COMPARING NEW CONTROL CONCEPTS FOR HEAT PUMP HEATING SYSTEMS ON A TEST BENCH WITH THE CAPABILITY OF HOUSE AND EARTH PROBE EMULATION

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ABSTRACT

A test bench for dynamical tests on a brine-to-water heat pump is presented. The test bench at the Measurement and Control Laboratory of ETH allows the comparison of heat pump control concepts under real conditions. The thermal behaviors of a fictitious house as well as of a fictitious earth probe are emulated for a real heat pump installed at the test bench. The weather is also emulated using synthetic weather data. Since these conditions are reproducible, the controllers can be compared among each other equitably under the same conditions. A new control concept for heat pumps is also introduced, which makes use of weather forecast data to optimize the heat distribution during the day. The results of the comparison between a conventional relay-type controller and the new model predictive controller show that with the new controller concept the heating costs are reduced by 10%.

Key Words: ***heat pumps, house emulation, predictive controller, comparison of controllers***

1 INTRODUCTION

The procedure for developing new control concepts for heat pump heating systems aiming at increasing the overall efficiency of the system usually consists of three major steps. In a first step the controller algorithm is developed in the simulation environment. It is then implemented in the controller hardware, which is tested in an HIL test environment (HIL: hardware in the loop). The task of the final step is to show that the new control concept truly is an improvement from the conventional control concept when it is applied in the real environment. The main disadvantage of the first two steps is the fact that the heat pump is only simulated. The final step involves a real heat pump, but the main problem of this step is the fact that two control concepts can only be investigated sequentially. Since the conditions are different, the comparison generally fails.

For the purpose of comparing different controllers sequentially at any period of time (not only during the heating period) and under identical conditions, a test bench for dynamical tests on a brine-to-water heat pump has been built at the Measurement and Control Laboratory. On this test bench it is possible to emulate dynamically, for a real heat pump, the thermal behavior of a house as well as the thermal behavior of an earth probe. Models of the thermal behavior of the house and of the earth probe are thus simulated in real-time. As a result the reference temperatures for the inlet of the heat pump are calculated on the basis of the measured outlet temperatures of the heat pump and of selected weather data such as outdoor temperature and solar radiation. A control system ensures that these set-points are tracked by the corresponding physical quantities at the test bench. Since these conditions are reproducible, the controllers can be compared among each other equitably under the same conditions.

The paper also includes the description of a new control concept developed within the research project "Pulse-width modulation for small-sized heat pump heating systems" under a grant by the Swiss Federal Office of Energy. This concept, called model-predictive controller with pulse-width modulation (MPC-PWM), quantifies optimal heating energy portions to be delivered into the house that are optimally distributed throughout the day with respect to the weather forecast, the thermal behavior of the house, the most efficient operation of the heat pump, low-tariff periods, and power cut-off periods, while still guaranteeing the desired indoor temperature and minimizing the costs for the electrical energy consumed.

The MPC-PWM controller approach was investigated on the Laboratory's test bench and was compared under the same conditions to the conventionally available relay-type controller approach with respect to comfort, energy efficiency, and costs. The experimental results from the test bench clearly show that this new approach reduces the electrical energy costs by 10% without penalizing the comfort aspect.

The paper is organized as follows. In Section 2 the construction of the test bench is explained. Particularly the interface between simulation models and heat pump is illustrated. Section 3 describes the new controller concept for heat pump heating systems developed by the Swiss Federal Institute of Technology (ETH), while Section 4 shows the results of a comparison between the new control concept and a conventional relay-type controller.

2 HOUSE AND EARTH PROBE EMULATION

As shown in Fig. 1, the test bench can be subdivided in three parts. The first part (the real test objects, on the right side in Fig. 1) includes the brine-water test heat pump (SATAG, model BW108.1) with the controller under test. The controller algorithm can be implemented in the controller box (a commercial controller integrated in the heat pump) or in an external device. The second part (simulations, on the left side in Fig. 1) includes the real-time software with the simulation models generating the set-points for the heat pump inlet and the synthetic weather data. The third part is the interface between the heat pump and the models. This interface is a controlled hardware installation, which supplies the test heat pump with brine and heat-circuit water.

