Journal of Loss Prevention in the Process Industries 31 (2014) 70–81

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Dynamic behavior of direct spring loaded pressure relief valves in gas service: Model development, measurements and instability mechanisms

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ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form
29 May 2014
Accepted 24 June 2014
Available online 4 July 2014

Keywords:
Pressure-relief valve
Gas dynamics
Instability
Quarter-wave
Hopf bifurcation
Chatter

ABSTRACT

A synthesis of previous literature is used to derive a model of an in-service direct-spring pressure relief valve. The model couples low-order rigid body mechanics for the valve to one-dimensional gas dynamics within the pipe. Detailed laboratory experiments are also presented for three different commercially available values, for varying mass flow rates and length of inlet pipe. In each case, violent oscillation is found to occur beyond a critical pipe length, which may be triggered either on valve opening or closing. The test results compare favorably to the simulations using the model. In particular, the model reveals that the mechanism of instability is a Hopf bifurcation (flutter instability) involving the fundamental, quarter-wave pipe mode. Furthermore, the concept of the effective area of the valve as a function of valve lift is shown to be useful in explaining sudden jumps observed in the test data. It is argued that these instabilities are not alleviated by the 3% inlet line loss criterion that has recently been proposed as an industry standard.

1. Introduction

This paper summarizes and extends recent scientific investigations into the mechanisms of instability in pressure relief valves (PRVs) and considers their implications for practical operation. The overall aim is to develop a new comprehensive understanding of the issues that affect valve stability in operation, in order to influence a new set of design guidelines for their operation and manufacture. In particular we shall combine theoretical model studies with tests of fully instrumented valves within representative pipe geometries. This paper will focus specifically on direct spring-loaded PRVs in gas service, particularly considering the combined effect of the valve dynamics with acoustic pressure waves within its inlet pipe.

A considerable amount of scientific literature has been published on the description and analysis of valve systems. Green and Woods (1973) provided the first comprehensive discussion of the possible causes of valve instabilities, suggesting that they can be induced as a result of five different effects: the interaction between the poppet and other elements, flow transition from laminar to turbulent during opening and closing, a negative restoring force, hysteresis of the fluid force, and fluctuating supply pressure. This paper shall focus on the first of these, specifically instability due to interaction between the valve and the inlet pipe (although, as we shall see, this can also be interpreted as an effective negative restoring force on the valve provided by an acoustic wave). Instabilities due to the other four effects identified by Green and Woods have been analyzed by a number of other authors (Kasai, 1968; McCloy & McGuigan, 1964; Madea, 1970a,b; Nayfeh & Bouguerra, 1990; Vaughan, Johnston, & Edge, 1992; Moussou et al., 2010; Beune, 2009; Song, Park, & Park, 2011). Conventional PRVs subject to built-up back pressure have also been widely investigated (Francis & Betts, 1998; Chabane, Plumejault, Pierrat, Couzinet, & Bayart, 2009; Moussou et al., 2010). In this paper we do not consider effects of downstream piping. Oscillations in other valve systems have also been studied, e.g. in plug valves (D'Netto & Weaver, 1987), compressor valves (Habing & Peters, 2006), ball valves (Nayfeh & Bouguerra, 1990), pilot-operated two-stage valves (Botros, Dunn, & Hrycyk, 1997; Zung & Perng, 2002; Ye & Chen, 2009) and control valves (Misra, Behdinan, & Cleghorn, 2002). Again, such studies go beyond the scope of the present work.

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http://dx.doi.org/10.1016/j.jlp.2014.06.005

The first serious discussion of self-excited instabilities of poppet valves emerged in the 1960s. Funk (1964) discussed the influence of valve chamber volume and pipe length within a hydraulic circuit on the stability of a poppet valve. He found that such valves are inclined to become unstable at a critical frequency that coincides with the fundamental vibratory mode of the pipeline. Moreover, the severity of the instability increases with the length of the pipe. Kasai (1968) developed this analysis by deriving equations of motion for such a poppet valve and inlet piping system. Based on linear stability analysis, he established formulas for predicting instability in the valve. The results were shown to be in broad agreement with experiments. A similar configuration was studied by Thomann (1976) who found that the valve motion can couple to the acoustic oscillation of the pipe, leading to amplified oscillation of the system. He also developed analytical criteria for the loss of stability, finding good agreement with experiments. Later, MacLeod (1985) developed a model that includes gas dynamical issues such as choked flow capable of predicting the region of stable operation of a simple spring loaded PRV mounted directly onto a gas-filled pressure vessel.

In the 1990s Hayashi (1995) and Hayashi, Hayase, and Kurahashi (1997) carried out detailed linear and global stability analyses of a poppet valve circuit and showed representative examples of 'soft' and 'hard' self-excited vibration. They revealed that for the same conditions several pipe vibration modes can become simultaneously unstable, with the number of unstable modes increasing with pipe length. These results agree with those obtained by Botros et al. (1997) who find that for higher values of the pipe length two modes evolve in the system while for lower values of the pipe length the vibration is primarily in the fundamental, quarter-wave mode. They also found that maximum amplitude occurs when the oscillation frequency coincides with the quarter-wave natural frequency; for lower and higher values of the pipe length the amplitude decreases.

