Experimental and numerical analysis of the rail with the heat control valves

G Romanik\textsuperscript{1}, J Rogula\textsuperscript{1}, A Machalski\textsuperscript{1}

Wroclaw University of Science and Technology, Faculty of Mechanical and Power Engineering, Department of Mechanics, Machines, Devices and Energy Processes, ul. Wybrzeze Wyspianskiego 27, 50–370 Wroclaw, Poland

E-mail: grzegorz.romanik@pwr.edu.pl

Abstract. The article presents the results of experimental and numerical tests of a surface heating flow control system consisting of a distribution rail along with the fixed valves set. The flow rates of single and parallel installed valves were measured, their three-dimensional models were prepared and used to make a flow models. The coefficient of \( k_v \) is computed for a single valve on the rail and for the set of valves. In a flow model geometry the measurements of the test stand elements were considered in order to compare the results. The influence of the addition of the valves to the rail on the flow rate distribution was determined.

1. Introduction

The main purpose of using low-temperature heating systems is to provide the expected thermal comfort using significantly lower temperatures. Low temperature waste heat and heat pumps require the heat exchangers of a large surface. Large-area heating can be an element of zero-emission heating systems \cite{1}, such as heat pumps and solar or photovoltaic panels. Broad description of the solar assisted compressor heating system is contained in \cite{2,3}. A radiant heating system is not a new idea. It has been used successfully for over 50 years \cite{4}. As the thermal comfort is a subjective parameter felt by human feet, it is strongly recommended that the temperature field of the floor should be uniform \cite{5}. In addition to this, the floor temperature should not exceed 30°C in order to avoid thermal discomfort caused by an excessive vertical radiation asymmetry. One of many parameters that essentially affect comfort is the localization of the heat source in the room \cite{6}. The following possibilities are typical: floor, ceiling-floor, wall, ceiling. The localization of heating source affects heat comfort, heating effectiveness, and hence, the energy consumption \cite{7,8}. The comfort issues, energy and economic efficiency of the system are determined by the appropriate flow system settings \cite{9} and insulation parameters \cite{10,11}. Water flow and pipe heat resistance have the essential influence on heating efficiency \cite{12}. In order to decrease the energy consumption, the knowledge of heat transfer coefficients is also extremely important \cite{13}. Authors decided to consider the significance of the control valve in the aspect of influence on the flow through the heating system and thus on thermal efficiency. Especially when the successive valves are opened or regulated. And it was done both: with prepared tests and mathematical model for the flow through the valve. Determination of the valve coefficient \( k_v \), defined on a test stand as well as numerically, by means of a CFD software, is helpful to specify pressure losses in a heating system and to choose an appropriate pump \cite{14}. A predictive
approach is possible thanks to computer simulations using various models of a fluid flow, heat flow and temperature distribution in the room [15-18]. Floor (Figure 1a) or wall heaters (Fig. 1b) in buildings need a control system [19], especially an intelligent system that guarantees a higher level of energy savings. Heat exchanger pipes from the outside are embedded in the concrete and they are connected to the heating system in one place.

![Figure 1. Large-area heating systems. a) floor heaters, b) wall heaters.](image)

The system connecting the heating pipes consists of a rails (Fig. 2) that performs two functions: the water manifold and the flow regulator at the same time. An advantage of large surface heating system is a closing possibility of the installation in several independent branches. It allows to control the heating - for example to keep temperatures separately of each branch from one rail. Collection of all control valves in one rail simplifies the regulation and automation way.

Control valves fixed to a distribution rails (Fig. 2) decide on the efficiency of a surface heating system and the accuracy of the temperature regulation in a room. The water flow rate is distributed up to the group of several control valves fixed on one rail [20]. From heating boiler warm water flows through the upper rail 2. Then it is divided into particular 4 streams flowing through the branches. The quantity of water in the branches is controlled by the special valves 3 fixed in a lower rail. Flow control by means of valves causes the changes of ball position in the rotameters 1. It gives information about the change of flow rate in the branch. Rotameter usage is optional in the rail application. Every change of a valve head position gives an increase of local resistance in a stream of a liquid.

![Figure 2. Exemplary floor heating manifolds with rotameters, 1 – rotameter, 2 – rail, 3 – control valve, 4- inlet of water pipe for one branch, 5 – outlet of water flow.](image)
2. Experimental research

2.1. Objects of a study
A set consisting of a brass distribution rail and a flow control valves plug were applied for the analysis concerning the operation of control valves of the surface heating. The elements presented in Figure 3 were assembled together, connected to the test stand and further tested. The designs of a distribution rail and cooperating valve were analyzed.

![Figure 3](image)

**Figure 3.** Object of analysis: a) distribution rail cross-section, b) model valve, 1 – spindle, 2 – valve head, 3 – threaded tip with valve seat.

