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Analysis of PRV Stability In Relief Systems

Part III – How to Avoid the Singing PRV Problem

An ioMosaic White Paper

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Analysis of PRV Stability In Relief Systems

Part III

How to Avoid the Singing Pressure Relief Valve Problem

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1 Abstract

Excitation of acoustic standing waves in a main process flow line closed side branch, such as the inlet line of a pressure relief valve (PRV), can occur due to vortex shedding generated by increased flow in the main process line. The flow velocity for process lines where pressure relief devices are mounted via a side branch should be limited to [1]:

$$u < \left(\frac{1}{2.4}\right)\left(\frac{d}{L}\right)c_e \tag{1}$$

where c_e is the effective isentropic speed of sound of the main process flow pipe fluid system, u is the maximum allowable fluid flow velocity in the main process line, and d/L is the pressure relief device inlet line diameter to length ratio. This limit can be very restrictive for flashing two phase flow.

2 Vortex Shedding

As a result of increasing steam flow rates, several boiling water reactor (BWR) nuclear power plants have recently experienced the excitation of acoustic standing waves in closed side branches, e.g., safety relief valves (SRVs), due to vortex shedding generated by steam flow in the main steam lines (see Figure 1). Flow past a valve entrance cavity excites a standing wave, resulting in noise and vibration [2]. A similar tone is produced when air is blown across the mouth of a glass bottle. There are many similar installations of pressure relief valves in the process industries where the pressure relief valves are mounted on large process lines such as overhead lines for distillation columns.

The amplitude of the acoustic pressure waves can be several times higher than the dynamic pressure present in the system (see Figure 2). The acoustic waves propagate in the steam lines, eventually reaching sensitive components such as steam dryers and turbine stop valves. In addition, the acoustic waves generated in the side branches may generate vibration problems locally and may lead to complications such as valve-seat wear. Therefore, the structural components are subjected to high-cycle fatigue loads, which over time may severely impact those components functionality and safety.

3 Instability Caused by Resonance

Resonance occurs when the vortex shedding frequency coincides with the acoustic frequency of the standpipe or the valve components. The natural frequency of the standpipe/valve combination for a closed end pipe is given by the following equation:

$$f_a = \left(\frac{2n-1}{4}\right)\frac{c_e}{L+L_e} = \left(\frac{2n-1}{4}\right)\frac{c_e}{L+0.425d} \tag{2}$$

where n is the mode number (1 for 1st mode, 2 for 3rd mode, etc.), c_e is the acoustic speed through the pipe contents as defined earlier, and L_e is an end correction corresponding to Rayleigh's upper limit.

The frequency of pressure oscillations (sound) created by vortex shedding, the energy source for the standing waves, is given by the following equation:

$$f_s = N_{str} \frac{u}{d+r} \simeq 0.33 \left(n - 0.25\right) \frac{u}{d+r} \tag{3}$$

Typically peak oscillations occur at a Strouhal Number around 0.4 as shown in Figure 2. Note that the root mean square pressure amplitude shown in Figure 2 is the ratio of pressure oscillations divided by dynamic pressure ($\frac{1}{2}\rho u^2$). RMS begins increasing at a specific onset Strouhal Number and flow velocity depending on acoustic speed, pipe diameter, and pipe length, reaches a peak value and then decreases.

4 Flow Velocity Limits

In order to avoid fatigue failure from resonance caused by the coupling of normal flow vortex shedding frequency and the acoustic frequency of the standpipe ($f_s = f_a$), the normal flow velocity in the main line has to be limited to less than this critical value:

$$u_{max} < \frac{f_s}{N_{st}} (d+r) < \frac{1}{4} \left(\frac{c_e}{L+L_e} \right) \left(\frac{d+r}{N_{str}} \right) < \frac{1}{4} \left(\frac{c_e}{L+0.425d} \right) \left(\frac{d+r}{0.6} \right) \tag{4}$$

As shown in Figure 2 the pressure fluctuations start to increase at a Strouhal number of 0.6 and then decrease after they reach a peak value around a Strouhal number of 0.4. Field test data from forty valves indicate that a value of 0.6 is conservative as shown in Figure 3.

