MATLAB AS A PROTOTYPING TOOL FOR HYDRONIC NETWORKS BALANCING

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Abstract

The objective of this note is to describe the prototyping stage of development of a system that is used for balancing the complex hydronic networks, particularly complex heating systems. Matlab is an ideal tool to test the proposed algorithms for balancing as it contains a set of tools allowing communication with external devices.

1 Introduction

The hydronic networks are used to distribute different sorts of fluids. The typical objective of a hydronic network is to delivery a given amount of the fluid into the certain region. Therefore, it is necessarily to have a mechanism how to control the network, particularly how to control the amount of the delivered fluid. An example of such system is the central heating system for a building or for several buildings. The objective of the central heating system is to delivery required amount of heat under all considerable weather conditions to all regions. The hydronic heating systems are equipped with balancing valves that are used to control the flow in the network. The networks may be control by many approaches.

To achieve reliable operation of a hydronic heating network containing a pump, several main loops, raisers and terminals, it is necessarily to perform so called static balancing of the network at the beginning of the network lifetime, see [1], [2], [3], [4]. Many hydronic heating networks are balanced, or better say unbalanced, manually by "hand" without using systematic approaches. Performances of unbalanced networks are usually poor. It means that the flows in individual regions are different than their designed values. The main objective is to achieve desired flows in all regions which can be done by setting the balancing valves to appropriate positions. Usually, there is more solutions (valve settings) how to get the desired flows. From the mathematical point of view, the solution to the problem is not unique and therefore, using these degrees of freedom, the network may be optimized. The criterion for optimization may be formulated in different fashions.

Before implementing any algorithm for static balancing it is necessarily to do the development work and to do extensive testing of all proposed approaches, if possible, in the field. It would be very demanding and expensive to implement all the tested approaches as final embedded applications for target devices. For example, the optimization usually requires implementing a routine to solve a mathematical programming problem which may be a complicated and time consuming task. To avoid similar situations it is common to use a prototyping system to test and to select the best approach for final implementation. The decision to use Matlab for the prototyping has been supported by availability of all required functions for optimizations and tools for communication with external devices using standard serial line.

2 Model of Hydronic System

In this section, the hydronic heating system will be briefly analyzed from the modeling point of view and a suitable mathematical description for the multivariable auto-commissioning system will be provided. The mathematical model of the system can be used to simulate the steady-state behavior, to estimate the parameters or to calculate settings of balancing valves. In the following sections, the basic components of the system will be analyzed, i.e. pipe segments, valves and pumps. After that, the mathematical description of basic hydronic circuit will be discussed. Note that the thermodynamic behavior of the system will not be considered in this model.

2.1 Pipe Segment

A pipe segment is a core element of each hydronic system. The most important relation that we are interested in is between liquid flow rate and friction pressure loss in a pipe. Equation describing this relation is known as Darcy-Weisbach equation (DW equation) that can be derived by dimensional analysis. The DW equation is given by

$$\Delta p = f \frac{L}{D} \frac{\rho v^2}{2} \tag{1}$$

where Δp [Pa] is pressure drop due to friction, f [-] is the coefficient of flow regime (laminar or turbulent) which is equivalent to the Darcy friction factor, L [m] is the pipe length, D [m] is the pipe inner diameter, ρ [kg/m3] is liquid density and v [m/s] is the velocity of the liquid flow.

The task of determining the friction factor f is not easy in general because it is influenced by many factors. A classical representation of the liquid behavior is the Moody diagram. The friction factor for individual flow regimes can be approximated by relatively simple equations based on the Reynolds number

$$\mathrm{Re} = \frac{vD\rho}{\mu} \tag{2}$$

where μ [kg/(m-s)] is liquid dynamic viscosity. The classification based on the Reynolds number is the following

- Laminar flow – Reynolds number (Re) less than 2000

$$f = \frac{64}{\mathrm{Re}} \tag{3}$$

- Critical zone ($2000 < \mathrm{Re} \leq 4000$) and turbulent regime ($\mathrm{Re} > 4000$), Colebrook equation

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon / D}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \tag{4}$$

where ε [m] is absolute pipe roughness, D [m] is inside diameter.