A distribution rail with standardized length is a pipe with flat ends and it is possible to connect four control valves in a serial configuration. Four threaded G1/2 holes were made in flat ends of rail in perpendicular direction to the rail main axis. It allows to fix four independent branches separately controlled. Moreover, two connectors G1 were made in the rail axis in its ends. One connector is used for fixing a pipeline with ball valve and supplied water and the second one allows to join another connecting rail or install a pipe cap. A valve seat ring was assembled to one side of the rail, on the other side there was the body with a fixed spindle and a valve plug of a diameter $\phi 17$ mm (Fig. 3). The rotation of the valve spindle 1 enables medium flow control, open it or close. The distance between valve head and seat were measured and connected with the spindle thread lead. Maximum lift of the valve plug amounts to 2.4 mm which at the same time characterizes the level of the valve regulation. The valve spindle for tests was driven by means of a handle. During the computational and object tests, calculated number of spindle rotations is bonded with percentage opening of the flow.

In order to prepare the distribution rail for tests one of the connectors as well as one pair of the outlet holes were covered.

2.2. Test stand and measurements methodology
The tests of flow suppression through the valve were carried out on a test stand adopted for testing central heating flow elements with standardized distances. The test stand was widely characterized in [21]. The Figure 4 presents the examined valves in rails and flowmeter.
Figure 4. Test stand for testing flow elements of central heating systems, 1 – control valve, 2 – pressure sensor.

Water flow on a test stand took place in a closed system and forced by means of centrifugal pumps. It included rails with threaded holes for four valves assembly and a flow in the system. Water temperature stabilization was controlled with water cooling system. To the rail three parallel set of valves was assembled. The test stand was also equipped in a manually operated control valve (1) throttling the flow in front of the tested valve. The flow through the rails and working valves was measured by means of an electromagnetic flowmeter in grade 0.2. The flowmeter was located in the distance of 10 diameters behind the rail. The measurement of static pressure was realized by means of electronic manometer sensors in grade 0.2. The water pressure was measured on inlet and outlet (2) channels. The temperature of the medium was determined by means of a PT100 thermometer and infrared camera. The pumped medium was pure water supply.

During the test, the data was collected to the characteristics of the change of valve coefficient $k_v$, determination as a function of the percentage opening the valve (number of the spindle rotations between close and full open state). It was assumed, that on the rails, regardless of its setting the drop of pressure equal to 1 bar would be kept in accordance with standard [1]. To enable the implementation of pressure drop condition on the rails and valves, rotations of the pump were controlled with computer system and locally regulated with a control valve (2, figure 4) for a given setting of the regulation wheels of the tested valves.

To determine the flow coefficient $k_v$, the following formula was used:

$$ k_v = \frac{Q}{\sqrt{\Delta p}} $$

where:

- $k_v$ – flow coefficient, $m^3/h$
- $Q$ – volumetric flow, $m^3/h$
- $\Delta p$ – pressure drop on the tested valve, bar

2.3. Results of the tests

Every examined valve and its valve head can be positioned separately like in real set. The idea of test was to achieve the same opening level for each valve; the position of the valve heads to valve seat was the same for three examined valves. 100% of valve opening for two examined valves required 7.5 valve spindle revolutions; for the third valve full opening required 8.5 spindle revolutions. Tests were
done for three water pressures values: 0.4 MPa, 0.5 MPa and 0.6 MPa. Calculations of coefficient $k_v$ were carried out for single valve and for three parallel assembled valves to the rails. Figure 5 presents the channels thermograms for one opened valve and for three opened valves.

![Thermograms of the channels connecting the rails, a – one open valve, b – three open valves with the same opening level.](image)

**Figure 5.** Thermograms of the channels connecting the rails, a – one open valve, b – three open valves with the same opening level.

Temperature of flowing water changes the temperature of plastic channels. The temperature of water was used to calculate the water density. While taking measurements of parameters necessary to determine basic characteristic of the valve constant feeding conditions were maintained. The measurements were taken in the steady state.

Experimental data allowed to determine of the flow coefficient $k_v$ for a single valve and for three parallel connected valves. The results can be found in Figure 6.

![Summary characteristics of the tested valves fixed in a rail $k_v$ versus percentage of opening.](image)

**Figure 6.** Summary characteristics of the tested valves fixed in a rail $k_v$ versus percentage of opening.

While analyzing the linear approximation it should be noticed that for a full opening of the single valve the coefficient $k_v$ equals about 3.1 m$^3$/h for 0.4 MPa to 3.3 m$^3$/h for 0.6 MPa. The coefficient $k_v$ in the whole course of changes of the control valve rotation is increasing. For three valves linear characteristic for 0.5 MPa is higher than for 0.4 MPa and 0.6 MPa. For full opening of three valves the $k_v$ values changes from 7.5 m$^3$/h for 0.4 MPa to 9.3 m$^3$/h for 0.5 MPa. The reason of $k_v$ coefficient
changes values could be additional rotation of one of the examined valves to achieve its full opening. In this case the created valve chamber has different dimensions than others valves.