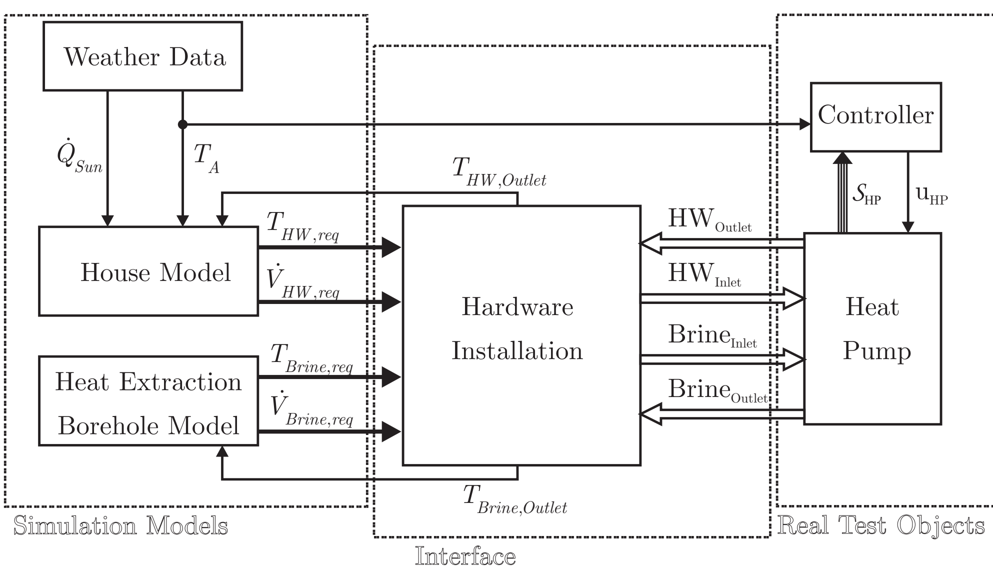

Fig. 1. Schematic representation of the test bench.

The controller box in the test heat pump has to carry out two tasks: the surveillance of the heat pump measuring the temperatures and pressures (S_{HP}) and the control of the switch u_{HP} of the heat pump. The monitoring program is provided by the manufacturer of the heat pump and prevents any damage caused, for instance, by errors in the controller algorithm.

The set-points for the heat-circuit water and brine at the inlet of the heat pump (the temperatures $T_{HW,req}$, $T_{Brine,req}$ and the flow rates $\dot{V}_{HW,req}$, $\dot{V}_{Brine,req}$) are determined by the simulation models of the house and the heat extraction borehole. A third-order model (Shafai et al. 2002) and two house models introduced in earlier projects (STASCH1 and STASCH2, (Afiej 2002)) have already been tested successfully on the test bench. The heat extraction borehole model corresponds to the model presented in (Huber and Schuler 1997). All these simulation models are implemented in Matlab/Simulink (the STASCH modules used here have been realized with the CARNOT block set). The synthetic weather data for the simulation models includes the outdoor temperature T_A and solar radiation $\dot{Q}_{Sun}$. The outdoor temperature is also communicated to the heat pump controller. Other signals that are necessary for the simulation models, such as the measured outlet temperatures of the heat pump $T_{HW,Outlet}$ and $T_{Brine,Outlet}$, are provided by the hardware installation.

The hardware installation consists of the heat-circuit water side and the brine side. Each side has a hot and a cold tank. The reference temperatures of the fluid at the inlet of the heat pump are tracked by mixing the fluids from the two tanks. A set of heat exchangers permit the heat exchange between the tanks and an external circulating medium. The controller for the hardware installation ensures that the reference temperatures of the heat pump inlet are tracked and that the temperature spread between the cold and hot tanks is kept steady.

The models and the controller for the hardware installation are compiled in a stand-alone computer using the XPC real-time operating system. The communication between computer and the sensors and actors is provided by a CAN-bus.

