting and defined as the permanent effective pressure drop. In the case of two phase flow, it consists of the pressure loss in the unit and the sum of the reversible pressure drops due to acceleration, deceleration and geodetical elevation. Indeed, the pressure loss in the unit is larger than the effective pressure drop, but the latter is nevertheless used in the design calculations, since a pressure recovery in real discharge lines does not occur.

The effective pressure drop of the unit is made up by the rupture disc pressure loss and the flow resistance of the safety valve. Assuming identical nominal inlet diameters, the loss in the rupture disc will be relatively small in comparison with the valve pressure drop, since the narrowest effective flow cross section is in the safety valve and is by far smaller than in the disc. This suggests itself to relate the unit pressure drop by a relative discharge reduction coefficient to that of the safety valve, particularly since this is readily available from the

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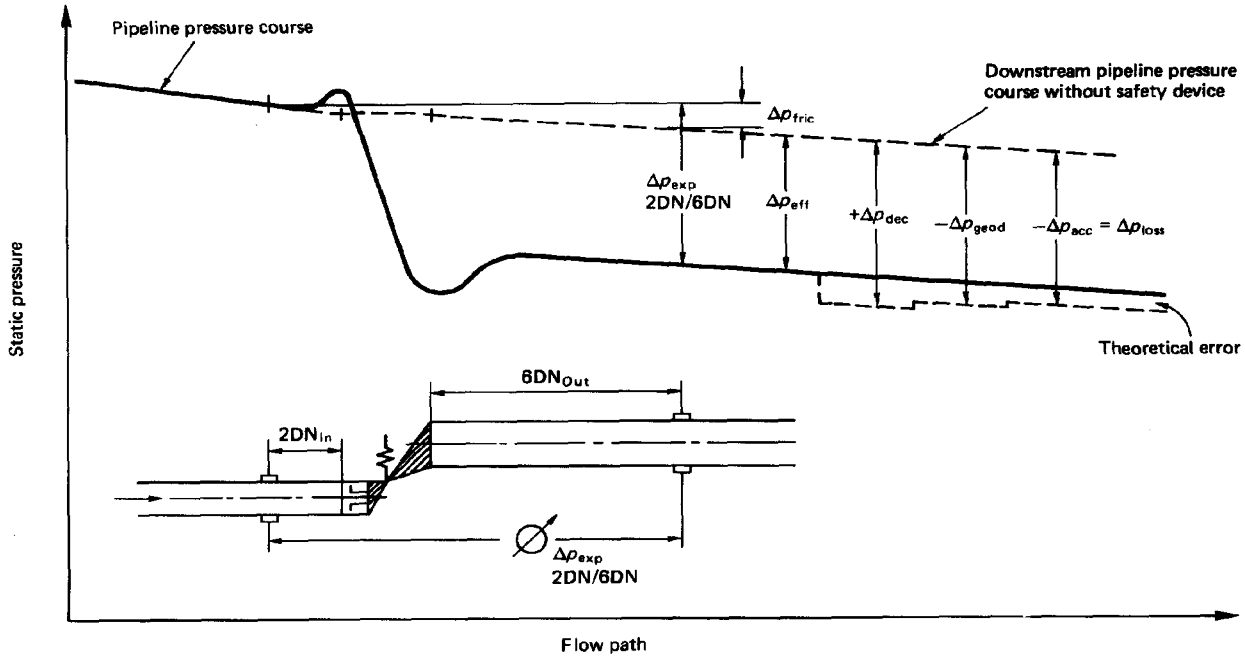

Figure 1 Pressure course in pipe flow with open rupture disc/safety valve unit

suppliers' catalogues, or obtainable from the fitting correlations of S. D. Morris or H. C. Simpson *et al.*

In the following, the relative discharge reduction coefficients relating both discharge capacities or effective pressure drops are defined. The derivation starts from the general discharge equation:

$$\frac{M^*}{A} = \alpha \cdot \sqrt{2 \cdot \Delta p \cdot \rho},$$

whereby M* denotes the mass flow due to the pressure difference Δp across the valve or the combined unit; A the narrowest geometric flow area; ρ the fluid density, and α the discharge coefficient characterizing the losses in the device. It is obtained by experiment, and is defined as the ratio between the actual and theoretical (isentropic) mass flow.