In the case where $d << L$ and r is small, the requirement for d/L for avoiding instability due to vortex shedding can be simplified to:

$$\frac{d}{L} > 2.4 \frac{u_{max}}{c_e} > 2.4M \tag{5}$$

or

$$u_{max} < \left(\frac{1}{2.4} \right) \left(\frac{d}{L} \right) c_e \tag{6}$$

Where M is the normal flow Mach number. The use of a conical reducer instead of a cylindrical branch connection to the main line has been shown to be an effective means of reducing or eliminating vortex shedding [3]. Installation of valves 8 to 10 diameters downstream of elbows or other flow disturbances sources can also help to reduce turbulence. Reduction of turbulence in the free shear layer can disrupt the feedback mechanism necessary to sustain a resonant vibration due to vortex shedding as shown in Figure 4. The above equation indicates that vortex shedding may be more pronounced for two-phase and vapor systems than liquid systems.

Figure 1: The Singing Safety Relief Valve [4]

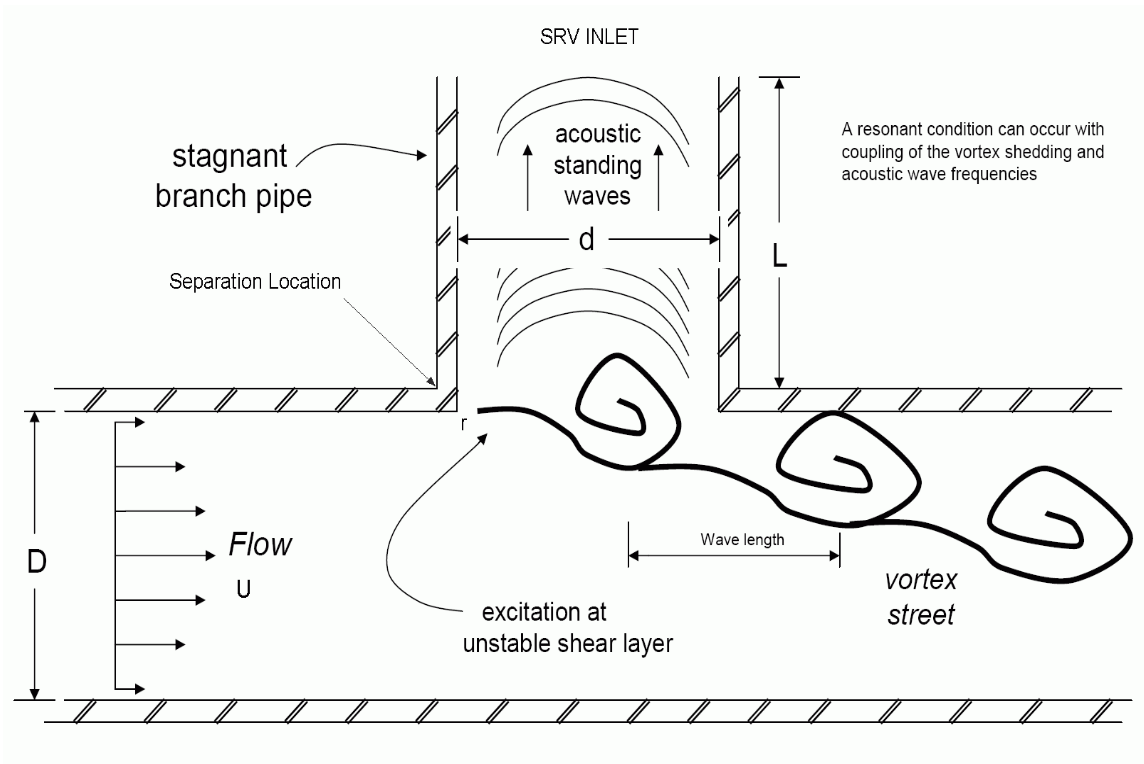


Figure 2: Comparison of Calculated and Measured Pressure Fluctuations as a Function of Strouhal Number [5]

