

Assurance of complex pressure control system operability in high-temperature media

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Abstract. For the purpose of control and overpressure protection in pipeline systems of power industry and pressure vessels, indirect-action valves consisting of a main valve and a pilot valve are often used. Such devices are characterized by smaller reliability due to complication of their structure depending on operability of these two valves. A pilot valve controlling the whole safety system is the weakest element of the system. It is especially typical of machines operated in severe conditions, since life of sensing elements quickly decreases during work with high-temperature and polluted media. The authors considered the ways for improving reliability of pressure control systems operated in severe conditions by redundancy of the sensing element of the valve with a system equipped with a metal bellows. The authors analyzed reliability of initial systems and redundant systems at various operating temperatures.

1. Introduction

The increase in the capacity of processing units used in nuclear and oil-and-gas industries, as well as in operating characteristics thereof (pressure, consumption and temperature), place increasingly higher demands on their trouble-free operation. As a consequence, demands on reliable operation of control systems and overpressure protection systems also grow. It first of all applies to safety valves, which risks of failure to operate or incorrect operation during use increase under the influence of such negative factors as high temperatures, aggressive working environments, vibrations, etc. [1].

Units with big volume flow rates require pressure control systems consisting of numerous spring pressure-relief valves (SPV) due to low throughput of such valve. Increase in the number of same-type elements in a safety system facilitates the probability of their failure and failure of the whole system in general. Whereby, it is more desirable to install pilot-operated relief valves (PORV) possessing high throughput. A PORV consists of a main valve and a pilot valve (PV) functioning as an operating mechanism and taking up the power pressure for pressurization or depressurization in a PORV chamber. Yet, structures of a PORV are less reliable as compared to a SPV due to a bigger number of nodes and elements. During operation, PVs executed in a form of spring-type valve units are influenced by such negative factors as wear and tear, stress and high and low medium temperatures; in a result of which reliability of safety valve operation decreases leading to faults and consequential partial and complete failures of the safety system [2, 3]. Sometimes it is executed in a form of a solenoid-operated valve, but such device has major deficiencies, namely, a need for constant power supply, frequent maintenance and decrease in reliability at high operating temperatures [4]. That is

why in most cases a pilot valve is executed with no solenoids, in a form of valve units with a spring-type sensing element.

Therefore, assurance of pressure control system operability in high-temperature media is a priority task of power industry.

2. Analysis of failures of pilot valves in pressure control systems

During PV operation, its elements are influenced by such negative factors as wear and tear, stress, corrosion, high and low temperatures, and their rapid change, in a result of which reliability of the valves decreases leading to their faults and consequential failures. Percent composition of frequent faults and types of failures of PVs executed in a form of spring valves is presented in Figure 1 [5].

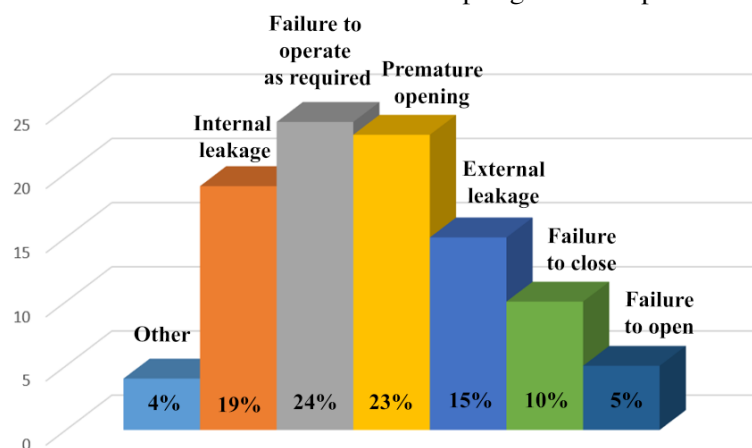


Figure 1. Percent composition of pilot valve faults and failures

Item “Failure to operate as required” (Figure 1) includes such PV faults as wrong speed of valve response and its opening outside the preset pressure. PV faults in a result of breakage of a spring-type sensing element amount to about 3% and are distributed among several items of the diagram. This type of fault is easily identified unlike faults related to changes in properties of a construction material of the spring under the influence of permanent stresses and high operating temperatures resulting in smaller stiffness and loosening of the springs. During operation, valve springs experience up to 40% of the maximum possible load when the valve is closed and up to 80% when the valve is open. That is, the aggregate of permanent stresses and high temperatures is the main reason of irreversible changes in operating characteristics of a spring. Significant influence of a sensing element on valve operability is that about 30% of the fault types “Premature opening” and “Failure to operate as required” is caused by irreversible changes in characteristics of a spring. Such operating conditions create a need for the increase in pilot valve reliability.

3. Assurance of pressure control system operability

When considering means for improvement of pilot valve reliability, it is necessary to follow the single-failure criterion, according to which a system shall perform its functions in case of any initial event requiring its operation, including failure of any element of such system not related to such event [6].