This equation is now applied to the flow in the safety valve and in the combined unit. Hence, it follows that:

$$\frac{M_u^*}{A_u} = \alpha_u \cdot \sqrt{2 \cdot \Delta p \cdot \rho} \text{ and } \frac{M_s^*}{A_s} = \alpha_s \cdot \sqrt{2 \cdot \Delta p \cdot \rho}$$

If the mass flow in both configurations is reduced relative to the safety valve seat, this being the narrowest flow cross-section in both cases, then the discharge equations will read:

$$m_u^* = \alpha_u \cdot \sqrt{2 \cdot \Delta p \cdot \rho} \text{ and } m_s^* = \alpha_s \cdot \sqrt{2 \cdot \Delta p \cdot \rho}$$

Furthermore, assuming practically identical fluid densities, a relative discharge reduction coefficient is obtained as a quotient of the individual discharge coefficients or as the mass flow ratio at identical pressure differences:

$$f = \frac{\alpha_u}{\alpha_s} = \frac{m_u^*}{m_s^*}$$

From this definition it follows that equal pressure differences should prevail for an experimental investigation of the mass flow reduction in the combined unit in comparison with that in the safety valve alone. Since this is nearly impossible to maintain during the experiments, then for simplicity's sake, identical mass flows are imposed in both cases and the respective pressure differences were measured.

From these experiments, the relative discharge reduction coefficient is deduced as:

$$f \approx \sqrt{\frac{\Delta p_s}{\Delta p_u}}$$

The relative discharge reduction coefficient characterizes in this way the pressure drop increase in the combined unit, or the discharge capacity decrease due to the higher flow resistance in the unit in relation to the nominal rating of the safety valve included in the combined unit. The reduction coefficient always amounts to less than unity.

In the literature, only few relative discharge reduction coefficient values that are valid for specific configurations and narrow single phase flow conditions are available. Our own experiments were therefore performed.

Experimental investigations

The pressure drop measurements are carried out on a unit consisting of a metal foil rupture disc DN 25 with vacuum support and a pressure relief valve DN 25/40, the respective specifications are included in the appendix. For obtaining the maximum effect of a prearranged rupture disc on the total unit resistance, a disc with a relatively high specific pressure drop is combined with a valve with relatively low specific flow resistance. In this way, the relative discharge reduction coefficient gives a lower limit for engineering design assessments.

The experiments have been carried out using a multipurpose two phase test rig during two phase flow of air/water, air/water–ethanol and air/water–glycerine mixtures *Figure 2*. Under steady state conditions, the pressure drop across the unit as well as across the two components alone is measured at distances of twice the upstream nominal disc/valve diameter and six times the downstream nominal valve diameter. With this arrangement, measurements can be taken in the inlet line in an undisturbed upstream flow, and in the outlet line the disturbance of the downstream flow should have faded down to a negligible degree. Hence, the downflow static pressure is assumed to be that of a practically fully developed flow. However, there still remains the problem of accurately predicting the friction pressure drop of the non-developed inlet and outlet flow within these two pipe sections ahead of the disc/valve, and behind the valve for calculating back to the effective pressure drop of the device. Here, this is solved by additionally measuring the static pressure at further distant upstream and downstream tap positions for the development of pressure courses that can be extrapolated up and back to the device.

During all measurements, care was taken that no choked conditions occurred in both the unit and the safety valve. This was repeatedly checked before taking a measurement by opening a throttling-valve mounted in the outlet piping for regulating a constant system pressure. Generally, by this procedure the upstream pressure in the inlet line of the unit and the safety valve was changed distinctly and the mass flow rate increased. According to the usual definition, no choked flow in the fitting should have occurred.

The parameter ranges of the experiments are listed in *Table 1*. At the moment, about 120 measurements are at hand covering experiments with three model fluid systems at safety valve openings of 75 and 100%. By the use of aqueous glycerine and ethanol mixtures, the viscosity of the liquid phase and the surface tension can