To summarize this section, we will transform equation (1) to the form

$$\Delta p = f \frac{1}{2} \frac{L}{D} \frac{1}{\rho A^2} Q^2 = K \cdot Q^2 \tag{5}$$

where A [m2] is the cross-section area of the pipe segment, Q [kg/s] is liquid mass flow rate. The pipe segment hydraulic resistance is represented by K which can be regarded as a constant under certain assumptions (constant friction factor and liquid mass density). The approximation by constant K is valid only for small changes of flow rates where the Reynolds number is close to a constant value. Note also the analogy with electrical circuit theory.

The equation (5) holds only for the case when there is no elevation, i.e. the absolute height is the same for pipe segment inlet and outlet. If this is not true, the pressure drop equation (5) must be corrected

$$\Delta p = K \cdot Q^2 + \rho \cdot g \cdot \Delta z \tag{6}$$

where Δz [m] is the elevation and g [m/s-2] is the gravity acceleration constant. Note that a positive elevation means that the pipe segment outlet is higher that inlet.

2.2 Valve

The valves are typically characterized by its Kv value, which is defined as follows; the volume flow in cubic meters per hour of water at a temperature of between 5° and 40° Celsius with a pressure drop of 1 bar

$$Q = K_V \sqrt{\Delta p} \tag{7}$$

A similar definition is given for the imperial units where the characteristic number is Cv. The other important valve parameter is a valve characteristic. There are three commonly used characteristic groups – linear, quick opening and equal percentage. The characteristics of balancing valves are typically provided by the valve manufacturer and these characteristics are used to determine the flow rate from the pressure drop measurement. Generally, the relation between the pressure drop across the valve and flow rate is given by

$$Q = f\left(\Delta p, V\right) \tag{8}$$

where the scalar function $f(.)$ is a valve characteristic, Q [m3/h] is the flow rate, Δp [kPa] is the pressure drop and V [%] is the valve opening. In this project, we suppose that the characteristics of all balancing valves are known.

2.3 Pump

The pump is described by a characteristic. The characteristic is typically a function of two variables for a constant-speed pumps or three variables for variable-speed pumps. The general relation is given by

$$\Delta p = f\left(Q, \omega\right) \tag{9}$$

where Δp [kPa] is the pump head, Q [m3/h] is the flow rate and ω [rpm] is the pump speed. Note that this characteristic is not usually known and therefore we have to focus on both cases in this project, i.e. known and unknown pump characteristic. The variable speed pumps have the advantage that we can reduce the pumping work in the well-balanced systems by decreasing the pump speed as much as possible.

3 Configuration of the Experiment

The objective of the experiment was to control the demo hydronic system. The system contains four risers with several terminal units (radiators), variable-speed pump and several balancing valves. The scheme of the system is depicted on Figure 1.

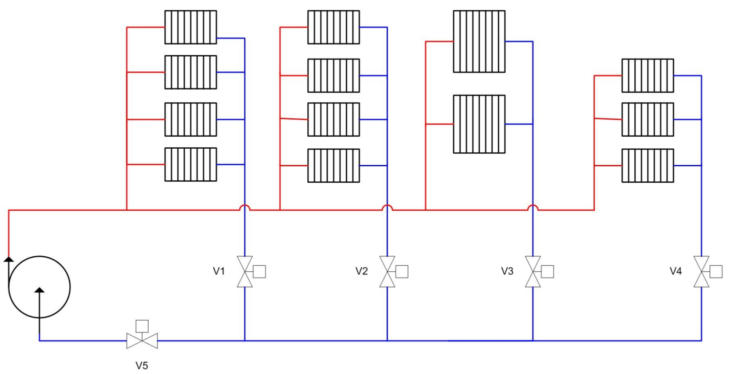
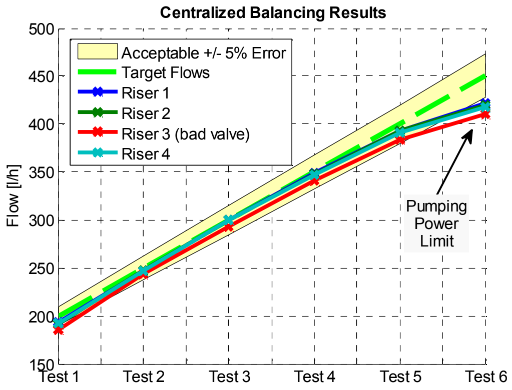


Figure 1: Configuration of the hydronic system for the experiment

The objective of the experiment is to find setting of all balancing valves based on model of the network so that the flows in all risers will be as close as possible to their designed values.



