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An Investigation of the Two Phase Flow and Force Characteristics of a Safety Valve

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Abstract

The two phase flow of air and water is studied in a safety relief valve commonly used in the industrial refrigeration industry. In some blowdown conditions a valve which has been specified for gas only operation may encounter flows which include liquid droplets, these having been entrained from upstream processes. Of particular interest is the operation under two phase flow conditions which will be dominated by the altered flow capacity and forces acting on the valve. To examine these effects the characteristics of the flow through the valve and the forces acting on the valve disc have been examined for an air water mixtures for a range of pressures, 5-14 bar, and a wide range of gas mass fractions for various different opening positions. These characteristics determine the capacity of the valve to control pressure, the sizing of the spring and the dynamics of the valve during operation. The data on such effects for safety valves is very limited and here we show the trends that result from the introduction of two phase flow mixtures and reflect on the limited previous work in the literature that is available. The tested range of conditions the results indicate that the flow and force characteristics are influenced by liquid injection with a significant influence on the flowrate. The disc forces resulting from the two phase impacts show a small but notable effect from liquid mass fractions. This is in contrast to previous limited data found in the literature.

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Keywords: Safety Relief Valve; Two Phase ; Flow Charactrestics

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1. Introduction

Nomenclature

A_{ref}	reference area (piston seat area taken in this study)
$\bar{F}$	force scaling parameter F_{net} Net piston force (N)
$\bar{M}$	mass flow scaling parameter
$\dot{M}$	mass flowrate (kg/s)
P_a	atmospheric pressure (N/m^2)
P_0	total pressure upstream of valve (N/m^2)
T_O	total temperature upstream of valve (K)

The safe operation of pressurised components requires the automatic venting of the fluid (liquid or gas), when excessive pressure levels have occurred. To achieve this, a wide selection of pressure relief devices are available to the plant engineer, ranging from the sacrificial bursting disc to the controlled pilot operated device. National standards are available to ensure the correct specification, installation, operation and manufacture of the valves [1]. While these standards provide detailed guidance on the application and use of the valves, the equivalent engineering knowledge for the analysis and design of the valves is less evident in the general literature. The reason for this is apparent when one considers the operation of safety relief systems. The opening and closing of a safety valve and its resulting dynamic response is directly related to the forces acting on the valve disc (piston), the moving element of the valve. In simple spring loaded relief valves the forces are dominated by a spring force and the pressure distribution on the disc which is directly coupled to the local flow conditions and the valve disc/nozzle design. The flow conditions can be complex involving high speed compressible flow resulting in multiple choked flow locations and potential shock conditions. Computational analysis approaches using CFD techniques are necessary to appreciate the detailed interaction between the valve elements and the flow. At present these techniques can generally be applied to single phase steady flows with reasonable confidence but have been developed less for unsteady or multiphase operation. For two phase flows in safety valves varying degrees of complexity are possible and can involve mass transfers due to boiling /condensation and chemical reactions with multiple composition mixtures with complex rheology. In this paper, how a safety valve responds to a class of two phase flow restricted to constant composition will be examined. It will include a constant mass fraction of air and water. It may involve sensible heat transfer and velocity slip behaviour but will not include significant mass transfer processes. Even for this simplified case our understanding is limited and how CFD models perform is less known.

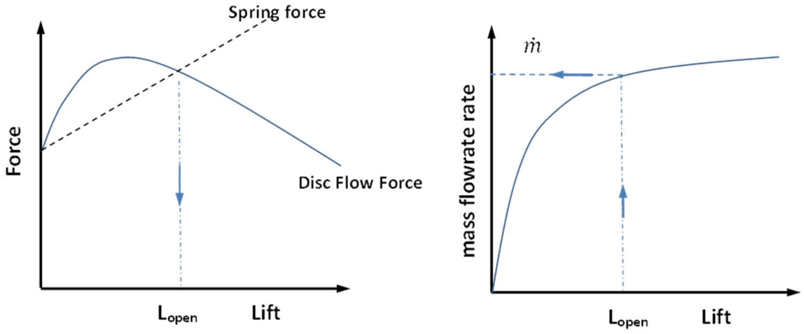


Fig. 1. Valve operational condition at steady state.