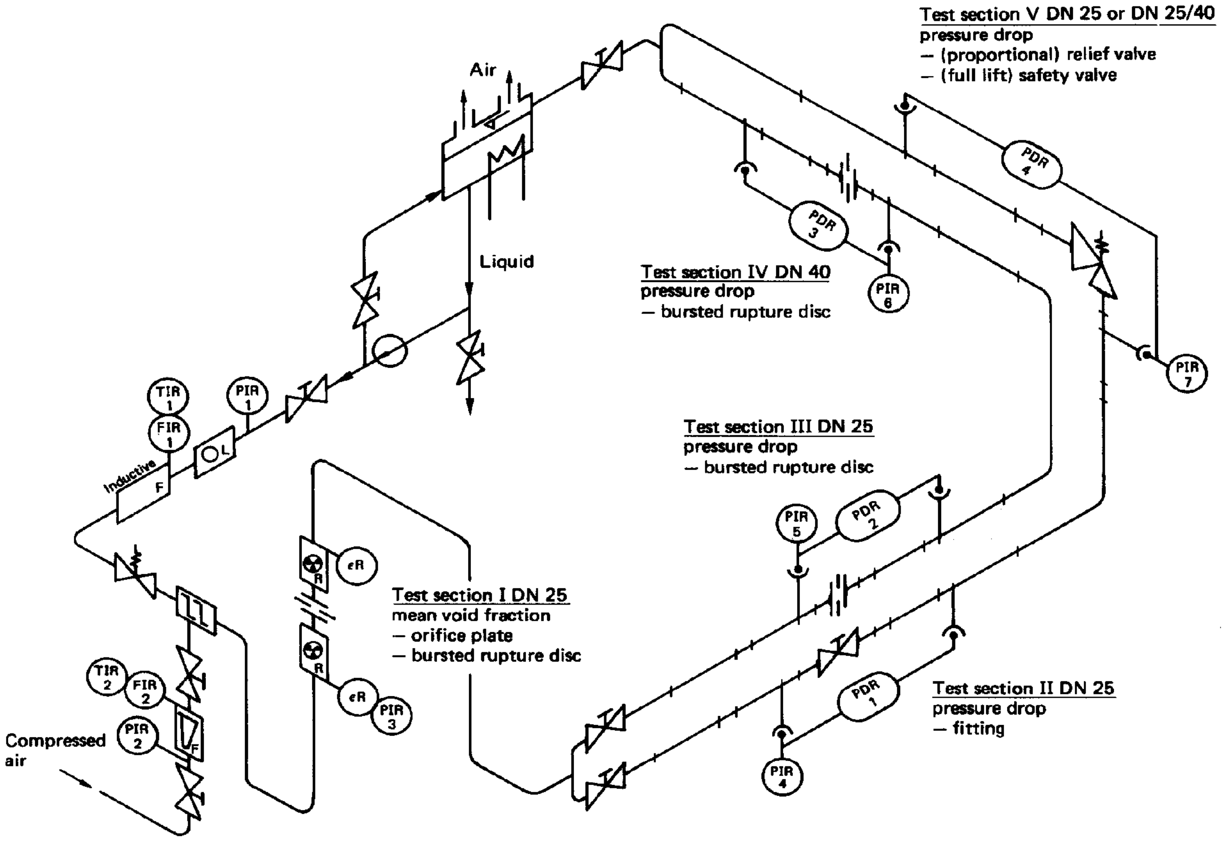

Figure 2 Multipurpose two phase flow test rig system: pressure $\leqslant$ 16 bar; temperature, $\leqslant$ 370 K; air mass flux, $\leqslant$ 500 kg m^{-2}s (DN 25); liquid mass flux, $\leqslant$ 6000 kg m^{-2}s (DN 25)

Table 1 Parameter ranges of measurements

Variable	Parameter range		
	Air/water	Air/water-ethanol	Air/water-glycerine
Mass flow quality (%)	0–17	0–17	0–5
Pressure (bar)	4–7	4–7	8–9
Density ratio —	119–218	118–214	115–124
Viscosity ratio —	48–57	66	164–165
Surface tension (N m^{-1} × 10^{-3})	72	60	66
Mass flow rate (kg m^{-2} s)			
upstream condition	2000–6010	1997–4004	1998–2010
valve seat condition	2468–10200	2466–6789	2469–3396
Diameter (m × 10^{-3})			
upstream condition	25	25	25
valve seat condition	19–23	19–23	19–23
Valve opening (%)	75–100	75–100	75–100
Data points	58	48	8.

be changed, and thus the influence of these fluid properties on pressure drop were determined.

The pressure drop across the bursted rupture disc with vacuum support as a function of air mass flow quality and with a mass flow rate parameter is shown in *Figure 3*. The complete pressure drop course exhibits a trend already well known from pipe flow pressure drop experiments. It starts at the value for single phase liquid flow ($x^* = 0$) and increases overproportionally with higher quality when a logarithmic scale is adopted for the ordinate axis. This trend is due to the large rise in the volumetric flow rate, the occurrence of substantially higher phase velocities and the increasing momentum exchange between the phases. For a higher air mass flow quality, the gradients begin to flatten out, since due to a probable transition from bubble flow to annular flow, the momentum exchange between the phases decreases and therefore the slip increases. The pressure drop course would finally terminate at a quality of 100% relating to the pressure drop of the single phase gas/vapour flow, whereby depending upon the mass flow rate a more or less distinct maximum is exhibited for qualities between 70 and 90%.

