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Study of mechanical aspects of leak tightness in a pressure relief valve using advanced FE-analysis

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ABSTRACT

This paper presents a numerical study involving the deformation of contact faces in the metal-to-metal seal in a typical pressure relief valve. The valve geometry is simplified to an axisymmetric problem, which comprises a simple geometry consisting of only 3 components. A cylindrical nozzle, which has a valve seat on top, contacts with a disk, which is preloaded by a compressed linear spring. All the components are made of AISI type 316N(L) steel defined using the multilinear kinematic hardening model based on monotonic and cyclic tests at 20° C. In-service observations show that there is a limited fluid leakage through the valve seat at operational pressures about 90% of the set pressure, which is caused by the fluid penetrating into surface asperities at the microscale. Nonlinear FEA in ANSYS using the fluid pressure penetration (FPP) technique revealed that there is a limited amount of fluid penetrating into gap, which is caused by the plastic deformation of the valve seat at the macroscale. Prediction of the fluid pressure distribution over the valve seat just before the valve lift is addressed in this study considering the FPP interaction on multiscale. This is the principal scope, since it allows adjustment of the valve spring force in order to improve the leak tightness.

1. Introduction

1.1. Problem statement

Leak tightness is one of the most important requirements to ensure correct operation of the valve components and specifically static seals. This paper presents an extended description of the investigation by Gorash et al. (2015) into static sealing and how advanced computational techniques might be used to understand and improve the design of static seals. In this paper only structural behaviour issues associated with conventional spring loaded safety valves have been investigated when metal-to-metal sealing is required.

Static sealing is a fluid structure coupled problem where the degree of leak tightness is dictated by the local and global deformation of the contact surfaces. The leakage paths result from gaps at the contact faces and are at a geometrical scale of the surface asperities which are at the micron scale. The contact face global geometry is at a macro scale where its resulting deformation is due to the global force loading which in the case of a safety valve is determined by the spring forces and the operating pressures. This coupling between fluid and structure at geometric scales that range from the micro to the macro imposes considerable challenges to the analysis of the problem.

Below the detailed results of the study by Gorash et al. (2015) are presented focusing on the development of computational analysis methods for the design of static metal-to-metal seals that address different scales. The investigation is limited to global deformation at a macroscale with some initial simplified coupling from the micro-to macroscale via pressure penetration and an imposed pressure variation across the sealing face.

1.2. Background

The safe relief of pressure is of utmost importance in industry to protect equipment from being subjected to pressures above their maximum ratings. Over-pressure can have potentially fatal consequences for the surrounding staff, cause damage to the plant equipment involved and have possibly damaging environmental repercussions. Pressure relief valves (PRVs), as discussed by Malek (2006), are commonly used as a safety device in industrial processes to provide a self-regulating pressure release. The PRV is a

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type of valve used to control or limit the pressure in a system or vessel, which can build up by a process upset, instrument or equipment failure, or fire. The pressure is relieved by allowing the pressurised fluid to flow through the valve orifice out of the system. The operation, typical structure and different types of the PRV are addressed in detail by Malek (2006) and Hellemans (2009).

Song et al. (2013) observed that in actual usage PRVs can sometimes start to release fluid prior to their set pressures P_{set}. This is particularly true when P_{set} is defined as the opening pressure and can result in a degradation of leak tightness for operation pressure P_{op}, which is typically 90% of P_{set}. This study models the structure of the valve seat-disc interface in order to look at the fluid pressure penetration effects. Advanced FEA is used to investigate and quantify the influence of these effects on a spring force, which is required to provide a reliable leak tightness for pressures below P_{set}.

This study focusses on spring-operated metal-seated PRVs since they are not limited in temperature and pressure, when compared to the elastomer-seated PRVs, which have much more preferable leak tightness (Hellemans, 2009). This range of valves often operate at high temperatures (>300° C) which exclude the use of discs with soft seals, meaning that metal-to-metal contacts between the seat and disc are required to form the basis of fluid sealing. Fluid leakage is a major concern for metal-to-metal contacts across the entire range of operation, not just as the system pressure tends towards the set pressure P_{set}.

1.3. Previous research

There is a significant body of work existing in this and related areas, ranging in scope from dynamic analyses of PRV, operating motions, sealing efficiency to complex mathematical modelling of realistic surface defects.

One of the earliest collection of advanced studies addressing testing and analysis of PRVs performance was compiled by Singh and Bernstein (1983). The book covers the topics of test facilities design, safety valve experiments, analysis of PRVs performance, and loads on discharge piping.