For valve design or analysis how the valve force and flow behaviour varies with opening area/ disc movement is an important characteristic will influence the valve operational performance. It is generally considered that the steady state characteristics are applicable during transient conditions if quasi—static assumptions apply which is generally the case if pressure wave actions have no effect. Fig. 1 shows examples of the characteristics and how interaction between spring and flow forces determine a steady opening position Lopen and result in a flowrate $\dot{\mathbf{M}}$ open. It is the valve designer's objective to create a valve geometry that will allow the valve to open (and close) effectively at the desired valve set pressure required for the safe operation of the pressurized system. For single phase conditions it can be shown that the valve disc forces are generally a function of disc opening position and pressure. Fig. 2 below shows this when the scaling parameters $\overline{\boldsymbol{M}}$ and $\overline{\boldsymbol{F}}$, (1) are used to non-dimensionalise the force and flow data determined as part of this paper for single phase conditions. The non dimensionalised data for a pressure range of 4-14 barg allow single curves (within experimental error) to characterize the flow and force associated with the valve.

$$\overline{M} = \frac{\dot{M}\sqrt{T_0}}{P_0} \quad \overline{F} = \frac{\mathrm{F}_{\mathrm{net}}}{(P_0 - P_a\cdot)A_{ref}} \tag{1}$$

For quasi steady conditions these curves allow disc forces to be calculated at any pressure during blowdown. Song et al [2] uses this approach successfully in a validated cased study with a CFD generated force lift curve. For two phase conditions the dependency is less certain. How the valve responds dynamically under two phase flow conditions does not seem to have been addressed in any detail. The only paper to the author's knowledge is the work of Narabayashi et al [3] who measured the transient blowdown disc forces for a number of different two phase conditions. As is shown in Fig. 3, their data indicates that the forces were generally a function of the upstream pressures with little dependence on the two phase regime or mass fraction, suggesting that the same scaling criteria, expressed in equation (1) should work.

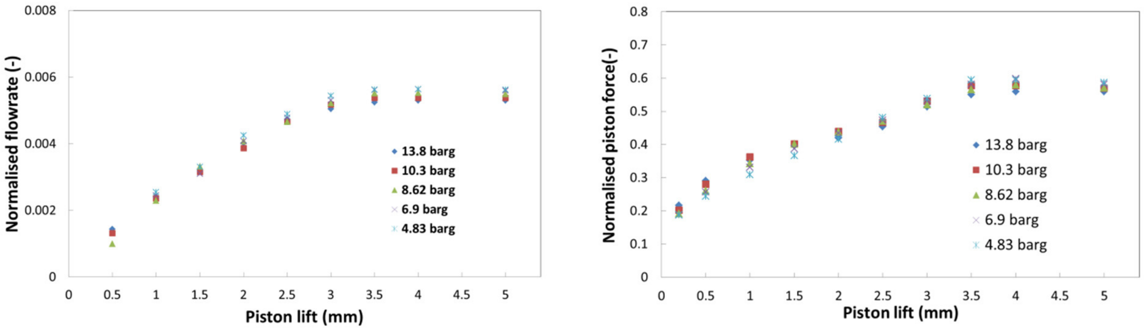


Fig. 2. Flowrate and force pressure scaling example.

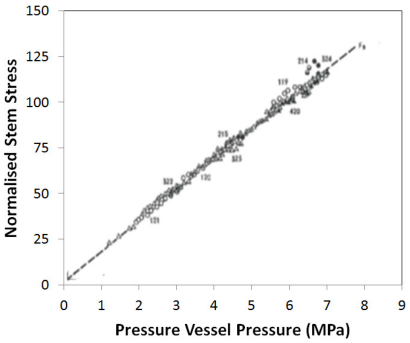


Fig. 3. Force-pressure relationship for a variety of steam- water two phase conditions, Adapted from Narabayashi et al [1].