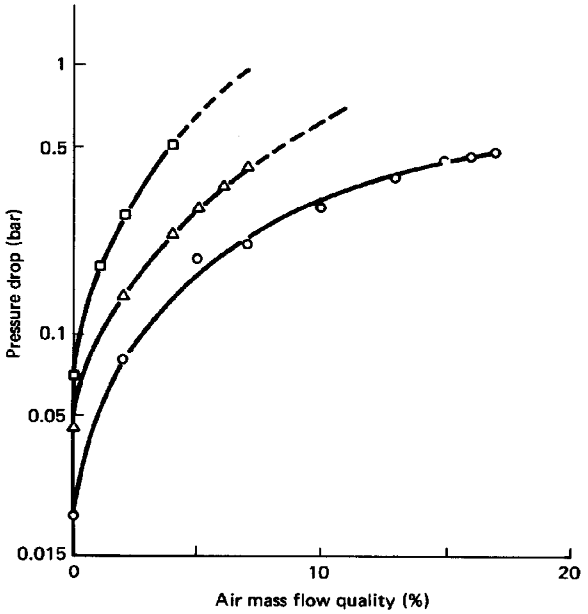

Figure 3 Two phase pressure drop across the rupture disc DN 25 with: vacuum support; air/water flow; pressure, 6 bar; temperature, 298 K. Mass flow rate: □, 4000; △, 3000; ○, 2000 (kg m^{-2} s)

An increase of the mass flow rate produces an expected higher pressure drop. At critical mass flow rates, such as would occur in emergency venting, correspondingly higher pressure drops would prevail. However, this range is by far unobtained here, since for comparison purposes only mass flows applied in the safety valve pressure drop experiments, which would produce quasi critical or subcritical flow conditions in the valve seat region, were deliberately used in these experiments. In this respect, the flow conditions in the rupture disc experiments are dictated by the parameter ranges of the safety valve or combined unit pressure drop measurements.

The effective pressure drop across a safety valve as a function of quality mass flow rate and valve lift is depicted in *Figure 4*. The trend of the obtained pressure drop course is similar to that with the rupture disc. Again, an increase in mass flow rate produces higher pressure drops. If the valve lift is decreased, an increase of the flow resistance also occurs due to the more intensive deviation of the average flow and the larger flow restriction in the valve seat and body. In total, the pressure drop across the safety valve at identical flow conditions is higher by a factor of six, confirming in this way the initial assumption with respect to the relative magnitude of the individual flow resistances.

The effective pressure drop across the fully and partly open combined unit along with the corresponding sum of the individual pressure drops is shown in *Figures 5* and *6*. It is obvious that during single phase and two phase flow, the combined unit always exhibits a lower pressure drop*. This might be due to the so-called

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*The lower total pressure drop of two components in close arrangement is well accepted[3,4]. A recent publication of P. Sookprasong[5] raises some doubts.

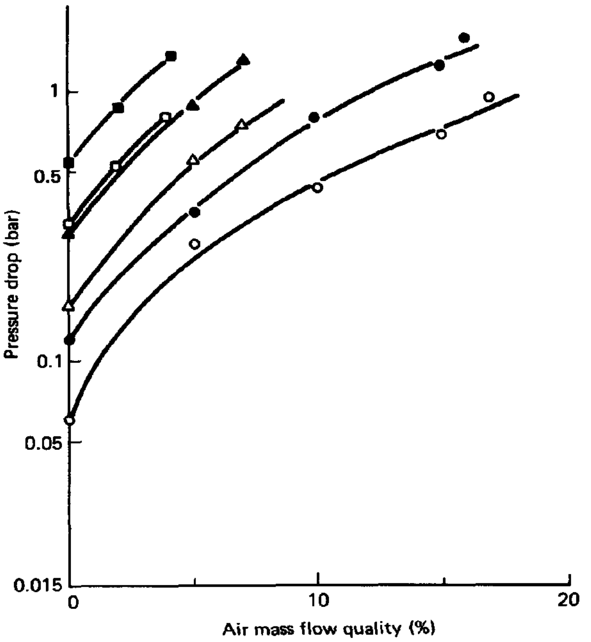

Figure 4 Two phase pressure drop across the pressure relief valve DN 25/40; air/water flow; pressure, 6 bar; temperature, 298 K. Mass flow rate: □, ■, 4000; △, ▲, 3000; ○, lift 100%, 2000; ●, lift 75%, 2000 (kg m^{-2} s)