2.1 Construction and Control of the Test Bench

The main task of the test bench is to ensure that the reference temperatures at the inlet of the heat pump given by the simulation models are tracked, independently of the state of the heat pump. The scheme of the hydraulics of the installation is shown in Fig. 2. The installation is composed of four tanks (two tanks on the heat-circuit water side and two on the brine side). The tanks slow down the dynamics of the test bench, filtering the interfering effects of the heat pump. At each side of the test bench the temperature of the hot tank is kept above the reference temperature at the inlet of the heat pump, while the temperature of the cold tank is kept below this reference temperature. The desired reference temperatures at the inlets of the heat pump are attained by mixing the fluids from the hot and from the cold tanks with controlled mixers (Mi4 for the heat-circuit water side and Mi5 for the brine side). Their fast dynamics permit a fast correction of temperature deviations at the inlet of the heat pump. The mixers Mi8 and Mi11 are used to adjust the flow rate of the brine and the heat-circuit water. The auxiliary heat pump maintains the temperature spread between hot and cold tank whenever the test heat pump is switched off. Four heat exchangers allow the heat exchange between the tanks and an external medium. Furthermore the heat exchanger HE3 allows the heat exchange between hot brine tank and cold water tank, it is used to recycle the heat energy furnished by the test heat pump, bringing back the heat energy from the heat circuit water side to the brine side. The amount of heat exchange can be controlled independently with five mixers.

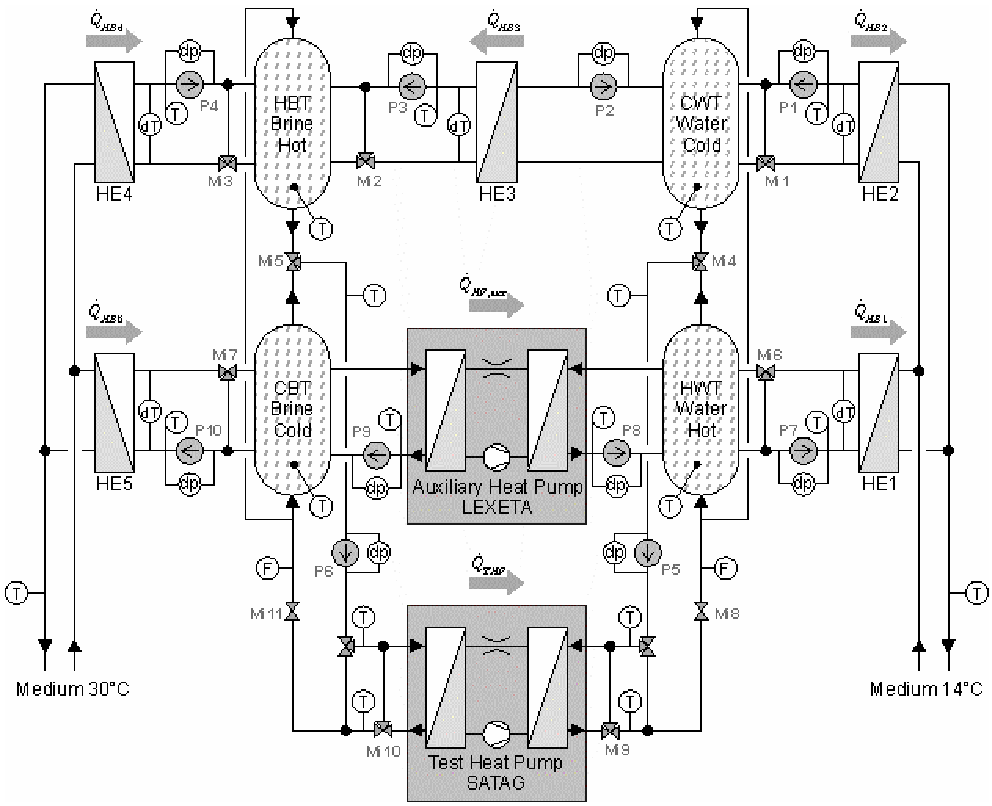

Fig. 2. Schematic diagram of the hydraulics of the test bench.