This is somewhat countered by the early work on drag discs as a means of measuring two phase mass flows [4] which showed that dependency on the two phase momentum flux , ie drag force has a dependency on mass fractions. To understand the dependencies better this paper investigates the forces acting on the disc of a safety valve. The conditions will invariably be choked and in contrast to either of the studies will measure the disc forces under controlled liquid mass injection conditions. The purpose is to show for a safety valve (in this case pertinent to the industrial refrigeration industry) what these steady state characteristics look like for a relatively simple two phase flow.

2. Safety Valve Details

A conventional spring loaded safety relief valve commonly used in refrigeration systems was investigated in this study. Fig. 4 depicts a cross section of ¼" inlet bore size of the safety relief valve which comprises a movable piston, loaded by a spring to the required relief pressure. The spring load is retained and applied by an adjustable gland. The valve establishes a seal through a piston sealing disk inserted into the piston which sits on the valve seat machined into the valve body, to maintain the system pressure.

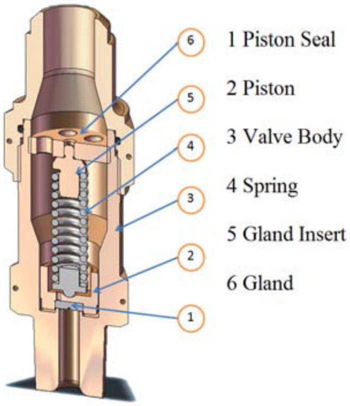


Fig. 4. Safety Relief Valve.

The operation of the valve is mainly a dynamic process therefore exceeding the set pressure leads to the piston lifting to allow mass to discharge via an available flow area. The piston lift relies essentially on the increasing system pressure which is expected to be limited due to the greater flow discharged. The current work is simplified as quasi static conditions are postulated assuming that pressure waves can be ignored. Thus the flow in the valve is adequately represented by a series of steady state conditions. It is expected that this would be more appropriate for the closing operation of a safety relief valve than the opening phase.

3. Experimental Set up and Procedures

An experimental flow facility for valve testing under steady state flow conditions was developed to allow independent control of the valve piston position and upstream water injection at various operating upstream air pressure conditions, Fig. 5. The rationale was to measure the air flowrates disc forces at constant upstream pressure for variations in injected water flowrate. Thus, for each test condition, determined by setting the piston lift, upstream pressure and liquid flowrate, the air mass flow becomes the uncontrolled quantity determined by the circumstances of the two phase interaction with the valve. The water is injected into the flowing air upstream of the valve using a spray nozzle allowing the liquid to mix prior to entering the valve. Downstream of the valve, a separator is used to separate the water and the air. The water collected in the separator also acts as a water supply for the water injection pump. The test rig, Fig. 5, consists of a 100 mm (4 inch) diameter pipe connected to a compressed air system to deliver high pressure (1-15 bar) compressed air to the valve. The tested safety valve is connected to the pipe via a brass converging section to adapt to the valve entrance. A liquid injection nozzle is fitted into the converging section to inject the water. The injection nozzle located in the center of the pipe produces a uniform full cone spray with a low spray angle of 30o. A PVC T junction with a 50 mm diameter side exit is connected to the valve to direct the two phase mixture to a separator. The T junction could be maintained close to atmospheric pressure. It has a pressure tapping fitted to measure the pressure at the valve outlet. The valve piston is attached to a 250 mm long 6 mm diameter rod which passes through the far end of the PVC tube end and is connected to a lead screw and traverse table allowing the piston position to be adjusted.

