Innovative Pressure Control System for Metallurgical Enterprises

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Abstract. The present study considers an innovative pressure control system for improving reliability of a hydraulic descaling plant. The pressure control system is based on a metal bellows hydraulic accumulator capable of withstanding high pressures. System installation diagram in the hydraulic descaling plant is shown. Design of the hydraulic accumulator is shown. This design allows effective pressure control in the whole plant due to its features of effective forces distribution on additional elastomers. The materials that can be used to create elastomers taking into account the peculiarities of metallurgical shops are shown. Dependencies are obtained which show possibility of reducing stiffness of the metal bellows unit when using additional elastomers. This reduces the cost of the pressure control system by using the metal bellows unit materials with less stiffness.

1. Introduction

Conventional methods of descaling are a major problem in the steel industry. Currently, various acids are commonly used as agents in the conventional descaling process: sulfuric, hydrochloric, nitric, hydrofluoric ones. Exhaust acid emissions pollute the environment. Demand for high-quality steel products has increased in recent years with much focus now on protecting the environment. Thus, there is a need to explore new ways to remove scale that are more environmentally friendly [1].

The scale removal by a jet of high pressure water is a relatively new technology that allows descaling effectively and without harm to the article surface. At the same time, this technology is environmentally harmless [2].

The operation of the hydraulic descaling plants often presents problems related to the cycling and fluctuation of hydraulic pressure. This negatively affects the operational parameters of the process as well as can lead to failures and accidents of the plant [3].

2. Hydraulic descaling plant

The basic principle of high pressure abrasive water jet technology is that water and abrasive particles are injected from a descaling nozzle and then hit the steel plate to remove scale. The impact of water and abrasive particles has a destructive effect on the scale and polishes the surface of the metal [4]. Figure 1 shows the scheme of hydraulic descaling [5].
3. **Hydraulic descaling plant with pressure control system**

High pressures are used in the hydraulic descaling plant to produce the proper pressure. In order to ensure that the pressure in the system does not exceed the permissible pressure and the impulse does not occur, it is possible to use the pressure control system including the hydraulic accumulator. The hydraulic accumulator allows reducing shocks and pulsations in the plant when critical pressures are exceeded in the system. Thus, the security of the entire system is improved. Figure 2 shows the diagram of hydraulic accumulator connection to hydraulic descaling plant (Fig.1).

4. **Developed hydraulic accumulator design**

Among the pressure accumulators there is the most stable and reliable type - metal bellows hydraulic accumulators. Their distinctive feature is [6, 7]:
- high reliability and low maintenance costs;
- it can be made of corrosion resistant material or material resistant to abrasive wear which allows such hydraulic accumulator to operate under extreme conditions;
- possibility to adjust stiffness of bellows by changing number of layers of multilayer corrugation (the more layers, the more stiffness).

Design of the metal bellows hydraulic accumulator is developed for installation of the hydraulic descaling plant (Figure 3) [8]. It operates under the action of working agent pulsations as follows. When the flow in the pipe 1 is uniform, the pressure in the system is constant and the bellows 2 and the elastomerics 4 are in a compressed state. When working agent fluctuations act, bellows 2 and elastomerics 4 receive dynamic disturbances damping working agent fluctuations and thus reducing dynamic action on equipment located further in the direction of working agent flow. When the pushers 9 act on the elastomerics 4, the latter are deformed in a cross-sectional direction.

Energy of working agent disturbances is transformed on the compression of the bellows and elastomerics 4 as well as on the operation of friction forces in the material of elastomerics 4 and the friction of elastomerics 4 on cylindrical surface of guide tubes 7 (Fig. 3).

Thus, the operating reliability of the bellows is improved and the range of operating pressures of the bellows hydraulic accumulator is increased.

This bellows hydraulic accumulator has a number of advantages, in particular:
- possibility of modular type design with inherent advantages;
- possibility of using bellows with fewer layers and larger bellows stroke;
- possibility of bellows hydraulic accumulator operation in wide ranges of back pressures without necessity of bellows replacement by selection of geometric dimensions of elastomerics, their material and quantity, or by replacement of elastic-unloading modules.

5. Materials
Elastomeric elements (elastomerics) can be made of different kinds of rubber; rubber-metal; with different thickness of rubber coating; with decreasing thickness of rubber shell as it moves away from
cover of elastic-unloading module. Thus, it is possible to provide the required stiffness coefficient and optimal stroke of the bellows. The most preferred option is to provide the elastomeric elements in the form of rubber-metal balls.