A transient analysis was carried out by Song et al. (2010) that focused on the effects of fluid flow on the valve disc. A deformable mesh is used to more realistically simulate the opening of the valve disc with CFD. The analysis is primarily useful to aid in understanding the behaviour of the valve, in particular the disc, once the set pressure has been reached. Then Song et al. (2013) produced a dynamic analysis of a PRV with the aim of creating a model to accurately predict the closing (blowdown) characteristics of a spring-loaded PRV.

As well as for spring-loaded PRVs, an important work has been done to investigate the behaviour of pilot-operated PRVs. Dasgupta and Karmakar (2002) simulated the dynamic response of a PRV using a bond graph method. Several key parameters were identified, which were associated with the valve operation, and primarily related to the geometrical design of the main valve and the configuration of the pilot valve.

Abid and Nash (2004) carried out a parametric study on the effects of geometry on sealing between two metal flanges using the FEA approach. This research is related to the simulation of PRV opening by virtue of its discussion of sealing effects between metal faces. The authors concluded that using a positive taper on the faces (i.e. the inner edge in contact, slight gap at outer edge) provides the best sealing characteristics.

A 3D non-linear elasto-plastic sequential transient analysis was performed by Griffin et al. (2012) for shakedown and fatigue assessments of fine radii within the PRV. The analysis utilised temperatures and heat transfer coefficients that were calculated from a separate 3D CFD analysis of fluid flow and heat transfer during operation of the valve. The use of elasto-plastic techniques combined with an innovative and fine meshing strategy allowed through-life strain ranges at very fine internal features to be calculated.

The series of works (Marie et al., 2003; Marie and Lasseux, 2007; Vallet et al., 2008, 2009; Ledoux et al., 2011) presents the development of experimental and theoretical approaches to characterise liquid leakage through the metal contact seal. An experimental facility for measuring liquid leakage over a wide range of tightening conditions was developed by Marie et al. (2003). The numerically predicted "permeability" of the contact was compared to experiments. Marie and Lasseux (2007) focused on an original experimental setup and procedure designed to measure the fluid micro (or nano) leak rate with great precision over several orders of magnitude. The issue of sealing performance of metal gaskets using a deterministic approach was addressed by Vallet et al. (2008, 2009). The analysis was focused on rough surfaces exhibiting fractal properties with the overall purpose to study the validity of the use of synthetic fractal surfaces as a representation of real ones. Ledoux et al. (2011) used complex mathematical models to generate surfaces with realistic defects, and suggested that leakages occur through sealing faces due to surface defects, and that the seal performance can be improved by surface defects shape optimisation.

Understanding, predicting and controlling the behaviour of surfaces in contact at micro/nano-scale have been extensively studied by Thompson et al. Thompson (2007) focused on the development of a multi-scale FE-model to predict thermal contact resistance between real surfaces which exhibited both surface form and roughness. Thompson and Thompson (2010b) presented methods for generating, using, and operating on non-uniform irregularities for the incorporation of probabilistic rough surfaces in ANSYS, which resemble natural and man-made surfaces. Thompson and Thompson (2010a) discussed the benefits, techniques, challenges, and considerations associated with the incorporation of measured surfaces in FE-models. Thompson (2011) focused on determining the modelling considerations and parameters necessary to accurately model real surfaces and to validate FE-models in the absence of experimental data.

Recently, the series of works (Darby, 2013; Aldeeb et al., 2014; Darby and Aldeeb, 2014) investigated the dynamic response of PRVs in vapour or gas service including mathematical modelling, experimental investigation and model validation. This study presents a model for the opening lift dynamic response of a PRV, which accounts for the effects of unstable dynamic response through a set of five coupled nonlinear differential equations. The set is solved numerically to predict the position of the valve disk as a function of time for given parameters.

Chabane et al. (2012) did experimental and theoretical studies of the force exerted by the pressure on a disk of a PRV, which is essential for a correct design of the spring and the inner ring. To understand the forces, a PRV was modified and the spring removed; a force measurement tool was mounted to measure the forces exerted at different inlet pressures at lift. These tests were conducted for several ring settings. Measurements were made using incompressible fluid on a water test loop.

There has been relatively little work done into analysing the behaviour of the contact surfaces during the valve opening in terms of the valve structure. However, some progress has been achieved by Johnson (2013), who implemented a structural analysis of a spring loaded PRV through two loading phases. The FE-analyses were carried out in ANSYS, and included effects such as lateral internal pressure on the seat, friction in the contacts and nonlinear geometry.