Chemical Engineering Science 188 (2018) 170–178

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

# An investigation into the effect of gas adsorption on safety valve set pressure variations

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## HIGHLIGHTS

- Set pressure difference in pressure relief valve is ascribed to adsorption pressure.
- Adsorption force of saturated steam is always higher than compressed air.
- Theoretical results agree well with experimental measurement qualitatively.
- A hydrophilic surface modification could reduce the set pressure.

## ARTICLE INFO

*Article history:*
Received 23 November 2017
Received in revised form 9 May 2018
Accepted 21 May 2018
Available online 22 May 2018

*Keywords:*
Pressure relief valve
Set pressure
Adsorption
Multiscale model
DFT

## ABSTRACT

The set pressure in pressure relief valves (PRVs) varying with the type of sealed medium has been a puzzling problem in the field of chemical machinery and equipment for many years. Here we propose a novel viewpoint to interpret this phenomenon, by which the set pressure difference is ascribed to the additional adsorption pressure of sealed medium adsorbed in the intrinsic nanoscale apertures of PRVs. To demonstrate, two individual types of medium gases (i.e., saturated steam and air) sealed in different PRVs are investigated, and upon a multiscale model of the apertures in PRVs, the additional adsorption pressures are evaluated by using classical density functional theory (DFT). Our calculation shows that the adsorption force of steam is always higher than that of air, resulting in a lower set pressure disregarding the use of different PRVs. The theoretical results are compared with the experimental measurements, displaying qualitatively good agreement, which supports our surmise. Finally, possible solution to reduce the set pressure difference is discussed. This work cast helpful insights for the design and application of PRVs.

## 1. Introduction

Pressure relief valves (PRVs) are ubiquitous safety accessories of pressure loaded installations in chemical engineering. For nuclear or thermal power plants, PRVs act as the last passive protectors to guarantee the safety of a plant. It has been widely acknowledged that the PRV's failure to function resulted in reactor core degradation, triggering the nuclear leakage accident of the Three Mile Island Nuclear Power Station in the USA (Rogovin, 1979).

All qualified PRVs are required to automatically open the valves when the loaded pressure is beyond a critical point, which is in prior set with the help of a proper spring compression. This pressure point is usually called set pressure, denoted as $P_{set.}$ Since the opening of a valve is not a single process, the value of set pressure for a PRV is slightly sensitive to the monitoring operational characteristics in practice (Inc, 1997). Specifically, if the set pressure is characterized with a measurable lift of the valve, it is equal to the opening pressure (Anwar et al., 2016). It has been found that a non-negligible difference exists in $P_{set}$ value when the sealed media are different (for example, saturated steam versus compressed air) (Darby and Aldeeb, 2014). This difference is conventionally reduced by a correction using an empirical coefficient (Makaryants, 2017); obtained by correlating a large amount of experimental data. The correction of the set pressure of PRV is important to ensure the valves to provide the required overpressure protection at high temperatures. ASME SECTION VIII DIVISION 1 requires the manufactures and (or) assemblers to identify the corrections for differentials in opening pressure between steam and air. However, few reports can be found so far on why such a difference exists although many efforts have been contributed into

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https://doi.org/10.1016/j.ces.2018.05.035

the study of steady state properties and dynamic behaviors of PRVs (Yang et al., 2017; Gorash et al., 2016).

The basic elements of a PRV are described in Fig. 1(A), in which a spring is compressed to generate a set pressure $P_{\text{set}}$ on the valve. When the operating pressure (designated as $P_{\text{oper}}$) of a pressure-loaded installation is below $P_{\text{set}}$, the orifice is kept tightly closed by the valve disc (the red zone in the figure), resulting in a sealed gas system. Consequently, we call this the sealed state. As the operating pressure reaches the set pressure $P_{\text{set}}$, the valve disc starts to open with the sealed gas being released, and we refer to this circumstance as the release state (see Fig. 1(B)). At the last moment when a PRV transits from its sealed state to release state, the operating pressure equals the set pressure (Anwar et al., 2015), and this moment is referred to as the critical state. The set pressure is usually measured by gradually increasing the operating pressure until the critical state occurs.

When the two metal surfaces of the valve disc and seat come into contact, small apertures and leakage passages are intrinsically present due to the microscopic roughness of both surfaces (Anwar et al., 2015; Bottiglione et al., 2009; Jackson and Streator, 2006). The apertures and leakage passages are related not only with the surface roughness, but also with the applied normal pressure and the toughness of the contact materials (Persson, 2001; Prodanov et al., 2014; Greenwood and Wu, 2001). To obtain the topology configuration of the contact area, analytical and numerical works were carried out focusing on rough surface reconstruction, surface contact mechanical models and leakage rate prediction (Dapp et al., 2012; Bottiglione et al., 2009; Putignano et al., 2013). For example, it has been reported the surfaces at a microscale level can be in the form of sinusoidal waves (Geoffroy and Marc, 2004) or vibrational Eigen models (Ledoux et al., 2011) or wedges (Mitchell and Rowe, 1969). Taking this into consideration, the pore sizes of apertures and leakage passage can vary from micrometer to nanometer. Specifically, for a single aperture with a dead end, the pore size becomes smaller and smaller by going deeper into the pore. The sealed fluids can be adsorbed into the apertures or diffuse through the leakage passages. In the latter situation a steady flow arise at a certain leakage rate.

