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Fluid pressure penetration for advanced FEA of metal-to-metal seals

Yevgen Gorash[1,*], **William Dempster**[1], **William D. Nicholls**[1], and **Robert Hamilton**[1]

[1] Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow G1 1XJ, United Kingdom

This numerical study investigates the behaviour of the contact faces in the metal-to-metal seal of a typical pressure relief valve in the commercial FE-package ANSYS. The valve geometry is simplified to an axisymmetric problem, which comprises a simple representative geometry consisting of only three components. A cylindrical nozzle, which has a valve seat on top, contacts with a disk, which is preloaded by a compressed linear spring. Analysis considerations include the effects of the Fluid Pressure Penetration (FPP) across the valve seat which exists at two different scales. In-service observations show that there is certain 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. At the macroscale, non-linear FE-analysis using the FPP technique available in ANSYS revealed that there is also a limited amount of fluid penetrating into gap, which is caused primarily by the global plastic deformation of the valve seat. Accurate prediction of the fluid pressure profile over the valve seat is addressed in this study by considering the FPP interaction on both scales. The shape of this pressure profile introduces an additional component of the spring force, which needs to be considered to provide a reliable sealing.

Static face seals are an essential requirement in pressurised components. Their effectiveness defines the performance and functionality of critical equipment in oil and gas, petrochemical and chemical industries, pipelines, thermal and nuclear power plants, etc. In this study the main objective is to improve an overall understanding of the design of static face seals, the associated loading and degree of leak tightness that is achieved. The application area is limited in the first instance to pressure relief valves (PRV) with metal-to-metal contact. The PRV is a type of valve used to limit the pressure in a system or vessel [1], 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 PRV is designed to open at a predetermined set pressure $P_{\rm set}$ to protect pressure vessels and equipment from being subjected to the pressures, which exceed design limits.

An idealised functional model of the PRV consists of the following three basic components as shown in Fig. 1:

- Cylindrical nozzle defined by the radius of orifice and the length of valve seat,
- Relatively rigid disc, which keeps the nozzle closed during the operation,
- Linear spring, which is initially compressed and prevents lifting of the disc.

Since the system pressure is usually 5-10% below $P_{\rm set}$ during the normal operation [2], the orifice is kept tightly closed by the disc. However, when the pressure builds up, a weak balance of forces is achieved. Even a slight excess of $P_{\rm set}$ starts the disk lifting, because of the imbalance of forces. This way of operation is true only for an idealised (perfectly elastic) model of the PRV. Since the real material – austenitic stainless steel AISI type 316N(L), which is used for manufacturing of the nozzle and disc, is quite far from perfectly elastic [3], it is defined using the multilinear kinematic hardening material model. Plastic strain is assessed based on the monotonic stress-strain curve obtained from a monotonic tensile test and the cyclic stress-strain curve obtained from a number of tests with stabilised cyclic response at 20°C by Chaboche *et al.* [4].

The FPP effects are observed at two different scales – macroscopic and microscopic, as shown in Fig. 1. Since they both are assumed to exist in the same location, there should be some kind of non-linear interaction between them. Prediction of the pressure distribution over the contact face as a result of this interaction is a way to assess an additional component of the force produced by pressure. An advanced FE-analysis using ANSYS is implemented for the prediction of pressure profile as a result of macro-micro interaction. An internal edge of the valve seat is subjected to significant plastic deformation on the macroscale. It is caused by high contact pressure on the internal edge, which undergoes yielding under the spring preload. Even a small amount of plastic deformation slightly distorts the valve seat and creates a gap between the contact surfaces. Once the valve is subjected to operational conditions, the pressurised fluid penetrates into the contact gap. This increases the effective area of orifice exposed to the full system pressure and decreases the effective area of contact. On the other hand, some limited degree of leakage is always practically observed in the metal-seated valves within the whole range of operation pressures. Surface roughness and presence of non-uniform asperities at the microscale allows pressurised fluid to penetrate into the contact [5]. Therefore, the total force F, which needs to be actuated in the spring, consists of the three components:

$$F = F_{\rm or} + F_{\rm ma} + F_{\rm mi} \quad \Leftarrow \quad F_{\rm or} = P_{\rm set}\,\pi\,r_{\rm in}^2 \quad \cup \quad F_{\rm ma} = P_{\rm set}\,\pi\left(r_{\rm fpp}^2 - r_{\rm in}^2\right) \quad \cup \quad F_{\rm mi} = \bar{P}\,\pi\left(r_{\rm out}^2 - r_{\rm fpp}^2\right), \quad (1)$$

$F_{\rm or}$ – orifice force produced by the internal pressure $P_{\rm set}$ acting on the disc surface corresponding to the area of the orifice;
$F_{\rm ma}$ – macro-fluid force, which is assumed to have a stepped pressure distribution in the area of the macroscopic FPP;
$F_{\rm mi}$ – micro-fluid force, which is calculated using the average pressure over the area of the microscopic FPP.