An Omega LCMFD-500 load cell is attached and inline with rod to measure the forces acting on the disc. The piston movement is in the range of 0-5 mm and was measured by a Mitutoyo digital dial indicator with sensitivity of 0.001 mm. The water injection system consists of a positive displacement diaphragm water pump (Hydra Cell D/G-04 series) connected to the injection spray nozzle via a high pressure hose. The pump has a maximum flowrate of 11 l/min and will deliver the flow independently of the downstream pressure up to 100 bar. The pump is driven by an AC motor controlled by a speed controller, which allows adjustment of the water flow rate. Upstream of the injection nozzle, a turbine flow meter (Omega Engineering FTB 1411) is fitted to facilitate measurement of the water flow rate; it has a flow rate range of 0.4 - 10 l/min and has an accuracy of +/- 1% of the reading. A bladder accumulator (FlowGuard DS-20) is also connected to the pump outlet to damp the pulsating water flow rate from the pump. The air flowrate was measured using a Sierra Vortex mass flowmeter (Innova mass 240) and accurate to <1% of reading. The upstream pressure, and outlet pressure are measured by Bourdon pressure gauges. The range of upstream pressures (1-15 bar) and water flow rates (1-10 L/min) give a working air flow rate from 0.015 to 0.12 kg/s and a water mass fraction range from 0 to 0.9.

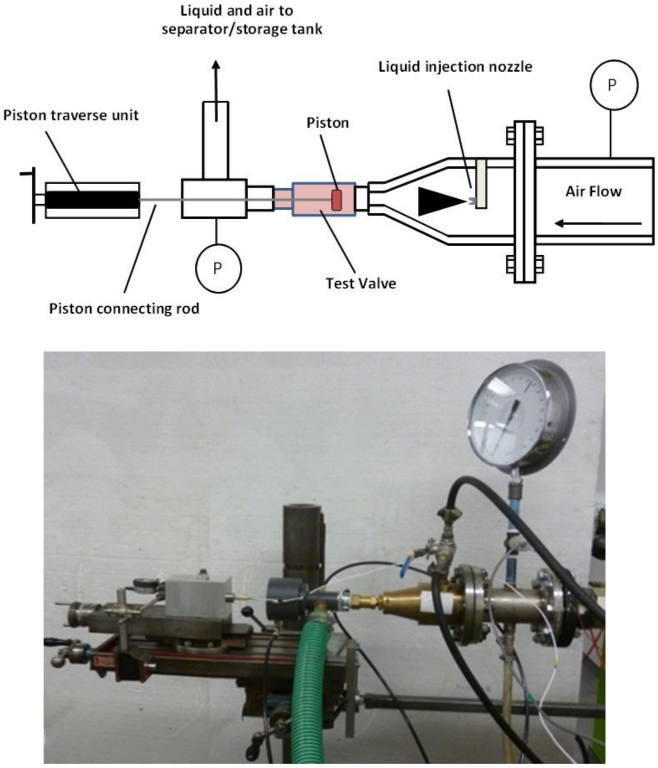


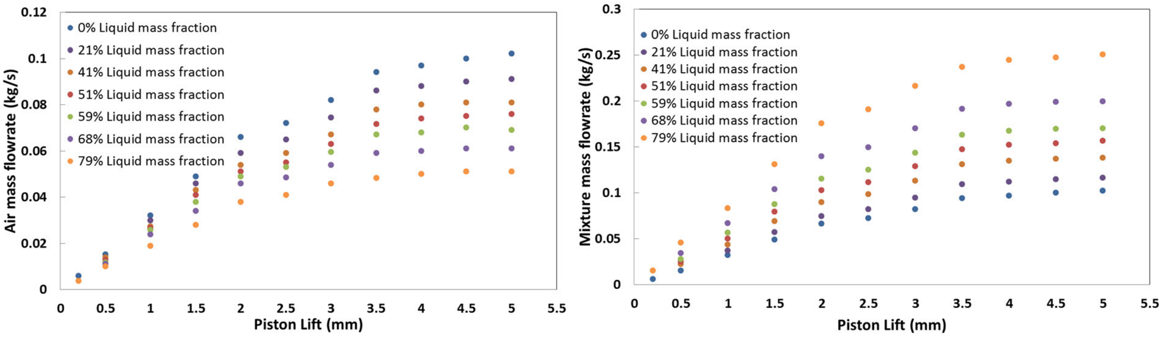
Fig. 5. Experimental Test Facility.