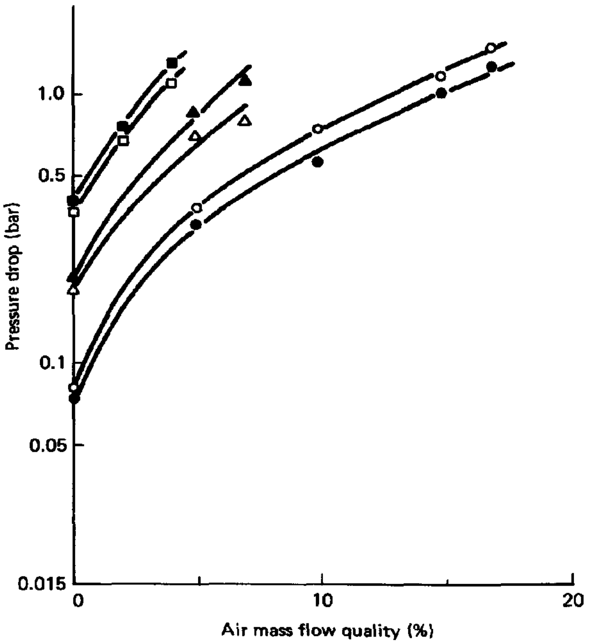

Figure 6 Two phase pressure drop across the fully open rupture disc (DN 25)/safety valve (DN 25/40) unit and the sum of both the individual two phase pressure drops; valve lift, 100%; air/water flow; pressure, 6 bar; temperature, 298 K. Mass flow rate; □, ■, 4000; △, ▲, 3000; ○, 2000, sum of individual pressure drops, ●, 2000, combined unit (kg m^{-2} s)

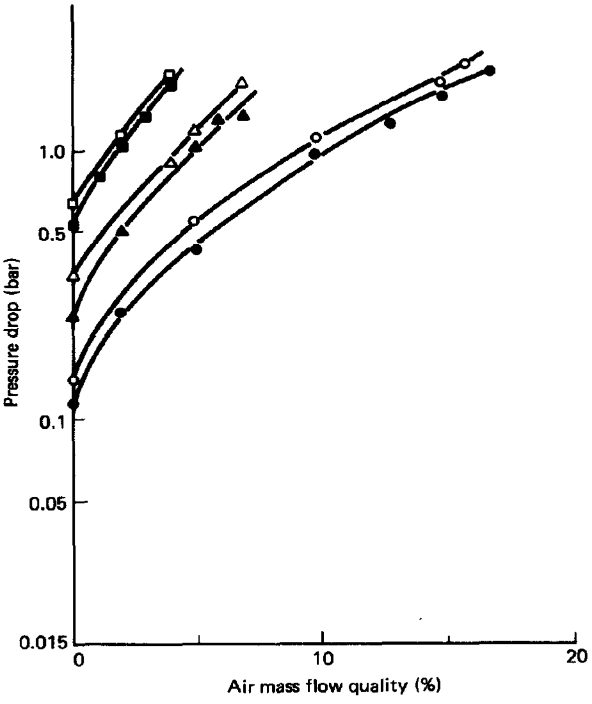

Figure 5 Two phase pressure drop across the partly open rupture disc (DN 25)/safety valve (DN 25/40) unit and the sum of both individual two phase pressure drops; valve lift, 75%, air/water flow; pressure, 6 bar; temperature, 298 K. Mass flow rate: □, ■, 4000; △, ▲, 3000; ○, 2000, sum of individual pressure drops, ●, 2000, combined unit (kg m^{-2}s)

interference of the flow resistances. In the pre-installed rupture disc, a flow profile is already formed. Due to the short flow path between the two components the disc is still fully or at least partly preserved until entering the subsequent safety valve, requiring in this context less additional energy for transformation to the final velocity distribution than in the case of no upstream disturbance. This interrelationship seems to be independent of the valve lift. Indeed, the influence of the rupture disc flow resistance on the unit pressure drop is less with a valve lift of 75% due to the higher specific pressure drop of the safety valve.

On the basis of these measurements, the relative discharge reduction coefficients are determined as a function of air mass flow quality for each fluid system at identical mass flow rates and valve openings, *Figures 7* and *8*. As expected, the coefficients amount to less than unity, they depend on quality (in the low quality region), mass flow rate, viscosity and surface tension provided that both these properties are adopted as characteristic for the fluid mixtures behaviour. In detail, for single phase flow and a valve lift of 75%, the reduction coefficients range between 0.91 for air/water-glycerine and 0.96 for air/water, indicating for all three single phase systems that there is only a slight influence of the pre-arranged rupture disc on the discharge capacity of the only partly open safety valve. Indeed, for a fully open valve the single phase relative discharge reduction coefficients range between 0.88 and 0.93, hence the influence of the rupture disc on the capacity