* Corresponding author: e-mail yevgen.gorash@strath.ac.uk, phone +44 790 978 0901, fax +44 141 552 0775

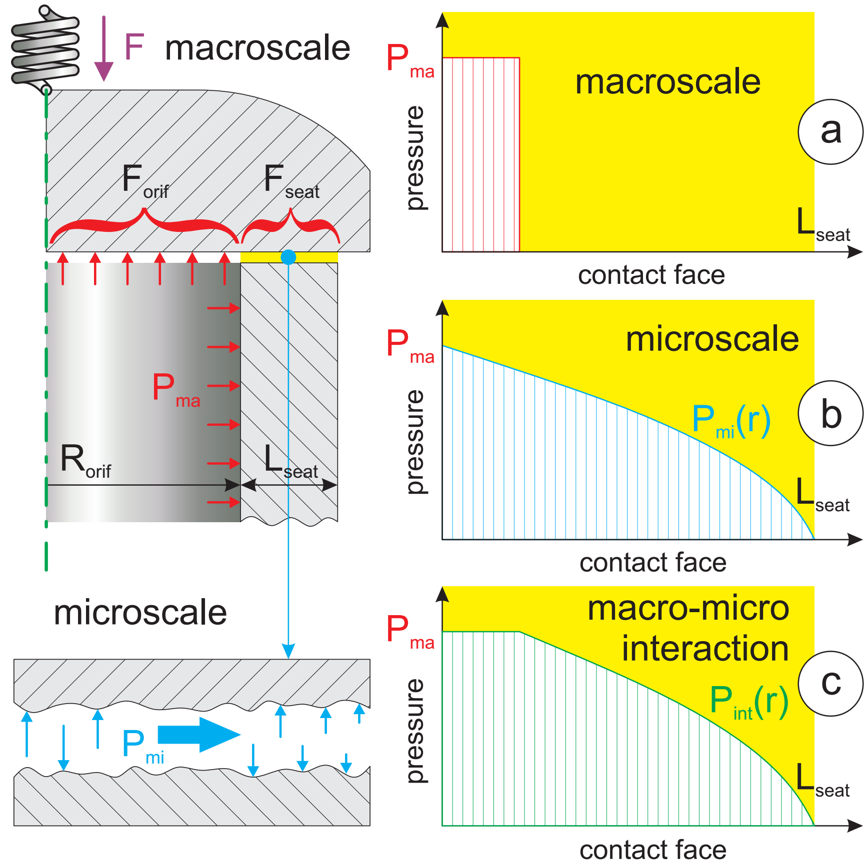

Fig. 1: Concept of macro-micro effects interaction in the contact area of metal-to-metal seal of a PRV: a) FPP at macroscale, b) FPP at microscale, c) interaction of FPP effects.

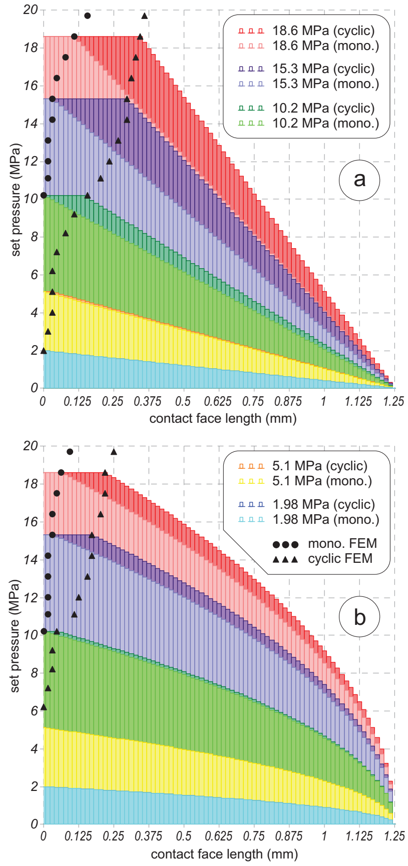

Fig. 2: FEA-based fluid pressure drop in contact area for (a) liquid and (b) gas.

In notation (1) r_{out} – outer radius of the contact area, r_{in} – inner radius of the contact area or radius of the orifice, and r_{fpp} – radius of macroscopic FPP. An average value of the pressure within the microscopic pressure profile $\bar{P}$ is obtained in analytical form [6] as $\bar{P} = P_{\text{set}}/(1+n)$, where n is a power-law exponent in mathematical fit for pressure drop profile in a seal [5], which is dependent on the type of fluid ($n = 0.5$ for gas and $n = 1$ for liquid) as shown in Fig. 2.

In order to provide a high resolution of output results, FE-simulations have been performed for the wide range of P_{set} comprising 21 values – from 2 MPa to 23.0 MPa. All these simulations were done for two different types of fluid (liquid or gas) and two different types of plastic material response (monotonic or cyclic). The obtained results are shown in Fig. 2, where markers denote the boundaries between macroscopic and microscopic FPP. Dots are used for all values of P_{set}, and the pressure profiles over the contact face – for 5 standard values of P_{set}. The degree of macroscopic FPP increases non-linearly with an increase of P_{set} for both types of fluids. However, the particular depth of global FPP is quite different for liquid and gas. An important observation from Fig. 2 is that the effective contact area decreases with cyclic operation of the valve. It is also demonstrated that the type of working fluid affects the shape of the pressure profile in the multiscale.

Other effects and observations are discussed in Gorash *et al.* [6] including the influence of the isotropic softening of the material on global deformation of the valve seat. For instance, a spring force required to provide a leakage tightness of the valve needs to be adjusted after several lifts. The obtained FE-results demonstrate that an alteration of the additional spring force during operation may be up to a quarter of its initial value [6]. A specific number of operating cycles required for adjustment of the spring force can be revealed in transient cyclic analysis with a Chaboche-type plasticity material model [4].

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