Development and testing of a steel regulating thermostatic valve

S A Antsiferov*, E A Usmanova, E V Chirkova
Togliatti State University, Belorusskaya st., 14, Tolyatti, 445020, Russia

E-mail: salan63@mail.ru

Abstract. A steel thermostatic valve group has been designed from a more affordable, cheaper domestic material - structural carbon steel grade PS08, which makes it possible to improve the manufacturability, installation, ease of the developed product operation, and reduce production costs. As a prototype, bronze thermostatic valves with threaded connections of foreign manufacturers were used, other geometrical parameters were determined by the production manufacturability. The results of the thermostatic valve steel body new design studies for two-pipe water heating systems are presented. A 3D model was built using the Solidworks design and graphics package, optimizing the geometric, mass, and strength valve characteristics. The application Solidworks Flow Simulation calculated the pressure loss in the digital 3D-model of the valve, its hydraulic characteristic was calculated. According to the numerical experiment results, a physical model of the valve group was manufactured and tested on a pouring stand. A comparison of the hydraulic characteristics of the digital and physical models was made, improvements to the design were made, and the purity of the internal surfaces was improved. A series of tests was carried out to determine the hydraulic characteristics for the regulating mechanism various values adjustment. In the heating season 2018 - 2019, full-scale tests were carried out at the operating facility with the installation of a valve and a thermal head on experimental convectors. The internal air average temperature measurements showed that the air temperatures in all the rooms with the same settings of the thermostatic head were within the acceptable limits. Therefore, the control quality of the pilot valve was adequate. The experimental thermostatic valve group was launched into small-scale production for the field tests in the buildings for various purposes.

Introduction
The need to develop domestic production is regulated by our legislation and is aimed at creating a coordinated system with the import substitution elements. The Russian government sets the priority of Russian products in accordance with the Part 8 Art. 3 [1], Art. 18 [2], which is one of the most important means aimed at the national economy development, in particular, energy, construction utilities. The competitiveness of our products should be ensured not only in the domestic, but also in the external markets. The most effective measures for import substitution in the economy areas, which have “national” features and can be implemented at the domestic products expense. One of these areas is the equipment production for heating systems, because in our country the longest heating period takes place, and the cost of heating is up to 40% of the maintaining residential and public buildings cost [15]. Modern requirements for energy savings [3] and the need to increase the level of comfort contribute to enhancing the search for solutions aimed at controlling the heating devices heat transfer.
[11, 12]. Paragraph 6.4.9 [4] recommends installing the control valves in radiators for the residential and public buildings, as a rule, with automatic thermostats, i.e. to provide local regulation of heat flow from the heater and automatically maintain the heating system hydraulic mode stability. The innovation consists in the thermostatic valve group design development, aimed at the use of more affordable, cheap, domestic material, allowing to improve the production manufacturability, installation and ease of the designed product operation.

Relevance of the work

The steel thermostatic valve group new design development for two-pipe heating systems will make it possible to abandon the use of expensive imported materials, in particular bronze cases. In this case, one of the serious problems is eliminated - the formation of a galvanic pair “steel pipe - bronze case” as a source of corrosion [14]. The use of steel will make it possible to abandon the threaded joints in favor of the welded ones, which, in turn, will increase the manufacturability of the valve installation at the factory directly on the supply pipe to the convector, and will decrease the metal consumption (Figures 1, 8).

Thus, the development and launch of a new steel thermostatic valve into production will make a contribution to the tasks’ solution for the domestic production development.

The valve group design process is conducted in the following order: a digital model creation; the theoretical hydraulic characteristics calculation; a prototype fabrication and its testing on a pouring stand with the regulating mechanism various settings.

Steel thermostatic valve supplied with a temperature regulator (thermostatic head) was developed taking into account the heating systems hydraulic calculations domestic practice, hydraulic tests and control valves and is designed to automatically or manually control the flow rate of the heat carrier with a temperature of up to 120 MPa heating device [8, 9].

The thermostatic valve group is a single piece made on metal-cutting machines from rolled steel of PS08 structural carbon steel (GOST 1050-88), with the necessary round holes and threads for mounting the regulating mechanism and the thermostatic head. The body has a spherical shape for the convenience of welding a gas pipeline with a nominal diameter of 20 mm without additional preparation; only edge cleaning is required. The lower part of the body is cut to obtain a flat surface, which is necessary for reliable fastening in metalworking machines. A longitudinal section and the main dimensions of the group are shown in Figure 1.

As a prototype, bronze thermostatic valves with threaded connections of foreign manufacturers were used, which dictated the mounting dimensions of the regulating mechanism and the thermostatic head. Other geometrical parameters were determined by the production technological capabilities. At the first stage of construction, a 3D model was built using the Solidworks design and graphics package from Dassault Systèmes, which optimized the geometric, mass, and strength characteristics in the Solidworks Simulation application.

To characterize the hydraulic parameters of control valves, the flow factors are used: $K_{vs}$ characterizing the maximum capacity of the valve at a pressure drop $\Delta P = 1$ bar (0.1 MPa) and $K_v$, determined from the volume flow rate of the heat carrier $G$ (m$^3$/h), with a certain valve setting. At the
same time, for different manufacturers the adjustment accuracy varies from 1 ° C to 3 ° C. Numerical values are calculated by the formula:

$$K_{vs} = \frac{G}{\sqrt{\Delta P}}$$  \hspace{1cm} (1)

When a real heating system is operating, the required pressure drop across the valve $\Delta P = 1$ bar is rather difficult to withstand, and the maximum $\Delta P$ value should not exceed 0.2 - 0.3 bar. According to the manufacturers recommendations for most valve designs $\Delta P = 0.1 - 0.2$ bar, this difference is dictated by the accuracy of adjustment and the noise level, which should not exceed 25 dB [10].

