

Article

Dynamic simulation of DH house stations

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Danfoss proceeds on developing simulation models of HVAC components including control equipment that the company produces for central and district heating systems. In this paper some examples are given. The example of a simulated domestic hot water service station is presented. Some of the model components included are described, and the link between mathematical model and simulation model is shown. Two simulation results are included representing different component specifications (thermal time constant for a temperature sensor). Furthermore, an example of hardware in the loop simulation is presented. In this case a domestic heating system is built up in the laboratory by hardware components connected with real time simulations. This system forms the basis for test and evaluation of new control strategies.

The Software used for modelling and simulations

*Simulink*¹ is a software package for modelling, simulating and analysing dynamic systems. For modelling *Simulink* provides a graphical user interface for building models as block diagrams using click-and-drag mouse operations. This is an improvement in user-friendliness compared to former versions of simulation packages requiring formulated differential equations and difference equations in a language or program.

Simulink includes a comprehensive block library including linear and non-linear components. Furthermore it is possible to create custom blocks. A *Simulink* block diagram is a pictorial model of a dynamic system. It consists of a set of symbols called blocks interconnected by lines.

Each block represents an elementary sub system that produces an output based on the inputs, states and time. The lines represent connections of block inputs to block outputs.

A block comprises of one or more of the following: a set of inputs, a set of states, and a set of outputs, see fig. 1.

When a model contains a number of built-up blocks it can be grouped and "hidden" behind a new block with a suitable number of inputs and outputs. In this way models containing different components or subsystems

can be built up one by one. These component models, e.g. a temperature sensor can be connected to form the desired system and is represented in a block diagram representing the main components connected by a number of lines.

Menus are accessible for each icon and facilitate the selection of different parameters, e.g. dimensions. It is very easy to reorganise and adjust the model, such as adding or replacement of individual parts of the system. Displays and scopes may be added to watch the simulation during execution. (1).

Component model examples

Example of a temperature sensor model:

The temperature sensor is often described by a first order differential equation (2). Assuming the sensor is represented by a finite mass with uniform temperature distribution during the transient process, the heat flux to this mass may be described by: (see abbreviation table).

$$q_{sensor} = (T_{ambient} - T_{sensor})hA_s \quad (1)$$

The change of sensor temperature is dependent on the heat flux described by:

$$q_{sensor} = cV\rho \frac{dT_{sensor}}{dt} \quad (2)$$

Combining equation (1) and (2) yields

$$(T_{ambient} - T_{sensor}) \frac{hA_s}{cV\rho} = \frac{dT_{sensor}}{dt} \quad (3)$$

where the thermal time constant τ [sec] is expressed by:

$$\tau = \frac{cV\rho}{hA_s} \quad (4)$$

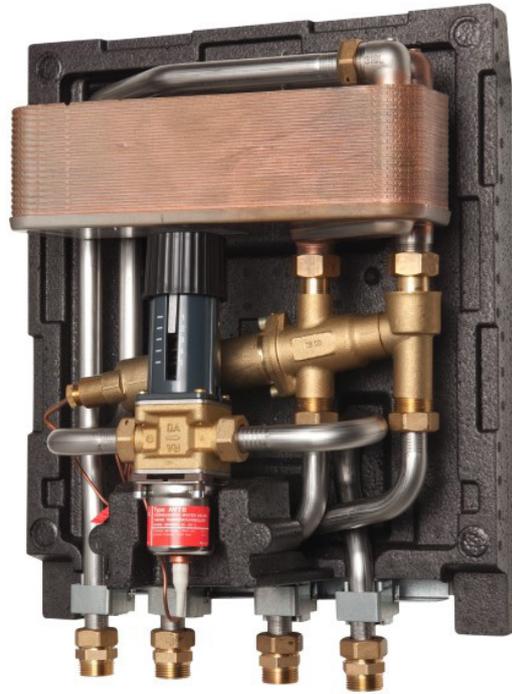
The step input for the system, $T_{ambient}$ is stepping from 20 to 60 at simulation time = 5 sec. The system output is shown in figure 3. This simple example shows the link between the mathematical equations and the *Simulink* model.

Example of a valve model:

This model example describes the static relation between the position of the spindle, differential pressure across the valve and the flow rate through the valve. The k_v value as a function of the spindle position is included in a lookup table. The lookup table includes the valve characteristic, performing linear interpolation between the measured data points. The flow rate through the valve follows the well known relation:

$$Q|Q| = k_v^2 \Delta p \quad (5)$$

The *Simulink* model for the Danfoss VS2 motorised valve can be modelled as in figure 4.