Pilot valve reliability can be improved by means of redundancy of the valve with a different-type system having a sensing element in a form of a metal bellows. The application of different-type systems and components, performing the same functions but differing in the principle of operation, for redundancy is the best solution, since reasons influencing the failure of one element will have no influence or will have small influence on the redundant element due to their diversity.

Probably, the best option would be a system shown in Figure 2, where in case of failure of a main element (spring), a redundant element (metal bellows), which is initially unloaded, gets into work, whereby the sensing elements are of different types.

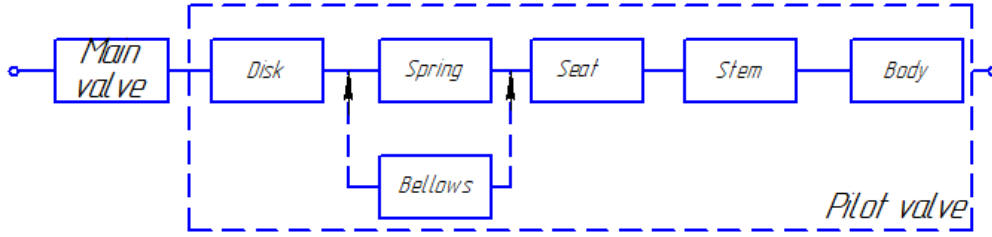


Figure 2. Redundancy scheme for a sensing element of a pulse safety device

The authors chose the element executed in a form of a metal bellows since bellows have long ago proved themselves as reliable and wear-resistant elements that can be used in various conditions. For example, as shaft seals in submersible well pumps influenced by high temperatures (up to 246 °C), abrasives and highly-corrosive extracted media [7]; as a part of bellows hydraulic accumulators in space reactor power systems operating in extreme temperatures [8].

4. Probabilities of failure-free operation of spring- and bellows-type sensing elements

When analyzing the column diagram of density of metal bellows failure distribution, we have found that the data are perfectly consistent with lognormal distribution [9]. The probability of failure-free operation of bellows $p_{bellows}(x)$ depending on cycles x in terms of lognormal distribution is determined as follows:

$$p_{bellows}(x) = \frac{1}{2} - \frac{1}{2} Erf\left(\frac{\ln(x) - \mu}{\sigma\sqrt{2}}\right) \quad (1)$$

where σ – mean-square deviation; μ – mathematical expectation.

In its turn, the probability of failure-free operation of spring in a valve unit is determined using the exponential distribution law, and the dependence of failure intensity is based on the ultimate strength of spring material which nonlinearly changes depending on a temperature [10].

The probability of failure-free operation of spring p_{spring} at the moment t is determined is follows:

$$p_{spring}(t) = \exp(-\lambda_{sp}t) \quad (2)$$

where λ_{sp} –intensity of spring failures determined as follows:

$$\lambda_{sp} = \lambda_{SP.B} \left(\frac{S_G}{T_S}\right)^3 \quad (3)$$

where $\lambda_{SP.B}$ – basic intensity of spring failures equal to 23.8 failures/million hours; T_S – ultimate strength of material, MPa; S_G – operating stress in the spring, MPa [10].

For special springs of pilot valves stainless steel S30200 is often used. The authors built dependencies of probability of fault-free operation of p_{spring} on the number of hours at different temperatures for springs made of such steel (Figure 3, A). The decrease in probability of fault-free operation of metal bellows $p_{bellows}$ depending on temperature growth (Figure 3, B) is caused by reduction of a ratio of life expressed in cycles at the sought-for temperature to life at a standard temperature [11].

The probability of failure-free operation of a valve before redundancy P is calculated as follows:

$$P(t) = p_{seat}(t)p_{disk}(t)p_{body}(t)p_{stem}(t)p_{spring}(t) \quad (4)$$

where p_{seat} , p_{disk} , p_{body} , p_{stem} , p_{spring} – probability of failure-free operation of a seat, disk, body, stem and spring, respectively.