The aim of this study is to explore the reason why a difference exists between the $P_{\text{set}}$ measured with saturated steam and with compressed air in the same set of PRVs. The saturated steam throughout this work refers to the water vapor at 573 K, and the compressed air is the conventional atmosphere mainly composed of nitrogen and oxygen gases subject to a certain applied pressure. The novelty of this work is to set up a multiscale model to address the effect of gas adsorption in apertures/leakage passages on the value of set pressure. Because the thermodynamic properties of steady flows in leakage passages are identical to those in the equilibrium adsorbed gas systems with corresponding gas concentration profiles (Hu, 2017; Zhao, 2017; Xin et al., 2015), here we ignore the effect of fluid flow kinetics on set pressure, and consider only the adsorption pressure effect originating from the presence of gas in both apertures and leakage passages. Classical density functional theory (DFT) (Zhao, 2015; Kierlik and Rosinberg, 1991) is employed, which allows for an accurate calculation of the adsorption pressures for fluids in apertures. The calculation results were qualitatively rationalized by the experimental measurements with saturated steam or compressed air in the PRVs.

## 2. Experimental

The experimental setup was established in WUJIANG DONGWU machinery Co., Ltd, China, in accordance with the ASME PTC 25 guidelines. For the test on the steam PRV, as shown in Fig. 2, a supercritical steam boiler supplied the saturated steam to a storage vessel at 573 K. The PRV was mounted on a testing vessel. During the testing, the operating pressure was increased by slowly introducing the steam from the storage vessel. When the operating pressure of the testing vessel reached 90% of the expected set pressure, the increasing rate was reduced to 13.795 kPa $\sec^{-1}$ which could avoid any pressure turbulence owing to the gas flow. Once the disk lifts, the operating pressure of the tested PRV is observed, which is recorded as the set pressure. In our tests, the measurable lift was set to be 0.5 mm. To confirm the accuracy of the measured set pressures, the opening of PRVs was recorded by a high-speed video (Integrated Device Technology, Motion Xtra N4, California). The set pressures obtained with the measurable lift of 0.5 mm in our cases agreed very well with those using high-speed video.

For the PRV test using air, as shown in Fig. 2, the air compressor replaced the supercritical steam boiler and supplied the air to the storage vessel at room temperature (298 K). The PRV was mounted on a testing vessel. The procedure for the set pressure measurement using air PRV was similar to that for steam, as mentioned above.

Seven new direct-spring PRVs of similar type were used. The measurement accuracies of the pressure transmitter (BP201/501Z, Hefei 126 Sentech Sensing Instruments Co., Ltd.) and the displacement transducer (ZS-LD200, OMRON) were ±0.5% and ±0.2%, respectively. The volume of the testing vessel is 15 $m^3$ and the tolerated pressure is 25 MPa. The diameter of the connecting pipe is 300 mm, and the flow rate is 480 ton/h. The same testing vessel was used for both steam and air. The Programmable Logic Controller (PLC, S7-300, Siemens) collected the pressure data of the testing vessel with an acquisition time resolution of 10 microseconds.

## 3. Multiscale model and theoretical method

A multiscale model is proposed to describe the apertures between the disc and seat. Generally, the apertures are cuneate if the gas is well sealed. Namely, by going deeper into the apertures, the pore size becomes smaller as depicted in Fig. 3. The tails of apertures can go to nanoscale before both surfaces of the disc and seat are "completely" in contact. Here, by using the term "completely", we mean the pores are dead ended so that no gas will be leaked out. In other words, the kinetics of gas flow in the leakage passages is not considered in our theoretical model. With this multiscale model, apertures can be constructed by a series of slit pores with a varying pore width $H$.

It is reported that fluid confined in nanopores behaves very different from its bulk counterpart due to a strong confinement effect (Zhao, 2017; Hu et al., 2016; Li et al., 2014; Turner et al., 2001). Studies upon theory and experimental measurements have showed that fluid in confined space could generate extremely high adsorption pressures against the surfaces, leading to interesting anomalous phenomena compared to the bulk environment (Urita, 2011; Takaiwa et al., 2008; Coasne et al., 2011; Coasne et al., 2009; Coasne et al., 2010; Kanda and Miyahara, 2007; Kanda et al., 2004; Kanda, 2000; Long et al., 2012). We believe the compressed gas or steam adsorbed in apertures would also generate an excess pressure over the bulk one, and it is interesting to examine the magnitude of the excess pressure and analyze whether it makes a noticeable contribution to the set pressure.

Firstly, regarding a sealed PRV at its critical state, we have the following force balance equation on the disc:

$$F_s^c = F_b^c + F_a. \tag{1}$$

Here $F_s^c$ is the spring force exerted by the installed spring. $F_b^c$ is the pressure force from the sealed gas associated with the operating pressure (equivalently, the set pressure $P_{set}$), and $F_a$ is the adsorp-