Test data presented in this paper was taken at a pressure of 13.7 barg for a liquid flowrate of 0-10 L/min and at a fixed piston lift position of 5 mm, which corresponds to a fully open position of the valve. This allowed a 0-0.8 range of liquid mass fractions to be examined which influences the degree of mechanical and thermal non-equilibrium, ie velocity differences and the temperature changes during the expansion process. The temperature of the gas decreases during the expansion process as the fluid accelerates but will be restricted by the heat transfer from the liquid which changes less due its larger thermal inertia. Likewise the increasing amount of liquid requires to be accelerated by the air resulting in an interfacial resistance by the liquid. This effect will increase as the liquid mass flow increases. In this study the increased liquid flow acts as a means to introduce greater non equilibrium and takes the form of an independent variable. The effect of the air flow is thus investigated and becomes the dependent variable.

4. Experimental Results

4.1. Flowrate Behaviour

The effect of injecting the water into the safety valve and generating a two phase flow through the valve and how it changes with valve opening is shown on Fig. 6. The data are for a fixed pressure 13.8barg (200 psig). For each liquid mass fraction the flowrates are for critical flow conditions and increase with valve opening until about 3mm disc lift when the critical flow location becomes fixed and the flowrate is independent of lift. As the injected liquid flowrate is increased, indicated by an increase in liquid mass fraction a number of observations can be made. Firstly, the maximum air flowrate decreases, Fig 5a and leads to a reduction in total flowrate, Fig.5 b. For the range of liquid mass fraction studied (0-0.8) the air flowrate can reduce by more than 50%, the total flowrate reduced by nearly 75% and is partly due to the two phase critical flow nature of two phase flow. Secondly, the flowrate reaches a maximum at lower lifts which decreases as the liquid fraction increases. The two phase behaviour at maximum lift can be reasonably predicted at lower mass fraction using the homogeneous model assumptions or across the liquid mass fractions using CFD models as been reported by Alshaikh and Dempster [5].



(a) Effect on Air Flowrate (b) Effect on Mixture Flowrate

Fig. 6. Effect of mass flowrates on two phase injection.

4.2. Force Behaviour

The force characteristics under liquid injection conditions are shown on Fig. 7 for variation in disc lift and again in Fig. 8 a and 8 b for variations in liquid mass fractions at fixed lifts. These Figs show that the forces acting on the valve disc will decrease as the liquid mass flow increases. However the change is relatively minor for the cases shown and leads to an approximate reduction of less than 10% in force. This largely supports the results of Narbayashi et al [1].

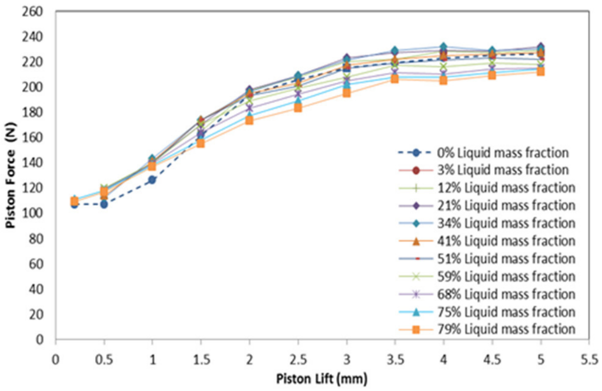
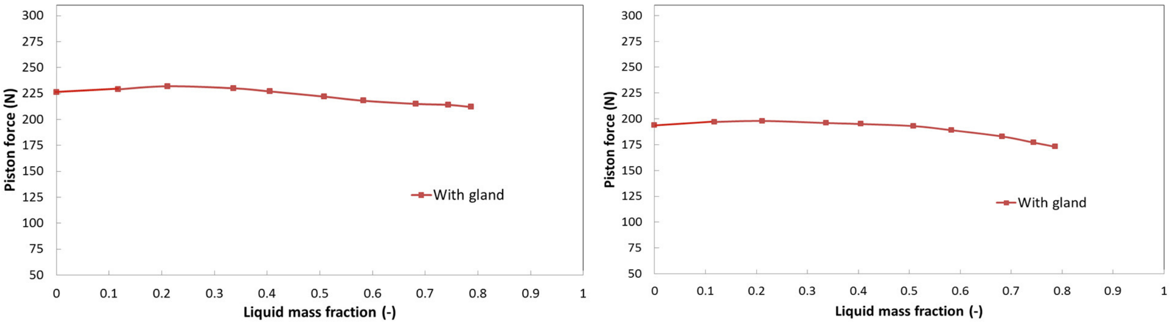


Fig. 7. Effect of liquid mass fraction on disc force.