The plate heat exchanger model:

The modelling of heat exchangers is typically based on dividing the heat exchanger into a number of elements, and set up the differential equations describing the temperature in each element (lumped model). The method has proven quite successful in

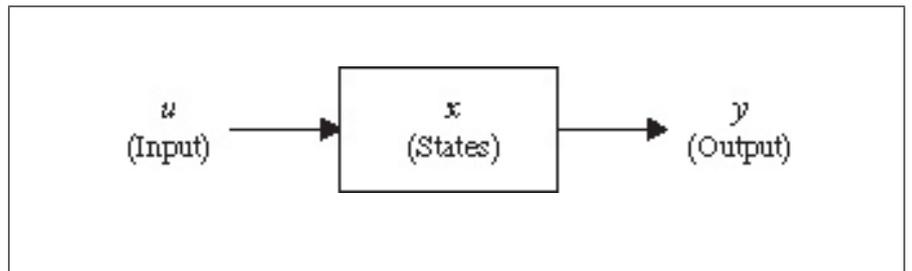


FIGURE 1: Graphical Simulink presentation of a dynamic block



compiling a good description of the dynamics of the heat exchanger. The model is described by geometrical data like number of plates, distance between plates, plate size, plate weight, number of passes etc. However, the model still requires more than geometrical data, since the influence of various plate forms on the heat transfer coefficient has not been explained.

In the same way, in principle, *Simulink* has also been used to set up a general model of plate heat exchangers which can be adapted to most types of exchangers. The geometrical data are keyed into a menu. The model has been verified using measured data from experiments on several types of plate heat exchangers in the range 50– 400 kW. Experience shows that the model is able to simulate all types with high accuracy, but also that it is necessary to use a scaling factor to adapt the heat coefficient to different plate forms.

System simulation

One of the areas where the simulation tool has been utilised is heat exchanger control. A common application for domestic hot water supply, as shown in figure 5, is an example of this. Each component itself may be simple to model and understand.

The interconnection of components, as shown on figure 5, makes it far more challenging to see the connections between output, input, and component parameters. The simulation system gives a tool for a better understanding of these.

The related *Simulink* model can be modelled as shown in figure 6. Based on the models as shown in figure 6 different combinations of differential pressure, temperatures and loads, and different combinations of control parameters, e.g. sensor time constant, sensor placing, control algorithm, actuator speed, valve characteristics, valve control ratio, etc. are investigated.

In the development of products for heat exchanger control, simulation models have thus been used to analyse which product design can be expected to give the best results when considering a broad spectrum of operating conditions. Prototypes

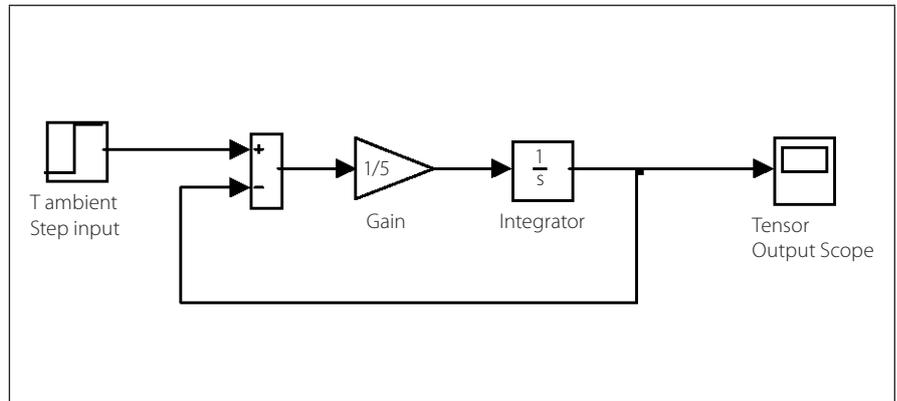


FIGURE 2: Simulink model of first order temperature sensor = 5 sec.