Foreign regulatory documents [5] establish the necessary differential $\Delta P = 0.1$ bar. For each type of control valve, the nominal values of the coefficients $K_{vs}$ and $K_v$ are calculated by (1), later the empirical corrections are introduced, taking into account the characteristic non-linearity.

At the next stage of the study, the diameter of the valve seat bore is determined to maintain the standard hydraulic characteristics that the third-party regulating mechanism provides in the designed housing. Figure 2 shows the isobars and streamlines in the section of the valve group, resulting from the 3D model calculations. Figure 3 shows the pressures and velocities distribution graphs in the valve group along the averaged flow line.

![Figure 2. Isobar and current line in the valve group section](image)

![Figure 3. Pressure and velocity distribution graphs in the valve group](image)

In the Solidworks Flow Simulation application, a calculation to determine the pressure loss of a digital 3D model of the valve group was made. The required value for the regulatory mechanism $K_{vs} = 0.75$. The hydraulic characteristic is shown in Figure 4 (with a solid line). The calculated dependence is described by the equation:

$$\Delta P = 1.65 \cdot G^{1.75}$$  \hspace{1cm} (2)
The prototype of the valve was tested on a pouring stand, its hydraulic characteristic is presented in Figure 4 (with a solid line). Table 1 shows the prototype hydraulic tests results and the numerical experiment with a 3D model.

**Table 1.** Results of testing a prototype and a numerical experiment with a 3D-model

| Prototype | 3D-model |
|-----------|----------|
| $G$ [m$^3$/h] | $P_{in}$ [bar] | $P_{out}$ [bar] | $\Delta P$ [bar] | $\Delta P$ [bar] |
| 0.75 | 2.5 | 1.5 | 1 | 1.00 |
| 0.7 | 2.32 | 1.43 | 0.89 | 0.88 |
| 0.6 | 2 | 1.32 | 0.68 | 0.67 |
| 0.5 | 1.7 | 1.18 | 0.52 | 0.49 |
| 0.4 | 1.84 | 1.51 | 0.33 | 0.33 |
| 0.3 | 1.82 | 1.61 | 0.21 | 0.20 |
| 0.2 | 1.54 | 1.45 | 0.09 | 0.10 |
| 0.1 | 1.88 | 1.83 | 0.05 | 0.03 |

**Figure 4.** The hydraulic prototype characteristics (with a solid line), 3D Models (with a dotted line)

Thus, having satisfactory convergence of the results of the full-scale and numerical experiments (Pearson's criterion $R^2 = 0.98$), we can conclude that the digital model of the valve group reproduces the prototype quite accurately and is further suitable for modeling the hydraulic mode with the regulating mechanism different settings. A prototype of the valve group was manufactured using a 3D model and tested in a flow lab (Figure 5). Hydraulic characteristics are shown in Figure 6.
According to the test results, it was revealed that the pressure loss at a nominal flow rate of 0.75 m$^3$/h is 1.19 bar, and the calculated differential $\Delta P = 1$ bar corresponds to a flow rate of 0.7 m$^3$/h. The increase in pressure loss is associated with unaccounted local hydraulic resistances in the valve group and the regulating mechanism; the machining cleanliness of the holes (roughness) [13]. Adjustments were made to the design of the valve group: internal surfaces additional grinding (brought to $Ra = 0.8$ against the initial $Ra = 6.3$ after drilling and milling); 1 mm chamfering at inlet and outlet.

A series of tests was carried out in the flow lab to determine the hydraulic characteristics for the regulating mechanism adjustment various values. The final diagram is plotted in a logarithmic coordinate system (Figure 7). Table 2 presents the throughput $K_v$ coefficient values depending on the setting.

**Table 2. The throughput $K_v$ coefficient values depending on the settings**

| Set-up | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| $K_v$ [m$^3$/h] [bar$^{0.5}$] | 0.116 | 0.162 | 0.255 | 0.418 | 0.508 | 0.547 | 0.620 | 0.75 |
A pilot batch of convectors with a nominal heat flow $Q_{nom} = 1.049$ kW equipped with thermostatic valves was manufactured. In the heating season 2018-2019, the full-scale tests were carried out on the existing facility: a two-story residential building with a total area of 360 m$^2$ with a two-pipe heating system with frontal wiring. Experimental convectors (figure 8) were installed on the east side of the building, on the west side - steel panel radiators $Q_{nom} = 0.96$ kW with a bronze valve prototype. All heaters are equipped with thermostatic heads of the same manufacturer. The average temperature measurements in the premises according to the requirements [6, 7] showed that the temperature difference in all the rooms, with the same settings of the thermostatic head, is within acceptable limits [6]. Thus, the experimental valve regulation quality meets the requirements [8].

Figure 8. General view of the pilot valve with a thermal head installed on the supply line to the convector

At present, the necessary technical documentation for the production and operation of the valve has been developed. The experimental thermostatic valve group is manufactured in small-scale batches for performance testing in buildings for various purposes. The manufacturing technology improvement using CNC machines is in progress. Feedback has been established with facilities where experimental valves are installed, a program of additional tests for the next heating period has been developed, aimed at identifying possible design flaws and temperature control accuracy in the room. Further research is aimed at developing a thermostatic valve group for one-pipe heating systems.

Summary
The thermostatic valve steel group has been designed and optimized on the basis of a numerical experiment with the construction of a 3D model. According to the field studies results in the flow lab, the compliance of the hydraulic characteristics and the experimental valve regulation quality with the regulatory documents requirements was revealed. The experimental thermostatic valve group is launched into small-scale production for the field tests in various buildings. The development and launch of a new steel thermostatic valve in production will contribute to the development of domestic production and reduce the imported components share in the heat supply systems of buildings.

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