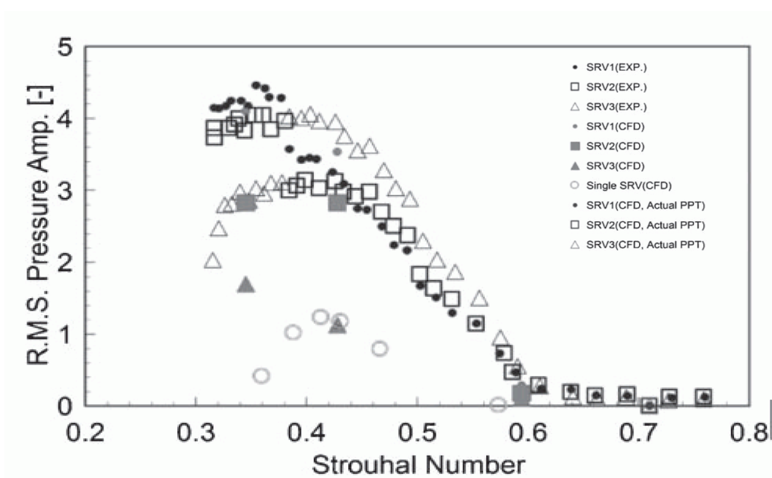


Figure 3: Critical Strouhal Number [6]

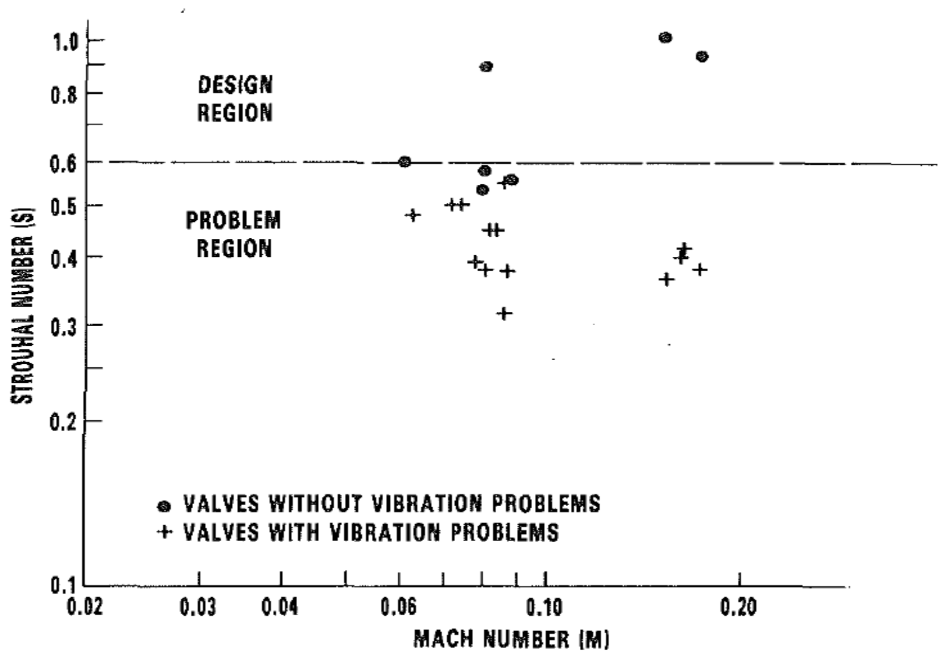
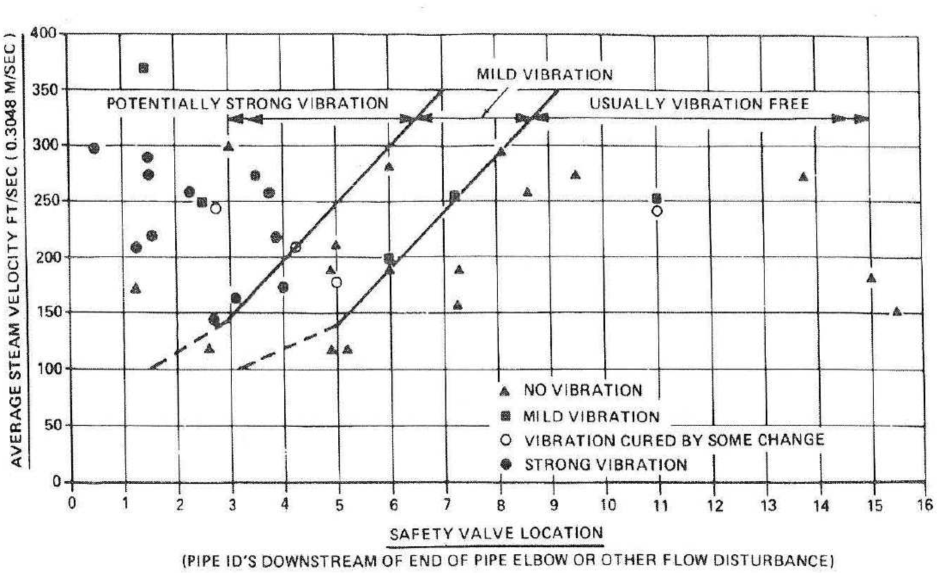