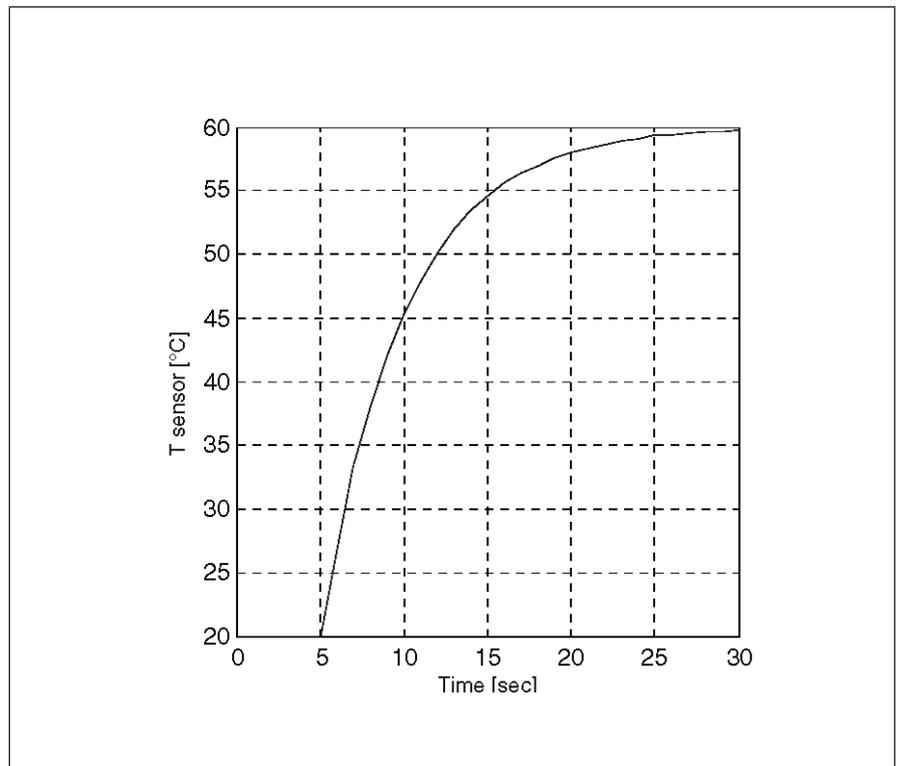


FIGURE 3: Output from the temperature sensor model

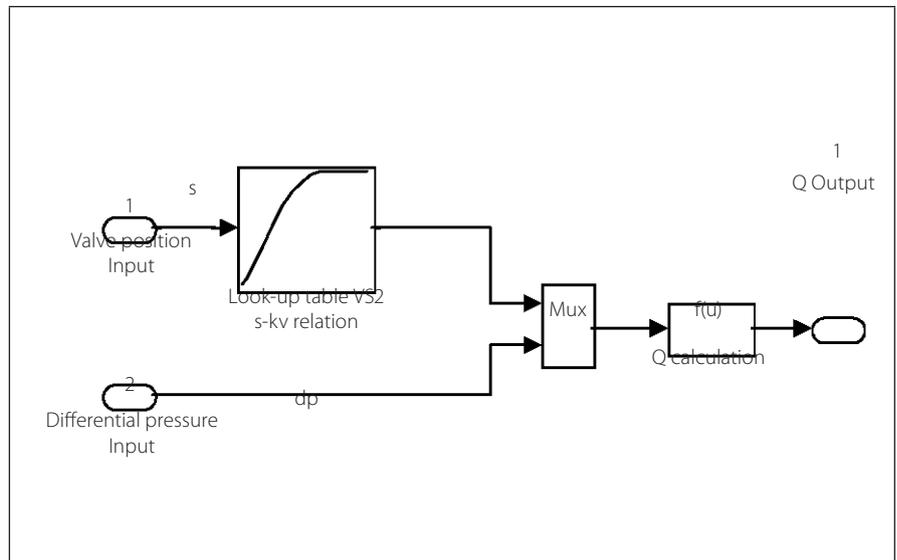


FIGURE 4: Simple static Simulink model of the Danfoss linear VS2 motorised valve

and results that have been verified by laboratory experiments do confirm that the simulation results are reliable.

As an example figures 7 and 8 show the output from a simulation based on the system shown in figure 5/6. In this case the subject was to investigate the influence of different time constants for the temperature sensor.

System specifications:

- Dimensioning of heat exchanger 65/30 – 55/10 °C.
- Actuator speed: 7 sec/mm.
- Control valve: linear valve with $K_{vs} = 1.0$ and stroke = 4 mm.
- P across control valve = 0.7 bar constant.
- No circulation flow.
- The PI controller parameters are tuned for optimum dynamic controller performance.
- Temperature set point = 55 °C.

In general, practical tests and simulations have shown that the following factors in controlling equipment are important if the control system has to perform well:

- Low sensor time constant
- Sensor placing in the system
- Suitable combination of valve characteristic (stroke) and actuator speed and actuator resolution
- Motor valve characteristic and control ratio
- Suitable settings for electronic PI-controller

Also lifetime improvement by influences of number of actuations and direction shifts are investigated by simulations.