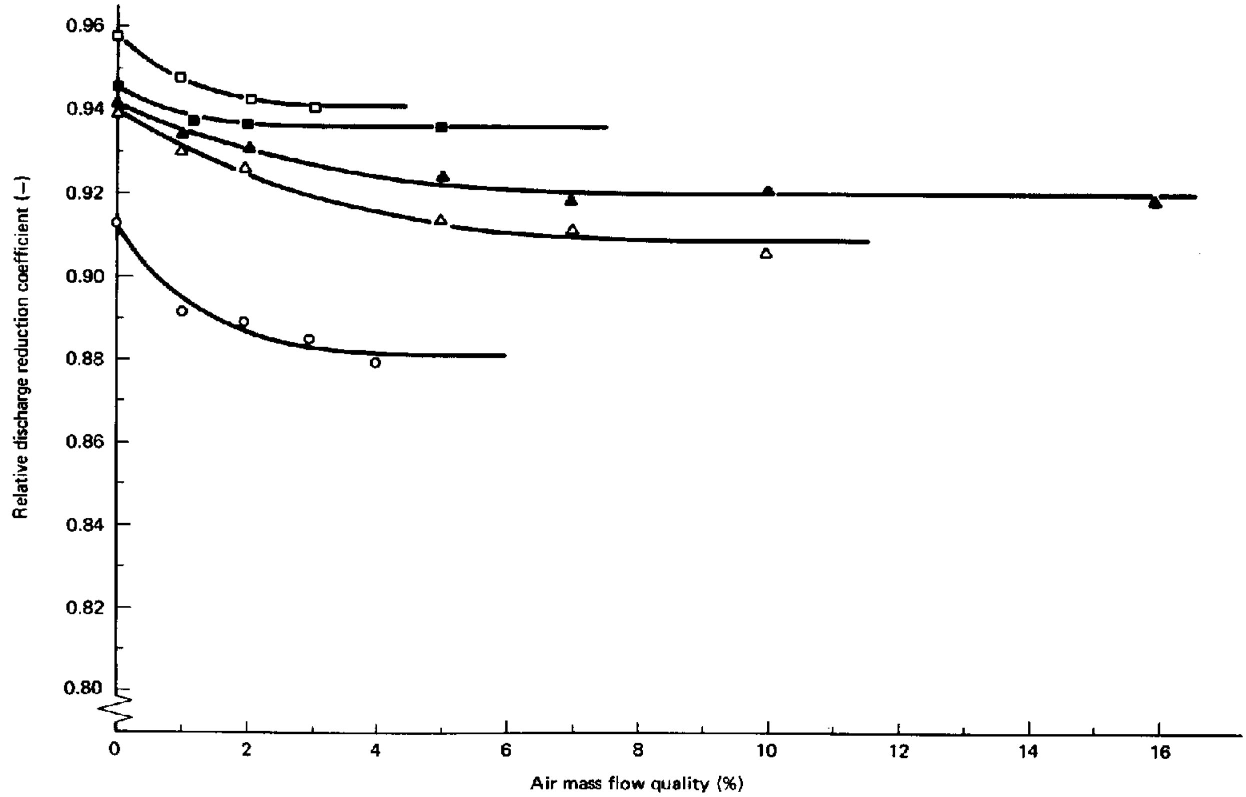

Figure 7 Relative discharge reduction coefficient of the partly open rupture disc (DN 25)/safety valve (DN 25/40) unit; valve lift, 75%; density ratio, 120; liquid viscosity, 1 ÷ 30 mPa; surface tension, 60 ÷ 73 mN m^{-1}; temperature, 293 K. Mass flow rate (kg m^{-2} s): □, 4000; ■, 3000, ▲, 2000 (air/water); △, 2000 (air/water-ethanol); ○, 2000 (air/water-glycerine)

reduction is slightly larger. Taking the experiments during single phase water flow as standard, then the coefficient increases slightly with increasing mass flow rate, while it decreases marginally with decreasing surface tension and drops with higher liquid viscosity.

The decrease of the coefficient with increasing air quality follows in almost all experiments a similar asymptotical approach towards an individual lower limit, which is achieved at quality values of about 5%. The initial systematic arrangement of the relative discharge reduction coefficients obtained in single phase flow with respect to the weight of mass flow rate, viscosity and surface tension is fully preserved, though the differences between the initial single phase values and the individual courses increase as well indicating a little larger influence during two phase flow conditions.

