Doctoral Thesis Review

Title of thesis: HYDRONIC NETWORKS: Concepts and Control

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The dissertation contains an extensive, detailed, and successful analysis of the issue of hydronic circuits distributing heat from sources to thermal zones with heat demand. The work is written in English, has a length of 186 pages, and consists of an introduction and four parts (I. Hydronic components, II. Load power control, III. Hydronic networks, IV. Building level control) and three appendices. According to the author, the main thesis objectives are:

- Study hydronic heating in buildings
- Define an enhancing concept by applying control theory to the building thermal control domain.
- Develop the necessary simulation tools for all involved control and estimation layers.
- Develop and validate the control and estimation algorithms involved in the concept.

Part I – *Hydronic components* contains a basic description of the components and relationships between hydronic network quantities. Furthermore, a new approximation method suitable for the simulation of a low-order heat exchanger is presented here.

Part II – *Load power control.* The temperature-feedback solution presented in this part enables the direct stabilization of the heat flow, relative heat flow in the case of the Power Control Valve, and absolute heat flow for the Power Control Pump. The power control pump is an original patented device with a patented heat flow control method. The invention is to estimate the mass flow from pump power readings and, consequently, control the heat flow. The results are supported by real-life measurements on the testbed. Practical contributions are within the design of the hardware and electronics of the devices and testbed. I highly appreciate the development and construction of this testbed, as the experiments carried out here made it possible to verify and possibly modify the obtained theoretical results.

Part III – *Hydronic networks*. The solution method to the network flow control by actuator opening proposed here employs unified virtual hydronic blocks and graph representation to solve the flow control problem in a few steps. This method speeds up related optimization problems. It is further proved here that although the heating power is affected by pressure coupling from other zones in two-pipe systems, the hydronic network is stable if the zones are identical and the individual zone controllers are locally stable for any inlet pressure from zero to the maximum pressure of the pressure source. This condition is certainly fulfilled if all individual zone controllers have an infinity gain margin. Note that this interesting result was achieved by using the earlier results published in the paper [106].

Part IV – *Building level control.* This part first presents building energy simulation tools; a building control model calibration is treated next as it is the most important part of optimal control, and a building control comes last.

For energy simulations in buildings, the author uses the EnergyPlus co-simulation toolbox for Matlab and one toolbox made for Matlab directly.

A building model used for control should satisfy several requirements; it has to be explicit, of reasonable simplicity, estimate important process dynamics well, and agree to measurement in steady-state. To achieve these requirements, the author uses gray-box modeling (connected sub-models with one-capacity thermodynamic circuit) and a distributed identification approach. This approach uses the dual decomposition method [208], which decomposes a large optimization problem into smaller local ones, which are then solved by local agents. The local models are found using a grey-box calibration, and coordinating agents´ mutual shared parameters, a global consistency is obtained. The presented distributed building model identification provides a previously unpublished modular calibration problem formulation by sub-model merging.

However, it should be noted at this point that the problem of distributed identifying the building model parameters formulated in this way is non-linear and non-convex, and therefore, the convergence of the presented method to the global extremum is not guaranteed.

Building control is discussed very briefly. First, the need for automatic tuning of local controllers in the case of decentralized control is discussed. Furthermore, the structure of centrally oriented control with distributed building identification and distributed MPC is presented. Using a simulation study, the control results of baseline control (PID controllers), MPC (model), and MPC (EnergyPlus) are compared without a clear result of the consumed energy in individual cases.

General comment on the thesis:

Present hydronic networks evolve only fractionally and don´t keep up with the ongoing rapid digitization of buildings. Therefore, the thesis rethinks hydronic network control from field components to the building-wide system level based on a "Hydronic 4.0 concept" to enable economic, self-commissioning, remote self-diagnosing hydronic heat delivery. The author discusses in detail the whole chain of engineering questions concerning the modeling and simulation of components of hydronic networks and their experimental identification and finally outlines the concept of distributed optimal control. Energy optimization is formulated in a plug-and-play manner and solved on edge devices via node-to-node communication, thus providing resistance to single-point failures and enhancing the maintenance and reconfiguration capabilities.

New thesis results are presented after a detailed analysis of existing solutions and have mostly already been published in high-quality journals.

The work is at an excellent level both in terms of formality and content. It has a logical structure and gradually introduces the reader to a whole range of connected problems. However, due to its broad scope, some related problems are only hinted at, and a more detailed explanation or a complete solution to the problem is lacking. For example, on p.50, it is stated without any explanation that a standard PID controller is not suitable for controlling a system with an unknown delay, and instead, a nonlinear controller [65] specifically designed for robust speed control of heat terminals is recommended.

The set objectives of the work were met.

Comments on the publication activity:

Jiří Dostal published the research results in three impacted journal papers (Mathematics, Control Engineering Practice, IEEE Transactions on Control Systems Technology) in three peer-reviewed journal papers (Heating, Ventilation, Installations, The REHVA European HVAC Journal) and in six conference papers. Jiří Dostál is a co-author of eight thesis-related patents. The candidate's publication activities clearly demonstrate his ability to produce scientific research results in an international context.

Jiří Dostál is the author or co-author of eight patents related to the field of hydronic networks.

Final recommendation:

The thesis meets the requirements of independent creative scientific work and contains original and published results of the author's scientific work. **I do recommend** the thesis for presentation/defense with the aim of receiving a Ph.D. degree in the field of Control Engineering and Robotics.

Question for discussion

1) On page 50, the use of the non-linear controller described in [65] is recommended. What are its advantages over a linear controller? Has a comparative study been done on a testbed?

2) In the stability analysis on page 79, all controllers, heat exchangers, and zone models are assumed to be identical. This assumption is very limiting in the context of hydronic circuits, as the author himself states in Remark 9. In the general case, the reader is referred to work [108] without further comment. Are the results obtained on the basis of this work really applicable in the case of real hydronic circuits?

3) Gray-box model parameter estimation on page 119 leads to a non-linear, non-convex optimization problem. In the case of real data, finding the minimum of the objective function (12.15) is likely to be highly dependent on the initial guess. What experience does the author have with solving this problem on real data?

4) On page 137, the author states that he has some experience with automatic tuning of local controllers. This probably refers to the regulators listed on page 38 in Fig. 4.7. What autotuner was used?

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