3. Numerical simulations

3.1. Computational model
The computational model was constructed basing on experience described by authors dealing with the topic [22,23]. Computational Fluid Dynamics makes it possible to conduct numerical tests of the control valves assembled to the rail. The three dimensional flow geometry model of single valve subjected to simulation was presented in Figure 7. Figure 8 presents the meshing for three valves. The process of model digitalization was conducted by use a nonstructural grid (tetrahedral). A prismatic grid was used close to the walls in the areas with rapid changes of diameters, i.e. valve areas. It was decided to carry out flow simulations for single valve and for three valves for four chosen settings of the valve. It was assumed that the valve plug lift would be equal to 0.8 mm (Fig. 9a and 9b), to 1.6 mm (Fig. 10a and 10b) and to 2.4 mm (Fig. 11a and 11b).

![Figure 7](image1.png)

**Figure 7.** Three dimensional cross-sectional projected model of the flow through partly open 0.8 mm (34% valve opening) valve fixed in a distribution rail subjected to CFD simulations.

![Figure 8](image2.png)

**Figure 8.** Meshing made for three valves.

Calculations have been carried out using resources provided by Wroclaw Centre for Networking and Supercomputing (http://wcss.pl), grant No. 444 and based on commercial software Ansys Fluent.
CFD. Calculations were performed by means of a turbulence model k-ω SST for all valves geometry. Working medium was pure water and numerical analysis was carried out as stationary. Convergence of the numerical results for all valves geometries was obtained at the level $10^{-5}$. For all configurations, the value of static pressure as well as estimated turbulence level were assumed at the inlet and outlet. The flow rate $Q$ was an output parameter. In the presented figures for better visualization of the phenomena taking place in the channels, the numerical model was divided by planes situated on rails axes. It allowed to make possible the presentation the swirls of the flow.

3.2. Qualitative results of numerical simulations

The computational models enabled to perform the qualitative identification of the water flow in the rail and valves.

3.3. Quantitative comparison of the results of real and numerical research

Performed numerical simulations and the experimental data were compared with each other and it made possible to conduct a comparative quantitative analysis of the flow through the investigated set of valves and single valve. The exemplary results can be found in Figure 12.
Figure 10a. Tracks of water particles in the valve, valve plug lift 1.6 mm, pressure 0.6 MPa.

Figure 10b. Tracks of water particles in the three valves, valves plug lift 1.6 mm, pressure 0.6 MPa.

Figure 11a. Water velocity distribution in the valve, valve plug lift 2.4 mm, pressure 0.6 MPa.

Figure 11b. Tracks of water particles in the three valves, valve plug lift 2.4 mm, pressure 0.6 MPa.

Figure 12. Comparison of numerical simulations results with measurements for three valves and pressure 0.6 MPa.
Table 1 presents the results of $k_v$ coefficient calculated from experimental data and from CFD modelling for situation of full opening valves flow. In Table 1 is presented discrepancy between test results and CFD results.

| p, MPa | $k_v$, m$^3$/h | discrepancy, % |
|--------|----------------|---------------|
|        | test | CFD |               |
|        |      |     |               |
| one valve | 0.4  | 3.231 | 2.935 | 9.1 |
|         | 0.5  | 3.197 | 2.801 | 12.4 |
|         | 0.6  | 3.357 | 2.759 | 17.8 |
| three valves | 0.4  | 7.089 | 8.857 | 19.9 |
|           | 0.5  | 8.136 | 8.678 | 6.2 |
|           | 0.6  | 6.925 | 8.748 | 20.8 |

While analyzing the values presented in Table 1 one should notice that discrepancy between the two research methods amounts to 20.8% for pressure 0.6 MPa and three full opened valves. The test values for pressures 0.4, 0.5 and 0.6 MPa of calculated $k_v$ and from computed with CFD usage are almost the same for single valve. One can find bigger differences of $k_v$ for three valves. It should be noticed (Fig. 12) that all result points for numerical simulations are placed above the curve defined by experiment.

It should be noticed that the conducted numerical simulations are close enough to the given real results accompanying the water flow through the rail and the valves. It allows to implement CFD method in a process of the valve design optimization.

4. Conclusions

Obtained experimental results related to the numerical simulations allowed to present the following conclusions:

- CFD simulations and laboratory tests can held to understand the physical phenomena of water flow through the rail with parallel mounted valves.
- For given control valve and rail geometry, used methods of flow simulations can be successfully applied to determine the valve flow coefficient $k_v$.
- Discrepancy between the CFD simulations and the experimental results for single valve are smaller for single valve than for three parallel mounted valves. It is caused by the changes of the real valve chamber limited by the seat ring and the valve head surface. The CFD model does not take into account the differences of dimensional values of valve heads and valve seats.
- Tracks of water particles behind the valves seat informs about the dead zones of flow. Water silt in a rail and in the valves perpendicular flow direction change has main influence on the coefficient $k_v$. It could be treated as elbows with additional geometry change.
- The swirl occurring behind the valve is inadvisable because it could generate noise, thus only properly adjusted valve gives possibility of quiet operation.
- Correct regulation settings allow to achieve comfort in the room for the required flow of the heat streams can be gained and thus saving energy.

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