An exception in the systematic and physically consistent trends of the relative discharge reduction coefficients is exhibited by the experiments with air/water-glycerine mixtures in the fully open combined unit. During the measurements in single phase liquid flow and also two phase flow with air qualities < 3%, two different values for the pressure drop could be measured repeatedly. The two dotted traces in *Figure 8* were developed from both of these values. The reason for this behaviour may be a random change between laminar and turbulent flow or of the flow patterns in the safety valve alone during the experiments.

The relative discharge reduction coefficients for single phase flow, so far obtained, confirm the range of 0.8 to 0.98 included in the proprietary technical literature[6,7]. Obviously, the coefficients are rather insensitive to the type of the components used, since surely different designs from those used here were combined. On the other hand, this coincidence of the magnitude can also only be incidental, since determination of the actual discharge capacity for a given pressure difference commonly incurs different measuring techniques and test procedures. For instance, in most cases the original discharge coefficients in the literature include the pressure drop of the discharge pipe nozzle, which, depending on the arrangement on the pressure vessel, may no longer be neglected. Thus, these values can only be adopted as a first approximation for pressure drop calculations or for the derivation of relative discharge reduction coefficients.

Implication of the results

The experimental results obtained with the combined unit and independently with the individual components during single and two phase flow reveal that the effective

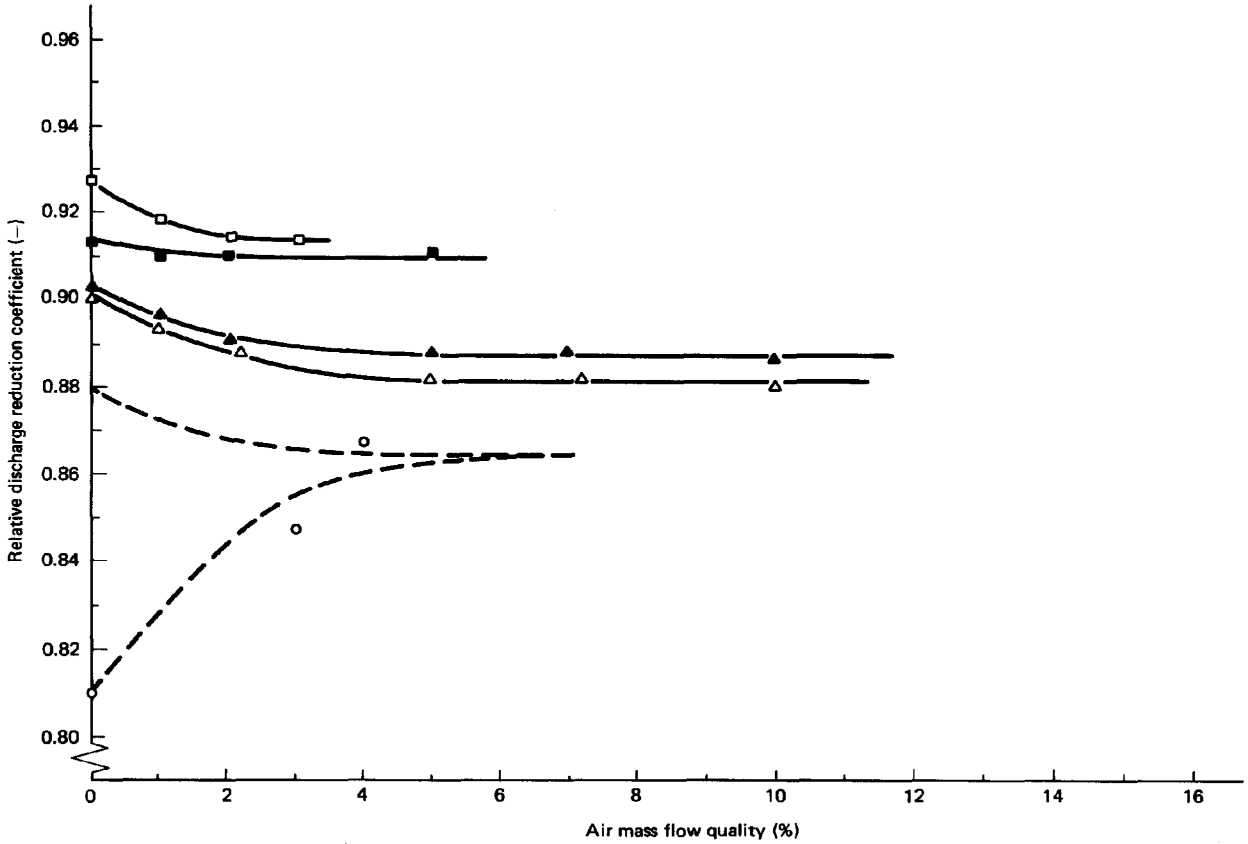

Figure 8 Relative discharge reduction coefficient of the fully open rupture disc (DN 25)/safety valve (DN 25/40) unit; valve lift 100%; density ratio, 120; liquid viscosity, $1 \div 30$ mPa; surface tension, $60 \div 73$ mN m^{-1}; temperature, 293 K. Mass flow rate (kg m^{-2}s): □, 4000, ■, 3000, ▲, 2000 (air/water); △, 2000 (air/water-ethanol); ○, 2000 (air/water-glycerine)