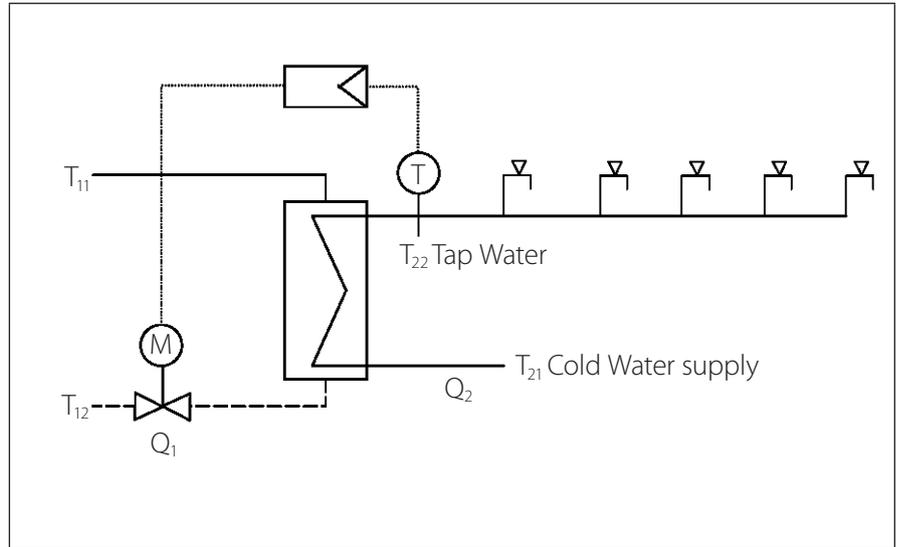


FIGURE 5: A schematic diagram of the hot service water system to be simulated

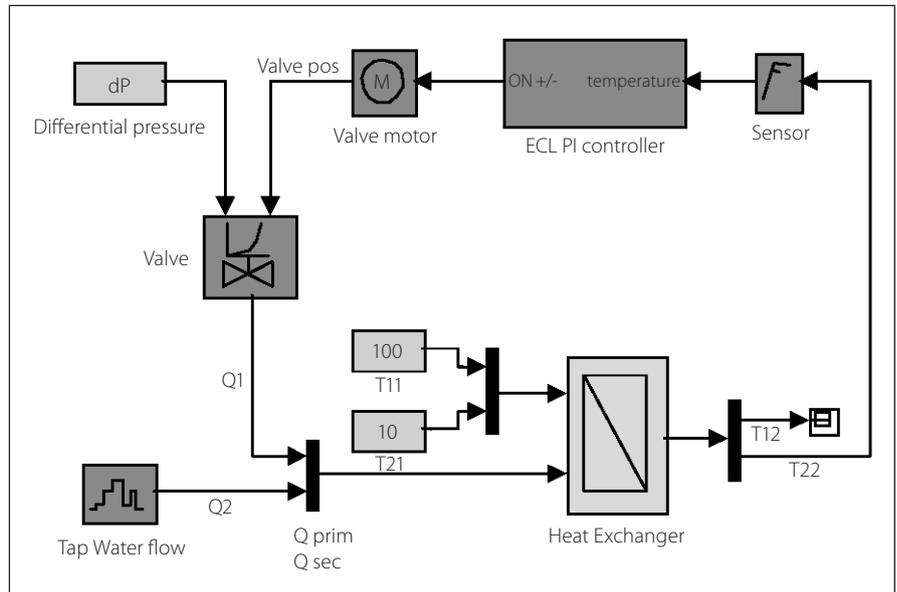