In early work by two of us (Licsko, Champneys, & Hős, 2009), we used nonlinear dynamical systems methods to analyze a low-order system of ordinary differential equations describing a simplified version of the set up used by Kasai (1968) and Hayashi et al. (1997), ignoring the effect of the pipe. Here we showed that upon reduction of the inlet flow rate, loss of stability is due to a *Hopf bifurcation* (also known as a flutter instability in aeroelastics) is initiated by a so-called self-excited oscillation; a dynamic instability which is present in the system even in the absence of explicit external excitation. The system was further investigated by Hős and Champneys (2012), where we elucidated the nature of grazing bifurcations in the system that underlie the onset of impacting motion between the valve and its seat, and performed detailed two-parameter continuation. At the same time, Bazsó and Hős (2013) report experimental results in a hydraulic system that showed qualitative agreement to the nonlinear dynamics predicted by Licsko et al. (2009). That paper also presented a preliminary stability map that shows the frequency of the evolving self-excited vibration along the boundary of loss of stability, again for hydraulic application. Furthermore, Bazsó, Champneys, and Hős (2014b) provide a detailed mathematical derivation of the model studied here in section 2, which extends the reduced-order model of Licsko et al. (2009) to include the more realistic effects of a downstream inlet pipe. The present paper though is the first to compare that model with experimental data and to consider the practical application of the findings of the model. It should be noted that our model and conclusions bear similarities with that used in the study by Izuchi (2010). Our work though has far more detailed test data and we have also identified the key parameters and mechanisms affecting instability.

In parallel to the scientific literature, there has been industry-funded studies into the safe operation of pressure relief systems. For example, the American Institute of Chemical Engineering (AIChE) founded in 1976 the Design Institute for Emergency Relief Systems (DIERS) whose twin aims are the reduce pressure producing accidents and to develop new techniques to improve the design of relief systems. Meanwhile, the American Petroleum Institute (API) have funded their own internal program into the causes of PRV instability. Many of their findings are included in the draft 6th edition of API standard RP520 Part II. In particular, the standard is careful to point out the difference between valves undergoing three different types of behaviour, all of which have previously been referred to as instability. These are

1. cycling,
2. valve flutter, and
3. valve chatter.

Here, cycling refers to a valve that opens and closes multiple times during a pressure-relief event. Typically this behaviour is of low frequency (<1Hz) and can be caused either by valve oversizing or inlet pressure loss causing the pressure to drop transiently, and the valve to shut. As pressure builds up again, the valve re-opens, with this chain of events happening repeatedly. In contrast, *flutter* is a high-frequency self-excited periodic oscillation of the valve (typically >10Hz) that does not result in the valve completely closing off. Finally, *chatter* is a more violent form of rapid oscillatory motion that involves the valve repeatedly impacting with its seat at high frequency. The API RP520 standard is less clear on the precise causes of flutter or chattering instability mechanisms, but resonant coupling between the valve and its pipework, or instabilities being triggered from periodically shed vortices have been postulated as possible causes of flutter.

One of the aims of this paper is to explain these three phenomena in terms used in the recent scientific literature. In particular, we shall show that the onset of flutter can be regarded as a Hopf bifurcation (which is also commonly known as flutter in the aeroelastic research community). As shown in detail in simplified models (Licsko et al., 2009; Hős & Champneys, 2012), chatter often arises as the amplitude of the limit cycle resulting from a Hopf bifurcation grows to the extent that the valve body touches the valve seat. This causes a so-called *grazing* bifurcation that causes the onset of more violent, repeatedly impacting motion. Cycling behaviour is, as we have mentioned, better understood industrially and is not the subject of this paper per se. Nevertheless we do show in Section 4.3 below that our mathematical model is capable of reproducing this behaviour.

To avoid cycling, the API standard proposes that the line pressure loss should be less than 3% of the set pressure. However, as we shall see, this is not sufficient to prevent self-excited flutter or chatter instabilities in the valves we have tested.

The remainder of this paper is outlined as follows. First, Section 2 presents a mathematical model that combines the rigid-body dynamics of a direct spring valve with 1D gas dynamics within the pipe. The valve model is sufficiently complex to consider realistic valve design parameters such as set pressure and a prescribed relation between the effective valve area and the valve's lift. Then, in Section 3 we present a detailed validation of the model against test data performed on three different commercially available valves. In each case we run a pressure run-up and run-down event for for several different mass flow rates and inlet pipe lengths. A detailed comparison between model and data is presented, and close agreement is found for both the nature of the instabilities observed and for the flow rates and pipe lengths for which instability is triggered. This leads to a detailed discussion in Section 4