unit pressure drop is less than the sum of both single pressure drops but higher than that of the safety valve alone. A design on the basis of the sum of the individual pressure drops without consideration for the so-called interference of the flow resistances thus leads to oversized flow cross sections. In this case, the seldom available specific rupture disc pressure drop during single and especially two phase flow must also be accurately known. The simple alternative is to neglect the additional flow resistance of the rupture disc and to base the design only on the effective safety valve pressure drop. This, on the other hand, will yield undersized flow cross sectional areas. Both procedures should hence only be used for first estimates. Indeed, a still unproven rule of thumb is to base the design on the arithmetic mean of both simple methods as a fictitious initial design pressure drop.

The alternatively advocated, more reliable and generally applicable design procedure on the basis of experimentally-determined relative discharge reduction coefficients reduces the design problem to the accurate prediction of the effective pressure drop of the safety valve used in combination with the rupture disc in the combined unit. In the case of single phase flow, the design is based on the discharge coefficients for liquid or gas/vapour flow readily available from the suppliers' catalogues and transformed into a pressure drop*. For two phase flow conditions the semi-theoretical fitting correlations of S. D. Morris or H. C. Simpson *et al.* are recommended for prediction of the pressure drop. They are at present the most accurate methods available, though in some extreme situations an unsatisfactorily average accuracy of ± 50% must still be accepted.

The proposed method displays the advantage that the pressure drop of the rupture disc used in the combined unit does not enter into the calculation. Indeed, this results from the initial assumption that its contribution is small compared with the total pressure drop. With all modern rupture disc devices this is nearly always applicable as long as equal nominal diameter devices are combined. Furthermore, if vacuum supports are introduced, they have to open fully during the bursting process.

The present experiments are restricted to nominal inlet diameters of DN 25. In the case of single phase flow, a reliable extrapolation to larger diameters or other fluid systems on the basis of the proposed relative

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*The conversion of the discharge coefficient to a pressure drop or vice versa is included in the appendix.

discharge reduction coefficients should be possible, since in a wide range of the flow conditions approved, single phase discharge coefficients form the basis of the concept. For two phase flow applications, a moderate scaling is also expected, since the predictive accuracy of both recommended two phase pressure drop methods is sufficient at larger diameter units. The restrictions are much more apparent from the insufficient knowledge about the thermodynamic nonequilibrium between the vapour and liquid phase resulting from the complex pressure changes, and moreover about the limits of critical flow in the safety valves.

Acknowledgement

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Nomenclature

A	flow cross section
f	relative discharge reduction coefficient
M^*	mass flow
m^*	mass flow rate
Δp	pressure difference
α	discharge coefficient
ρ	density
s	safety valve
u	combined unit

Appendix

Relationship between discharge coefficient and single phase pressure drop.

$$\Delta p_{\mathrm{exp}} = \frac{\overset{*}{m}{}^2_{\mathrm{inlet}}}{2\rho_{\mathrm{liq}}}\left(1 + \frac{1}{\alpha^2_{\mathrm{liq}}}\left(\frac{A_{\mathrm{inlet}}}{A_{\mathrm{seat}}}\right)^2 - \left(\frac{A_{\mathrm{inlet}}}{A_{\mathrm{outlet}}}\right)^2\right)$$

$$\Delta p_{\mathrm{exp}} \approx \frac{\overset{*}{m}{}^2_{\mathrm{seat}}}{2\rho_{\mathrm{gas}}}\left(\frac{1}{\alpha^2_{\mathrm{gas}}} - \left(\frac{A_{\mathrm{seat}}}{A_{\mathrm{outlet}}}\right)^2 - \zeta_{\mathrm{inlet}} \cdot \left(\frac{A_{\mathrm{seat}}}{A_{\mathrm{inlet}}}\right)^2\right)$$

Specifications of rupture disc/safety valve unit components: metal foil rupture disc DN 25 with vacuum support: Rembe Inc., Type BT-OBV; full stroke safety valve DN 25/40: Leser Inc., Type 441, D/G.7.