The detailed schematic diagram of the hydraulics between a heat exchanger and a tank is shown in Fig. 3. The fluid flow rate $\dot{m}$ through the heat exchanger is kept constant by a circulator pump. The mixer feeds part of the fluid v into the tank and the rest back into the heat exchanger. The controller can thus adjust the desired heat flow between the heat exchanger and the tank controlling the position of the mixer.

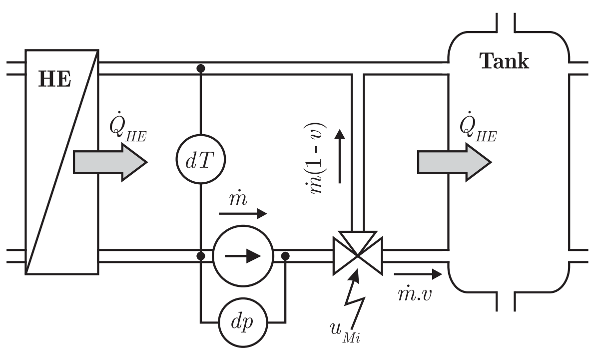

Fig. 3. Detailed illustration of the heat flow exchange between heat exchanger and tank.

The signals necessary to control the test bench are measured by sensors for the temperature (T), the temperature difference (dT), the pressure difference (dp), and the flow rate (F). The test bench controller consists of two independent parts (Fig. 4): The first part is the heat pump inlet controller that corrects the temperature errors at the inlet of the heat pump; the second part is the tank controller, which tracks the reference temperatures for the tanks.

The controller for the heat pump inlet temperature is a simple relay-type controller (upper side of Fig. 4, Heat Pump Inlet Controller): The input signals for the mixers Mi4 and Mi5 are calculated by means of the difference between the measured ($T_{HP,Inlet}$) and the reference ($T_{Brine,ref}$, $T_{HW,ref}$) temperatures of the brine and heat-circuit water at the inlet of the heat pump.

The controller for the tanks is conceived in two levels (lower side of Fig. 4, Tank Controller); the principal level controls the tank temperature by calculating the required heat energy for each tank. The subordinate controller is responsible for the tracking of these reference heat flows. Due to the complexity and the nonlinearities in the overall energy balance of the installation, each tank is considered separately and controlled independently. For each tank the following energy balance can be applied:

$$\frac{dE_{Tank}}{dt} = \dot{Q}_{Control} + \dot{Q}_{Dist}, \qquad \text{(Eq. 1)}$$

where E_{Tank} is the energy in the tank, $\dot{Q}_{Control}$ is the heat flow through the tank that can be controlled (with the heat exchangers or the auxiliary heat pump), and $\dot{Q}_{Dist}$ is the sum of the uncontrollable heat flows given by the circulating fluid or the losses between tank and air. The reference heat flow $\dot{Q}_{Control}$ is composed of a feedforward term, which compensates the uncontrollable heat flows, and a feedback term, which controls the energy variation of the tank, thus correcting the temperature error. The estimated value of the heat flow given by the circulating water is used as feedforward term. The feedback term is a simple PI controller (Geering 2004), which tracks the reference temperature; the integrator compensates the heat losses and the approximation errors of the feedforward term. The required heat flows for the four tanks are distributed to the heat exchanger and auxiliary heat pump controllers (which represent the subordinate controller). The division of the reference heat flows is accomplished taking into account that for the upper tanks of the installation the heat flow can be controlled actively in one direction only. Contrariwise the auxiliary heat pump allows the heat flows in the lower tanks to be controlled actively in either direction.