FIGURE 6: The model as presented in the Simulink graphical user interface



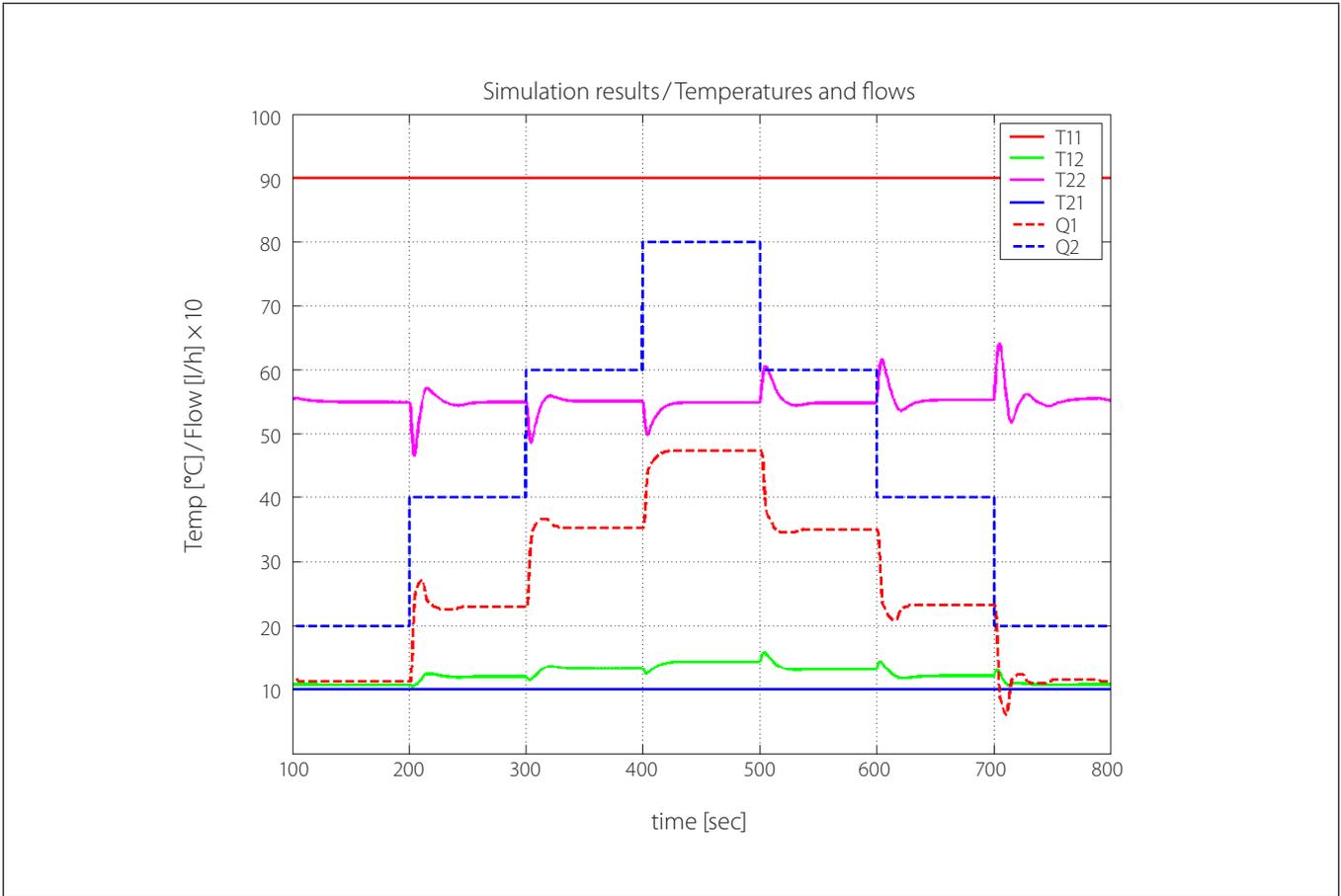


FIGURE 7: Simulation results for $\tau = 1.0$ sec.

