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Mechanism of interaction of pressure waves at a discrete partial blockage

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ABSTRACT

This paper analyses the mechanism of interaction between an incident pressure wave and blockages of different geometrical characteristics (i.e., a butterfly and a ball valves, two short stretches of pipe with a reduced diameter, and a device simulating a longitudinal body blockage) by means of laboratory and numerical tests. Experiments have shown that the mechanism of interaction with pressure waves is influenced by their path through the device: sinuous because of the device body for partially closed in-line valves (type I mechanism), and straight for the small bore pipe devices (type II mechanism). Type I mechanism is characterized by a rise followed by an almost constant value whereas in type II one a drop occurs after the rise. To complete the investigation the effect of the pre-transient condition is discussed.

1. Introduction

Partial blockages in pipelines are an important operational problem since they reduce flow, cause local low pressure values and increase pumping costs. Moreover they deteriorate water quality since they give a better chance of survival to different microorganisms serving as a food source as well as facilitating their interaction (Boulos et al., 2006; Douterelo et al., 2014). “Natural” partial blockages can be due to slow processes of deposition of chemicals in the oil industry or excess calcium carbonate scale in water pipelines (e.g., those fed by wells) whereas negligence in system maintenance is the cause of unintended partially closed valves (“artificial” partial blockage).

Within the variety of faults affecting real pipelines, partial blockages can be considered among the most insidious ones since no external evidence allows their detection. As a consequence, reliable, non-intrusive and fast techniques for partial blockage (hereafter referred to simply as blockage) detection are of great interest. The analysis and benchmarking of the available methods for blockage detection are beyond the scope of this paper that concerns with those based on the transient pressure response of pipelines, i.e. on the interaction between injected pressure waves and blockages. Last decade literature on this topic has analyzed the role played by the characteristics of such features – length and severity – on their transient behavior mostly for single pipes. For a given severity, the distinction between discrete and extended blockages is based on the significant frequency shift in the pressure signal (i.e., the pressure time-history) caused by the latter with respect to clear (i.e., blockage-free) pipes. On the contrary, no perceptible frequency shifts can be observed in pipes with discrete blockages as well as partially closed in-line valves (Lee et al., 2008; Lee and Vitkovsky, 2008). In other words, when the blockage can be approximated as a localized discontinuity in the system it is referred to as a discrete blockage whereas extended blockages occur when significant stretches of pipe are affected by the constriction (Brunone et al., 2008a; Duan et al., 2012).

Irrespective of blockage characteristics, the analysis of the pressure signal can be executed both in the frequency- (Lee et al., 2013) and time-domain (Meniconi et al., 2011a). More recently, a coupled frequency- and time-domain approach has been proposed (Meniconi et al., 2013b) and the wave scattering effect of rough blockages has been examined in the

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laboratory (Duan et al., 2014c). A totally different approach has been proposed by Massari et al. (2013, 2014, 2015) where the stochastic Successive Linear Estimator (SLE) – extended from groundwater hydrology (Yeh et al., 1996) – is used to infer the presence of extended partial blockages casting the inverse problem of the diagnosis in the probabilistic framework.

Frequency response techniques have been used by Mohapatra et al. (2006a,b), Mohapatra and Chaudhry (2011), and Sattar et al. (2008) to point out the impact of discrete blockages in terms of the amplitude of odd and even harmonics when sinusoidal oscillations are used to excite the system (Chaudhry, 2014). Frequency, phase, and amplitude of the blockage-induced pattern – with transients generated by operating a side-discharge valve – are quantified in Lee et al. (2008) where a simple analytical expression is also proposed. The so-obtained frequency response diagrams (FRD) can be used as look-up charts within the diagnosis procedure (Lee and Vitkovsky, 2008). A blockage detection method using blockage-induced pressure damping is proposed by Wang et al. (2005); a discussion in terms of total kinetic and internal energies (Karney, 1990) of such a method is offered in Meniconi et al. (2014). The case of extended blockages is examined by Duan et al. (2012, 2013, 2014a) where it is shown that, as mentioned above, the effect of blockages is a change of the resonant frequencies of the system and then the phase shift of the frequency peaks is used to detect and locate blockages. It is also demonstrated and checked by means of both numerical and laboratory experiments that friction does not affect the resonant peak frequencies as well as the assumed linear behavior of pipe connection junctions. On the contrary, the effects of viscoelasticity of pipe material must be isolated and removed from the data before executing the diagnosis. It is also pointed out that the location and length of the blockages can be detected to a greater accuracy than its severity. In a more recent paper (Duan et al., 2014b), the reasons of the blockage-induced shift in the system resonant frequencies are investigated by means of a wave perturbation analysis. In this paper, an analytical relationship between the blockage characteristics and the resonant frequency shift is given.