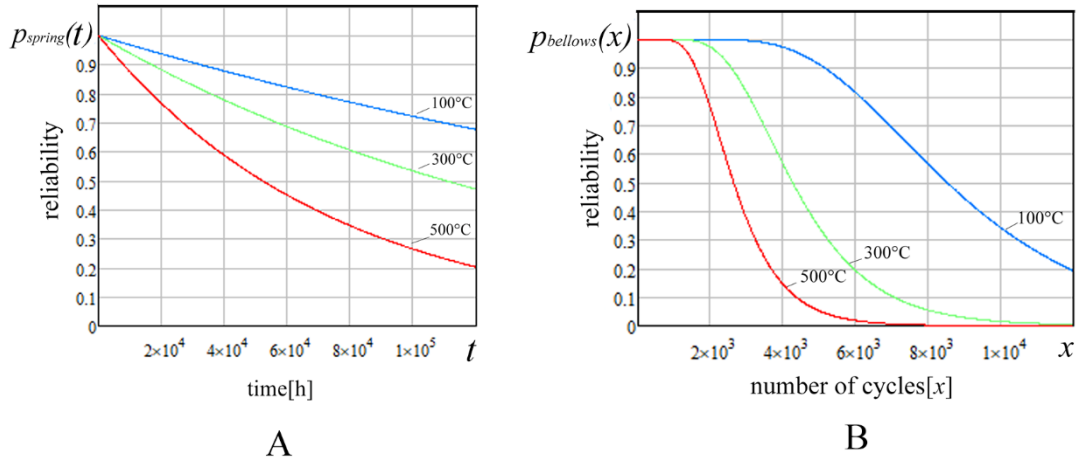


Figure 3. A – probability of fault-free operation of a pilot valve spring; B – probability of fault-free operation of a metal bellows intended for 6000 cycles

And after redundancy P' - as follows:

$$P'(t) = \frac{P(t)}{p_{spring}(t)} P_R(t) \quad (5)$$

where P_R – probability of fault-free operation of a redundant system calculated as follows:

$$P_R(t) = 1 - \frac{1}{2(1 - p_{spring}(t))(1 - p_{bellows}(t))} \quad (6)$$

where $p_{bellows}$ – probability of failure-free operation of a metal bellows depending on the assigned life and temperature.

5. Probability of failure-free operation of a redundant pilot valve system

The diagrams of probabilities of failure-free operation of a pilot valve before and after redundancy of a sensing element at various temperatures are shown in Figure 4 with a continuous line and dashed line, respectively.

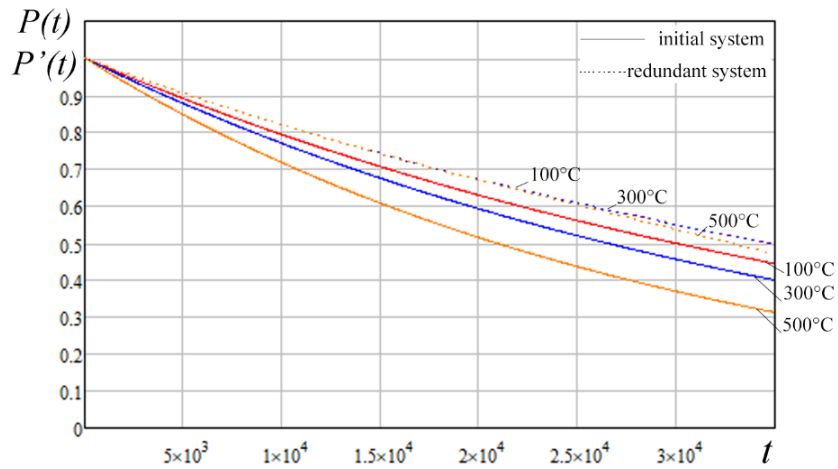


Figure 4. Probability of failure-free operation of a pulse valve before and after redundancy of a sensing element

The curves of probability of failure-free operation of a redundant system insignificantly change together with the increase in temperature, since reliability of a metal bellows remains quite high at such temperatures and production cycles. The advantage of a redundant system at small temperatures is not big, yet the efficiency of redundancy becomes more prominent together with the increase in temperature due to high reliability of a metal bellows at the predetermined operating characteristics.

6. Discussion

In order to provide for the determined reliability indicators at extreme operating temperatures, a corrugated shell of a multi-layered bellows shall be made of corrosion-resistant steel S32100. Whereby, if steel used in a particular medium is characterized by chloride or sulfide stress cracking, it is better to use heat-resistant alloys UNSN08800 or N06025 to produce a corrugated shell.

It should be noted that in order to reduce the cost of a bellows, its multi-layered corrugated shell intended for highly corrosive and high-temperature media can be made of several steel grades. An optimum choice for a layer contacting with a medium would be corrosion- and heat-resistant material, and for other layers - usual steel.

Further investigation of influence of a number of layers on the reliability of a metal bellows depending on various operating conditions is required.

7. Conclusion

1. When analyzing statistical data on faults and reasons of failures of spring valves in safety systems, significant influence of sensing elements on complete failure of the unit and partial operational failure under the influence of high stresses and temperatures leading to changes in properties of the construction materials was revealed.

2. The means for improvement of pilot valve reliability by means of redundancy with a system equipped with a metal bellows was proposed, and an optimum scheme of such redundant system was defined.

3. The densities of distribution of metal bellows failure intensity were analyzed, based on which probability of their failure-free operation was calculated.

4. The advantages of a redundant system in the areas with operating temperatures (up to 100 °C) and increase in the efficiency of redundancy together with the increase in temperature were identified. Redundancy of a sensing element of a pilot valve with a bellows-type system improves the reliability of the whole control and overpressure protection system in wide temperature ranges, increases life between overhauls and cuts the relevant expenses.

5. The construction materials for metal bellows were proposed in order to provide for the determined reliability indicators at extreme operating conditions.

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