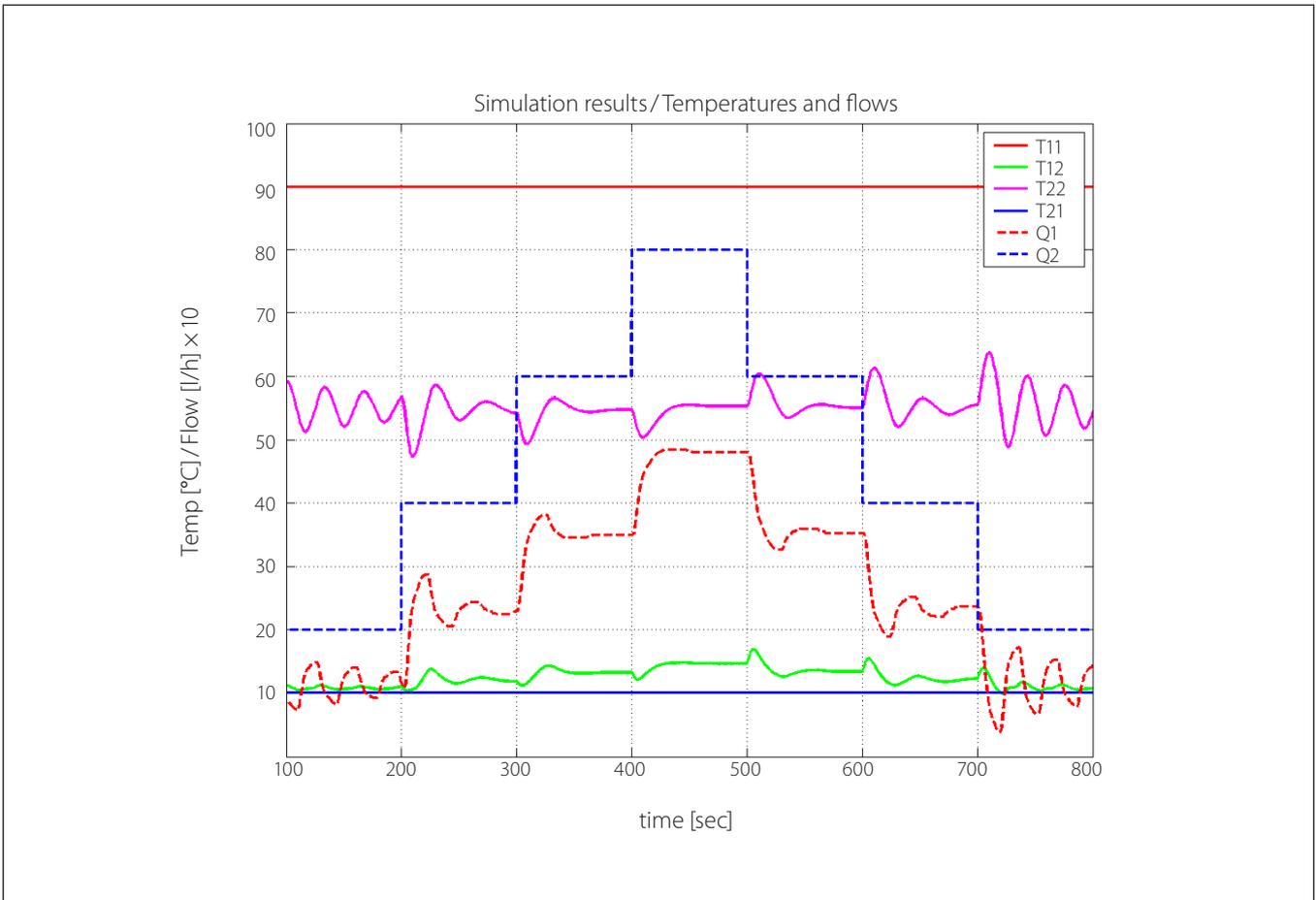


FIGURE 8: Simulation results for $\tau = 6.0$ sec.

Test and verification of controller code against simulated environments

At the time projects are running with the purpose to implement new functionality to the Danfoss ECL controller. For testing and evaluation a system as shown in figure 9 is built in the laboratory.

First step was to build up the model, as presented in figure 9, in *Simulink*. Hereby it is possible to test the controller code (new functionality) up against a dynamic model of the environment including rooms, radiators, pumps, heat exchanger etc.

The ECL controller code is programmed in the ANSI C program language. For the simulation model the feature of integrating externally compiled ANSIC program code is used. This code compatibility gives a comprehensive tool for rapid code prototyping.

Furthermore prior to code implementation in the ECL controller, it is possible to perform hardware in the loop simulations.

By this, the system, as shown in figure 9, is partly simulated and partly represented by real components. Communication between the processor and hardware is provided by an IO-board. During the simulation the system is running in real time.

In this case it is obvious that components like buildings, influence

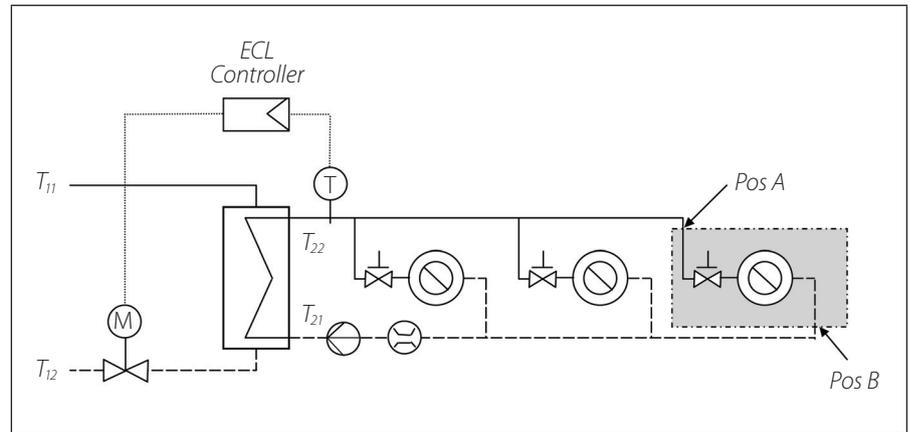


FIGURE 9: The two pipes indirectly connected in the heating system. Each radiator line is equipped with a thermostatic valve. The grey area is further detailed in figure 10

of surroundings (ambient temperature, sun radiation, secondary heat etc.) and radiators are simulated. Components like piping, heat exchanger, temperature sensor, actuators, valves and pump are included as hardware. The control loop for one of the thermostatic radiator valves in this system is shown in figure 10.