As the ball material, for example, Vamac ethylene-acrylic elastomer can be used. It has heat resistance (up to 175 °C) with peaks (up to 200 °C), durability, flexibility and chemical resistance [9].

In order to manufacture the bellows unit the main indicator for material selection is its formability. These are mainly corrosion-resistant and alloyed steels. The bellows unit is made of sheet material. It may be single-layered, but that bellows unit can’t withstand high pressures, so it is mainly made to be multilayer [10].

Some of the most common steel grades for manufacturing the bellows unit are 304, 304L, 304H, 600 and 800 steel grades. 304 steel grade is austenitic, it can stretch well. 304L steel grade is a low-carbon version of 304 steel grade having good overall weldability. 304H is high carbon steel having high resistance to high temperatures. 600 steel is a chromium nickel alloy having good corrosion resistance withstands high temperatures and is poorly oxidizable. 800 steel is a chromium nickel alloy resistant to high temperature oxidation [10, 11].

One of the main characteristics for selecting the bellows material is its stiffness. The more rigid the material has, the higher its cost. Features of the developed design of the bellows hydraulic accumulator allow selecting the bellows material with less rigidity which allows choosing cheaper materials for its manufacture.

6. Forces Redistribution in the metal bellows hydraulic accumulator

In order to demonstrate the dependence of the bellows stiffness on the stiffness of the rubber-metal balls inside the bellows let’s plot this dependence. For this purpose we express stiffness of the bellows unit through rigidity of balls. The dependence is presented in Eq. 1 [12].

\[
C = \frac{Q}{f} - C_h ,
\]

where: \(C\) – bellows unit stiffness; \(Q\) – force acting on the bellows unit; \(f\) – bellows unit stroke; \(C_h\) – stiffness of the balls.

Let’s express the force acting on the bellows unit through overpressure and geometric parameters of the bellows [12]. The result is presented in Eq 2.

\[
Q = p \cdot \pi \cdot \left(\frac{R_o + R_v}{2}\right)^2 ,
\]

where: \(p\) – overpressure; \(R_o\) – external radius of the bellows unit; \(R_v\) – internal radius of the bellows unit.

Let’s record expression for calculation of the ball stiffness through force, deformation and number of balls [13]. The result is presented in Eq 3.

\[
C_h = \frac{Q}{h} \cdot n ,
\]

where: \(h\) – ball deformation during compression; \(n\) – number of balls.

Let’s express the ball deformation through force, Young's modulus and radius of a ball [13]. The result is presented in Eq 4.
where: \( E \) – Young’s modulus; \( r \) – radius of a ball.

Having substituted Eq. 2-4 in Eq. 1 we obtain dependence of the stiffness Eq 5 of the bellows unit on the rigidity of the balls and geometric parameters of the bellows at constant pressure.

\[
C = p \cdot \pi \cdot \left( \frac{R_v + R_w}{4f} \right)^2 - \left( \frac{p \cdot \pi \cdot (R_v + R_w)^2 E^2 \cdot r}{8} \right)^{\frac{1}{3}} \cdot n.
\]  

(5)

External radius and internal radius of the bellows unit and stroke are according to GOST 21744 «Multilayer Metal Bellows. General Specifications». Overpressure is equal to 35 MPa. Other input data are provided in Table 1.

**Table 1.** Input data for calculation of the bellows unit stiffness dependence on the additional elastomerics stiffness.

| Configuration # | \( R_w, \text{mm} \) | \( R_v, \text{mm} \) | \( p, \text{MPa} \) | \( E, \text{MPa} \) | \( r, \text{mm} \) | \( f, \text{mm} \) |
|-----------------|-----------------|-----------------|----------------|--------------|-------------|-------------|
| 1               | 38              | 36              | 35             | 7            | 4           | 4           |
| 2               | 48              | 45.6            | 35             | 7            | 4           | 7.5         |
| 3               | 65              | 63              | 35             | 7            | 4           | 8           |

In the course of the calculations the number of balls and the parameters of the bellows (geometric parameters, number of layers) were changed resulting in a graph of the dependence of the stiffness of the bellows on the stiffness created by the balls. The dependency graph is given in Figure 4.