When the pressure signal is examined in the time-domain, attention is focused on the pressure wave reflected by the blockage: in fact, the capture of the instant of time when it reaches the measurement section allows locating the blockage whereas its magnitude derives from blockage severity. More precisely, for a given incident pressure wave, the larger the local head loss through the discrete blockage, the larger the reflected pressure wave (Contractor, 1965; Brunone et al., 2008b; Meniconi et al., 2010, 2011a). Within such an approach, in the case of extended blockages, the double reflection caused by the reduction and subsequent enlargement can be easily detected in the pressure signal (Brunone et al., 2008a). Turning points of numerical simulations of transients in pipes with a blockage by current methods – e.g., the method of the characteristics – have been highlighted for both gas (Adewumi et al., 2000, 2003) and liquid flow (Meniconi et al., 2012a; Tuck et al., 2013).

The above brief literature review shows that in the last decade of intense research activity, attention has been focused mainly on the distinction between discrete and extended blockages in terms of the induced-or-not time shift and magnitude of reflected pressure waves within the frequency- and time-domain approach, respectively. Some attention has been also devoted to the analysis of test conditions – pointing out the importance of the characteristics of the generated pressure waves (Lee et al., 2008; Brunone et al., 2008b) – and the negligible influence of the geometry of the section area changes between clear and blocked stretches of pipe in the case of extended blockages (Meniconi et al., 2012a).

Based on real pipe experience where different blockage features happen according to pipe material – i.e., a quite regular diameter reduction for metallic pipes (Fig. 1a) and longitudinal bodies for plastic pipes (Fig. 1b) – the aim of this paper is to analyze the mechanism of interaction between the incident pressure waves and a discrete blockage with different geometrical characteristics. In such a context, laboratory and numerical tests have been executed to examine the transient behavior of different devices (i.e., a butterfly and a ball valve, two short stretches of pipe with a reduced diameter, and a device simulating a longitudinal body blockage).

2. Laboratory set-up

The laboratory set-up at the Water Engineering Laboratory (WEL) of the University of Perugia, Italy, consists of a high density polyethylene (HDPE) pipe (length, $L = 164.93$ m, internal diameter, $D = 93.3$ mm, and wall thickness $e = 8.1$ mm)

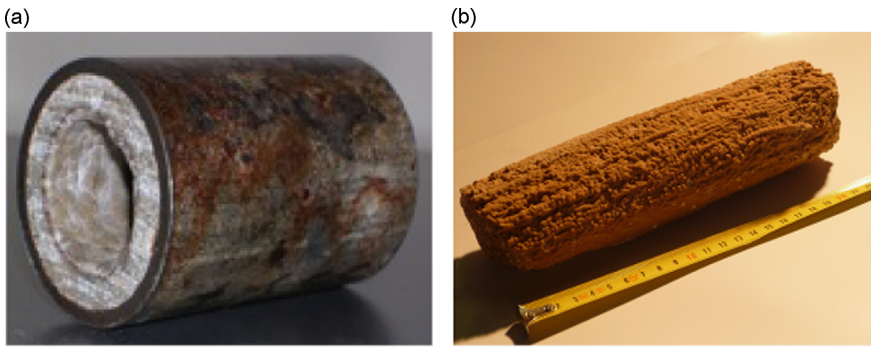

Fig. 1. Different shapes of real pipe discrete blockages: (a) internal pipe diameter reduction (often in metallic pipes); and (b) longitudinal body (often in plastic pipes).