Figure 4: Plot of Steam Velocity / Valve Location Vibration Experience [3]



5 Implications for Two-Phase Flow

The speed of sound for two phase flow can be substantially lower than the speed of sound for all vapor/gas or all liquid flow. A typical value for flashing two phase flow is approximately 15 m/s, while a typical value for gas/vapor is approximately 300 m/s. Liquid speed of sound is typically 1000 m/s or higher. This indicates that the the flow velocity in a main process flow line where $d/L = 1/10$ for a pressure relief valve inlet line will be very restrictive for flashing two phase flow:

$$u < < 0.042 \times 15 < 0.63 \ \mathrm{m/s} \ \text{ for two-phase flow} \tag{7}$$

$$u < < 0.042 \times 300 < 12.6 \ \mathrm{m/s} \ \text{ for gas/vapor flow} \tag{8}$$

$$u < < 0.042 \times 1000 < 42.0 \ \mathrm{m/s} \ \text{ for liquid flow} \tag{9}$$

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About the Author

Dr. Melhem is an internationally known pressure relief and flare systems, chemical reaction systems, process safety, and risk analysis expert. In this regard he has provided consulting, design services, expert testimony, incident investigation, and incident reconstruction for a large number of clients. Since 1988, he has conducted and participated in numerous studies focused on the risks associated with process industries fixed facilities, facility siting, business interruption, and transportation.

Prior to founding ioMosaic Corporation, Dr. Melhem was president of Pyxsys Corporation; a technology subsidiary of Arthur D. Little Inc. Prior to Pyxsys and during his twelve years tenure at Arthur D. Little, Dr. Melhem was a vice president of Arthur D. Little and managing director of its Global Safety and Risk Management Practice and Process Safety and Reaction Engineering Laboratories.

Dr. Melhem holds a Ph.D. and an M.S. in Chemical Engineering, as well as a B.S. in Chemical Engineering with a minor in Industrial Engineering, all from Northeastern University. In addition, he has completed executive training in the areas of Finance and Strategic Sales Management at the Harvard Business School. Dr. Melhem is a Fellow of the American Institute of Chemical Engineers (AIChE) and Vice Chair of the AIChE Design Institute for Emergency Relief Systems (DiERS).

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About ioMosaic Corporation

Through innovation and dedication to continual improvement, ioMosaic has become a leading provider of integrated process safety and risk management solutions. ioMosaic has expertise in a wide variety of areas, including pressure relief systems design, process safety management, expert litigation support, laboratory services, training and software development.

As a certified ISO 9001:2015 Quality Management System (QMS) company, ioMosaic offers integrated process safety and risk management services to help you manage and reduce episodic risk. Because when safety, efficiency, and compliance are improved, you can sleep better at night. Our extensive expertise allows us the flexibility, resources, and capabilities to determine what you need to reduce and manage episodic risk, maintain compliance, and prevent injuries and catastrophic incidents.

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