**Figure 4.** Dependency graph of the bellows stiffness on the stiffness of the additional elastomerics and the bellows parameters
7. Results
Taking into account obtained graph it can be concluded that when increasing the elastomerics it is possible to use the bellows unit with less stiffness. That is, the use of materials with less rigidity allows reducing the cost of the metal bellows hydraulic accumulator. It is also possible to use the bellows with fewer layers which also reduce the manufacturing costs of the device. It also reduces the number of failures of the bellows hydraulic accumulator when using the same material by unloading the bellows due to the use of elastomerics.

Table 2 shows the characteristics of different steels (Young's modulus [14] and relative value [15]).

| Steel grade                     | Young's modulus, MPa·10⁵ | Steel relative cost |
|---------------------------------|---------------------------|---------------------|
| Conventional-grade steel (S235, E335) | 2.00                      | 1.0                 |
| High quality structural steel (C22E, C45E) | 2.01                      | 1.0÷1.17            |
| Spring steel (60SiCr7)          | 2.03                      | 1.30÷1.40           |
| Die steel (9MoV6-3)             | 2.03                      | 1.38÷1.57           |
| Light alloy steel (30ChGSA, 37Cr4) | 2.05                      | 1.10÷2.02           |
| Bearing alloy steel (100Cr6)    | 2.1                       | 2.10÷2.70           |
| Stainless steel (1.4541)        | 2.1                       | 2.60÷2.85           |

According to the data (Table 2), we can conclude that less rigid steel has a lower relative cost. That is, the proposed design of the bellows hydraulic accumulator allows selecting the bellows materials with lower cost. For example, it is possible instead of the spring steel to use the conventional-grade steel which is 1.5 times cheaper.

8. Conclusions
Using the pressure control system was proposed in hydraulic descaling systems. The design of the bellows hydraulic accumulator for extreme pressures existing in the hydraulic descaling system was developed for this purpose. The main concept of the device is to unload the bellows by using the additional elastomerics in the device. It is shown that it is possible to use less rigid bellows materials with such unloading. For example, it is possible instead of the spring steel to use the conventional-grade steel which is 1.5 times cheaper. In addition, the use of such a system can result in reducing the number of failures when using the same material for the bellows of the hydraulic accumulator.

9. References
[1] Wang X C, Mao Z W, Yang Q 2012 Research on High Pressure Abrasive Water Jet for Cold Rolling Descaling Adv. Mater. Res. 572 31-36
[2] Totten G E, Funatani K, Xie L 2004 Handbook of Metallurgical Process Design CRC Press, Boca Raton, FL
[3] Watson J F, Rance J M, Anderson H J 1996 Analysis of the Fatigue Failure of Tee Pieces Forming Part of a Header in a Descaling System in a Hot Strip Rolling Mill Int. J. Pres. Ves. & Piping 68(1) 121-126
[4] Raudensky M et al 2007 Hydraulic Descaling Improvement Findings of Jet Structure on Water Hammer Effect La Revue de Metallurgie CIT 104 84-90
[5] Bodrov V V et al. 2016 Sozdaniye Sistemy Gidrosbiva Pechnoy Okaliny s Tsilindricheskikh Zagotovok MetalRussia 1 20-23
[6] Terasmes K S et al. 2019 Assurance of Complex Pressure Control System Operability in High-Temperature Media J. Phys.: Conf. Ser. 1353 012055
[7] Terasmes K S et al. 2020 Pulse Safety Device with Adaptive Controller for Technical Systems with High Reliability Requirements J. Phys.: Conf. Ser. 1515 042102
[8] Petrovsky E A, Bashmur K A, Terasmes K S 2019 Bellows Hydraulic Accumulator RU Patent 2 694 102
[9] Mark H F 2014 Encyclopedia of Polymer Science and Technology 4th ed. Wiley Hoboken NJ
[10] Dureja A K et al. 2011 Design, Analysis and Shape Optimisation of Metallic Bellows for Nuclear Valve Applications SMiRT 216
[11] Sorokin V G, Gervasiev MA 2001 Steels and Alloys Catalog, Intermet Engineering (Moscow)
[12] Burtsev K N 1963 Metal Bellows Mashgiz (Moscow)
[13] Landau L D, Lifshitz E M 1987 Theory of Elasticity Institute of Physical Problems (Moscow)
[14] Information on https://prompriem.ru/stati/modul-uprugosti.html
[15] Baraz V R, Filippov M A, Gervasiev M A 2016 Purpose and Selection of Metallic Materials *Ural University Publishing* (Yekaterinburg)