Finally, after code implementation in the ECL, the controller replaces the ANSI C program code block in the simulation model. Now the ECL controller can be tested up against the same environments as mentioned above before implementing it in field tests.

By using the real time hardware in the loop simulation tool some of the needed full-scale test activities are moved into the laboratory; especially regarding heating systems, where weather conditions have a major influence on the test results. Here it is essential to test and compare several control strategies under the same conditions. Simulations have a good feature here since it is a question of keying the desired values into a menu. The hardware components are very useful in regard to estimating measuring accuracy of flow and pressure signals provided by the hardware components.

Further examples of ECL functionality developed by support of simulations

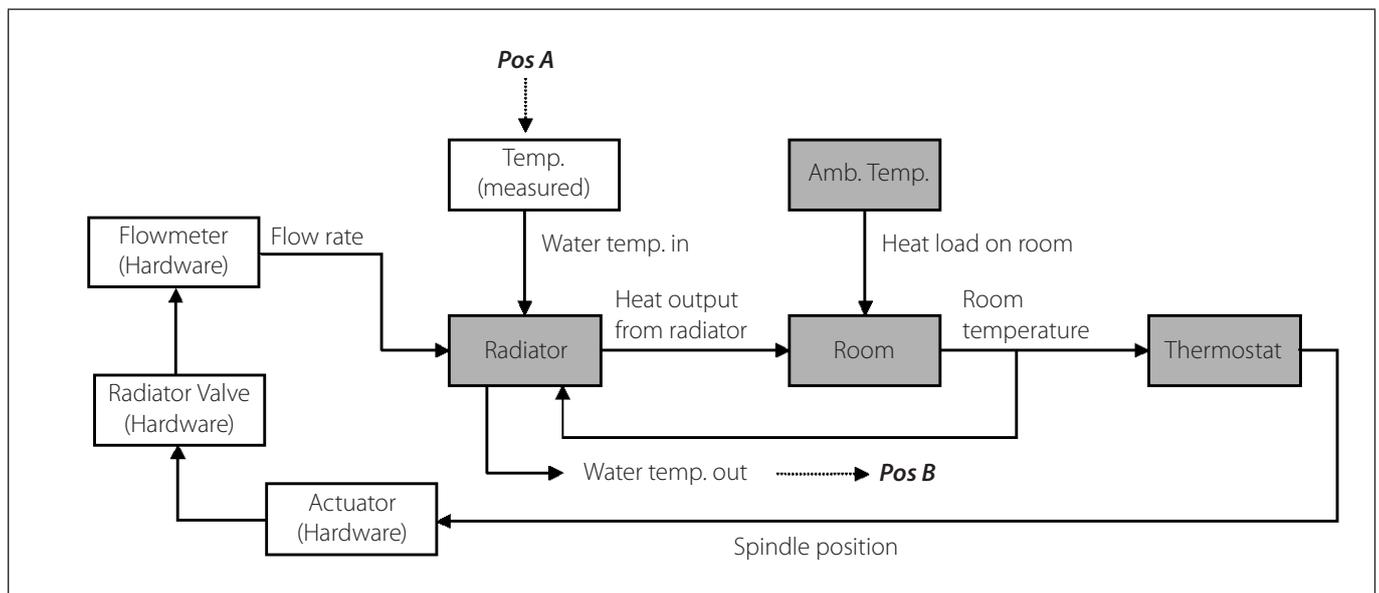


FIGURE 10: Control loop for thermostatic radiator valve. Grey boxes represents simulated components. Pos A and Pos B are related to figure 9