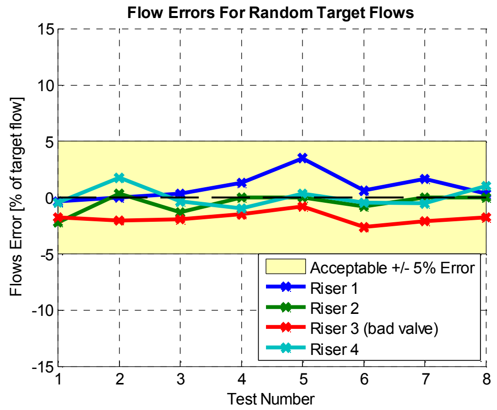


Figure 2: Achieved results – relative error of actual flows respect to the designed flows.

4 Matlab Interface

For the balancing of the system, we need to measure differential pressure across all balancing valves and flows in all risers. The output from the algorithm is the setting for all balancing valves so that the flows will be as close to desired values as possible. The summary for the interface is

- Number of differential pressure sensors: 5
- Number of actuators: 5

All the devices (i.e. differential pressure sensors and actuators) were equipped by the standard USB and were mapped as virtual COM ports. Therefore, the use of the Matlab interface for communication over the serial line was the natural choice (using Matlab serial port object). All the devices were connected with the computer (notebook) using standard USB hub. It was necessarily to implement the corresponding communication protocols in Matlab for the proper communication with all devices. The speed of data transfer was sufficient for our application as there was not need for properties of a real-time control system.

5 Results and Conclusions

In this section, we would like to summarize the results we achieved during the testing stage. Figure 2 shows results for different scenarios. The left-hand side graph shows relative error of achieved flows in the case when all the target flows were set to the same value. The corresponding valve positions and pressure drops over the balancing valves are depicted in Figure 3. The achieved accuracy 5 percent was satisfactory for the static balancing of the network.

The proposed approach, i.e. combination of use Matlab and connection of all devices over the USB line (with devices mapped as virtual COM ports), was a valuable approach as we were able to use and test several advanced numerical algorithms without necessity to code them for example in 'C ' language which enables to save time required for the development and testing stage.

References

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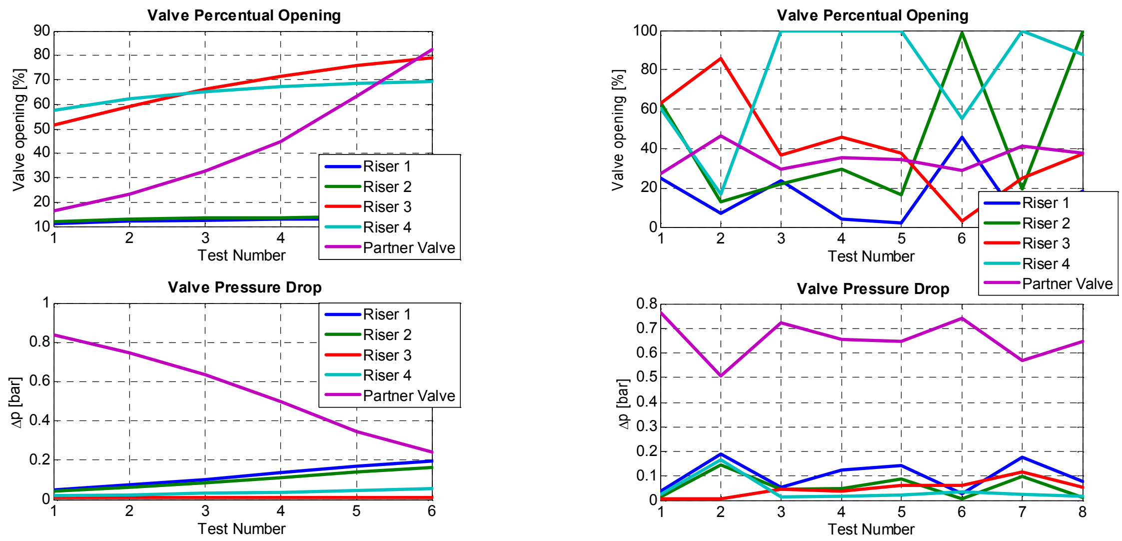

Figure 3: Achieved results – valve openings and differential pressures (for the same targets on the left picture, for random targets on the right picture)

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