(a) 5 mm lift

(b) 2mm lift

Fig. 8. Disc force variation with liquid mass fraction for 13.8 bar (a) 5 mm lift (b) 2 mm lif

While the effects of the liquid on the forces are not considered significant from these cases it is possible that more significant effects could result when considering the interaction of the disc force and spring forces. Fig. 9 shows the data with a typical spring line included, the intersection of the curves are the steady state operating point for the valve at the corresponding pressure.

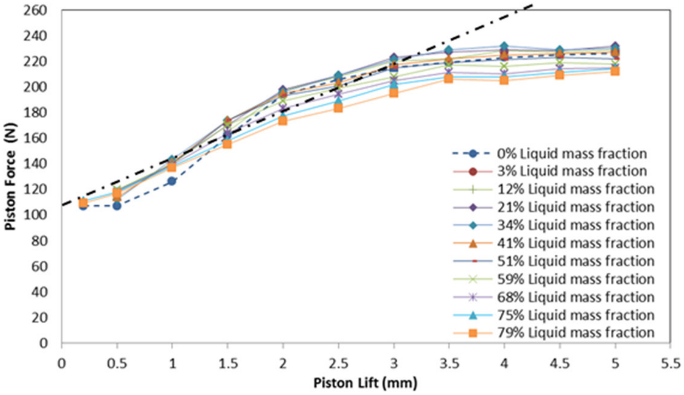


Fig. 9. Spring line and disc force-lift curve combined.

This Fig. shows that for the observed variations in force–lift characteristics due to the considered liquid injection effects the intersection of the spring line can vary between 2.5 mm and 4 mm and for a variable two phase inlet condition would lead to notable oscillation in the disc if these variations were to occur.

4.3. Back Pressure Effects: Gland Design

This type of through flow safety valve where the exit and inlet flow directions are inline, result in a build up of pressure at the rear of the disc (back pressure) due to the restriction imposed by the gland (see Fig. 4). This pressure increases with increasing mass flowrate and decreases the disc force. The gland flow area is a design choice and was investigated in this study by repeating the tests in section 3.1 and 3.2 but with the gland removed, thereby reducing the exit restriction. The gland has no effect on the mass flowrate since the flow is choked upstream. However, Fig. 10 shows the effect on the disc forces and shows a greater reduction in disc force over the liquid fraction range when the gland is removed. For this valve including the gland results in a disc force which has less sensitivity to the liquid mass fraction.

Figure 11 show the effect of variations of liquid fraction on the force lift curves and indicates that notable changes in force lift curves occurs due to liquid fraction without the gland the forces shows a greater sensitivity to varying liquid mass fraction and a reduction of approximately 18% across the liquid mass fraction range.

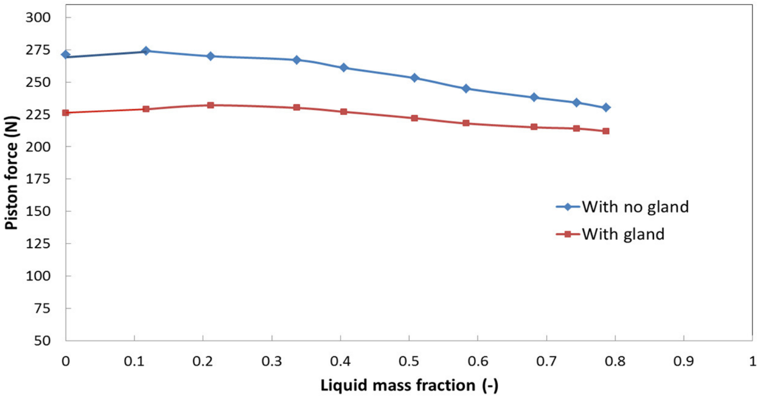


Fig. 10. Effect of valve gland on disc force, inlet pressure 13.7 barg, lift 5 mm (full lift).