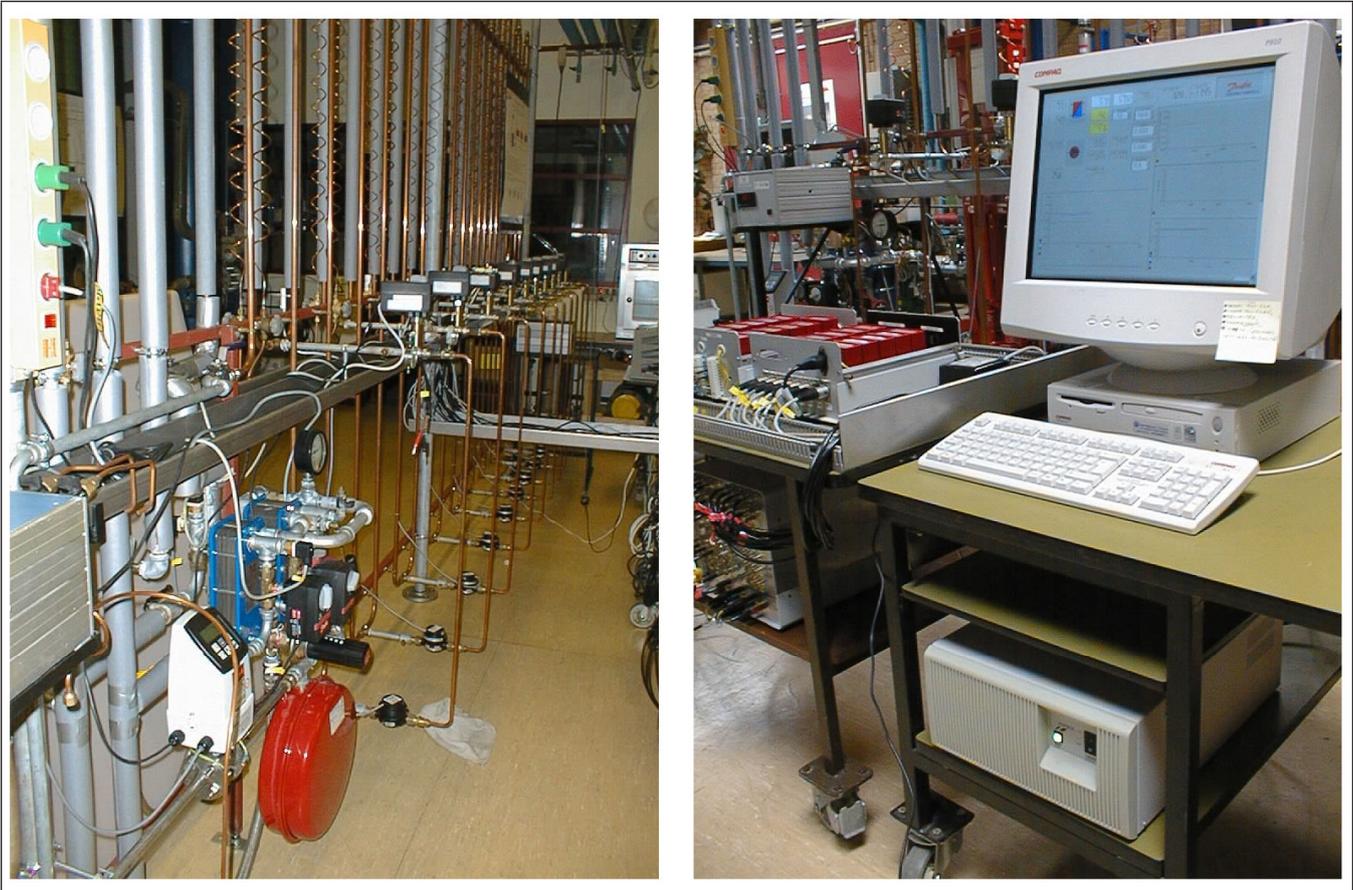


FIGURE 11: Left, picture of hardware components (pipes, heat exchangers, pump, valves, actuators, temperature sensor and flowmeters). Right, real time processor (below table) and PC for data acquisition and system control.

is the flow switch function and the Auto Tuning function both to be used in hot service water systems involving heat exchanger control.

The flow switch function detects tapping flow (on-off), in hot service water stations by means of a switch mounted into the secondary supply pipe. Hereby the primary flow is held on zero at idle, and furthermore this feed forward signal is used at tapping start and tapping end.

The Auto Tuning function automatically sets the PI controller parameters and secures a stable idle control (motor protection). By systematically reducing the proportional factor for the controller, oscillations will occur at a certain point. By increasing this proportional value by a factor, oscillations are avoided. The Integral value is calculated by means of the critical time period for the oscillations. /3/

Conclusion

Experience from the last 10 years of using dynamic simulation as a link in the development of controls for central and district heating systems has been positive. It has been shown that simulation can be used with advantage, not only to test particular design ideas, but also, just as important to gain a better overview and greater understanding of the inter-relationship between the parameters that influence how a heating or domestic hot waterservice system works.



Abbreviations

q	Heat transfer rate [W]
T_{sensor}	Temperature of sensor material, assumed to be uniform [°C]
$T_{ambient}$	Temperature of external medium passing the temperature sensor [°C]
c	Specific heat capacity [j/kg×K]
h	Heat transfer coefficient [W/°C×m ²]
ρ	Density of sensor material [kg/m ³]
V	Volume of sensor [m ³]
A_s	Submerged sensor area [m ²]
t	Time [sec]
Q_1	Flow - primary side [l/h]
Q_2	Flow - secondary side [l/h]

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