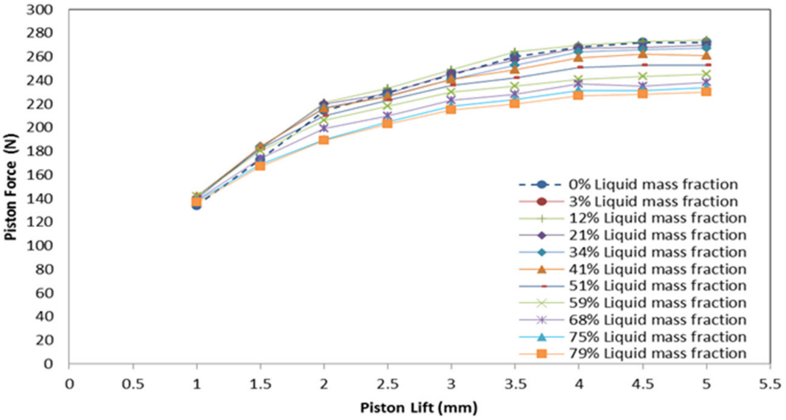


Fig. 11. Effect of liquid mass fraction on disc force 13.8 bar, no gland.

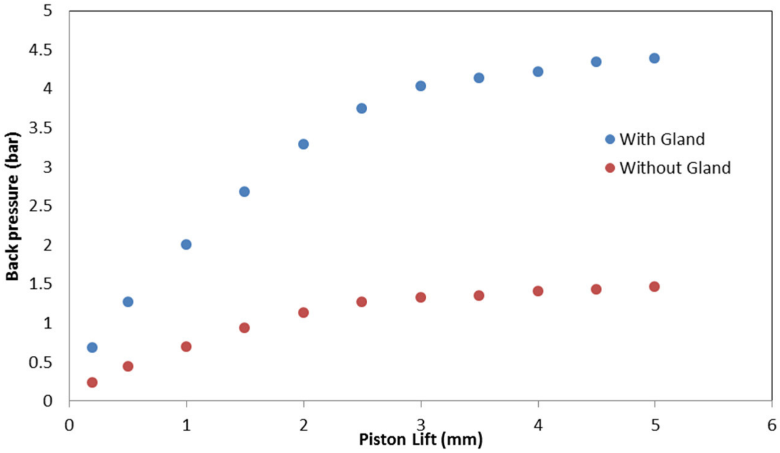


Fig. 12. Effect of gland on back pressure, 13.8 bar, liquid mass fraction 0.34.

The data indicate that the valve disc forces can be influenced by the liquid mass fraction but can be relatively insensitive depending on back pressure effects. Fig. 12 shows that back pressure for 13.8 bar upstream pressure and liquid mass fraction of 0.34 is nearly 4 times greater when the gland is in place. When the back pressure is higher, the gas density will be higher and differences between the phases will be less resulting in a more homogeneous mixture with a reduction in sensitivity to the phase fraction. Overall the suggestions from the Narbayashi et al [1] study that the valve disc forces can be normalized using pressure, similar to single phase flow studies cannot be generalized to all conditions. Their studies were conducted at higher pressure where non equilibrium effects due to phase velocity slip are less noticeable. However, in the studies presented here at lower pressure indicate that dependency on liquid fraction is more apparent. This may be due to non-equilibrium effects.

5. Conclusions

An experimental study examining the flow and force lift characteristic in a safety valve has been investigated. The study examines some of the conclusions from previous study regarding the potential for normalisation of force-lift characteristics and concludes that

- Two phase flow and force characteristics are influenced by liquid injection. The flowrate more so than the force characteristics
- For the conditions studied which relate to relatively low pressure (4-14 bar) the two phase disc force shows a small but significant effect from liquid mass fractions. This is in contrast to previous data from the literature.

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