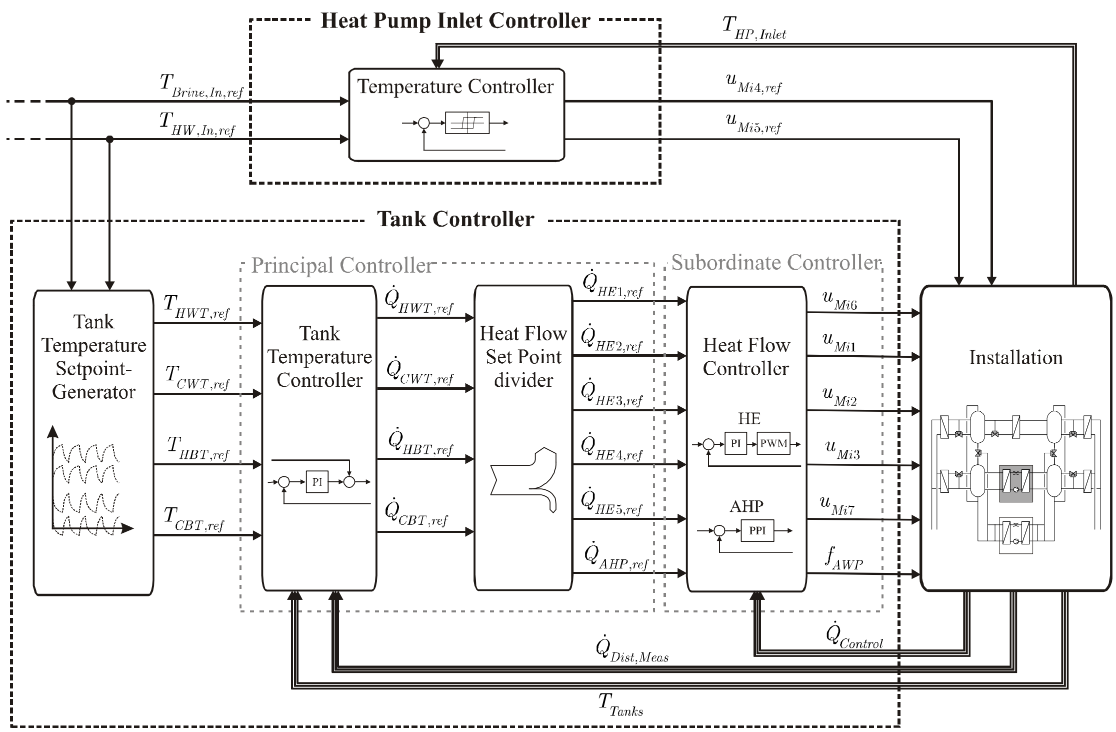

Fig. 4. Overview of the test bench controller.

The subordinate controller has to track the reference heat flows through the heat exchangers and the auxiliary heat pump. In other words, these set-points have to be transformed to open/close signals for the mixers and to compressor frequency for the auxiliary heat pump.

Apart from the position of the mixer (as shown in Fig. 3) the amount of heat flow through the heat exchanger also depends on the temperature difference of the fluids in the heat exchanger. Since this dependence is nonlinear, it cannot be taken into account by a simple linear controller with constant parameters. The nonlinearity is removed by scaling the set-point signal at the entrance of the controller, so that a linear PI controller can be used. Pulse-width modulation is used to compensate the constant open/close velocity of the mixer. The output signal is the open/close command u_{Mi} . The auxiliary heat pump is provided with a variable speed compressor, which permits the desired heat flow to be delivered. Analogously to the heat exchanger controller, the reference heat flow is first scaled, to remove the nonlinear dependence on the temperature. Then the required compressor frequency f_{AHP} is calculated by a predictive PI controller (PPI) (Geering 2004). The predictive part of the controller compensates the reaction delay of the heat pump of 3-4 seconds.

2.1.1 Tracking of the reference temperatures

The first step to verify the performance of the dynamic installation is to analyze its responses to different step excitations. In particular, the tracking of the reference temperatures of the heat pump inlet and of the tanks is relevant. Its dependence on external interferences, such as the state of the test heat pump, has to be investigated as well. The first plot in Fig. 5 shows the comparison between the nominal and the measured temperatures of the tanks, while the second and third plots show the comparison between nominal and measured temperature of the heat pump inlet on the heat-circuit water side as well as on the brine side. The results show that for small temperature set-point steps the installation response is fast. For larger steps the tracking of the inlet temperatures of the heat pump is slower because of the slow dynamics of the tanks. This problem can be simply resolved by increasing the temperature spread between cold and hot tanks. As the two first plots in Fig. 5 show, the influence of the state u_{HP} of the test heat pump (last plot) on the tank temperatures is insignificant.

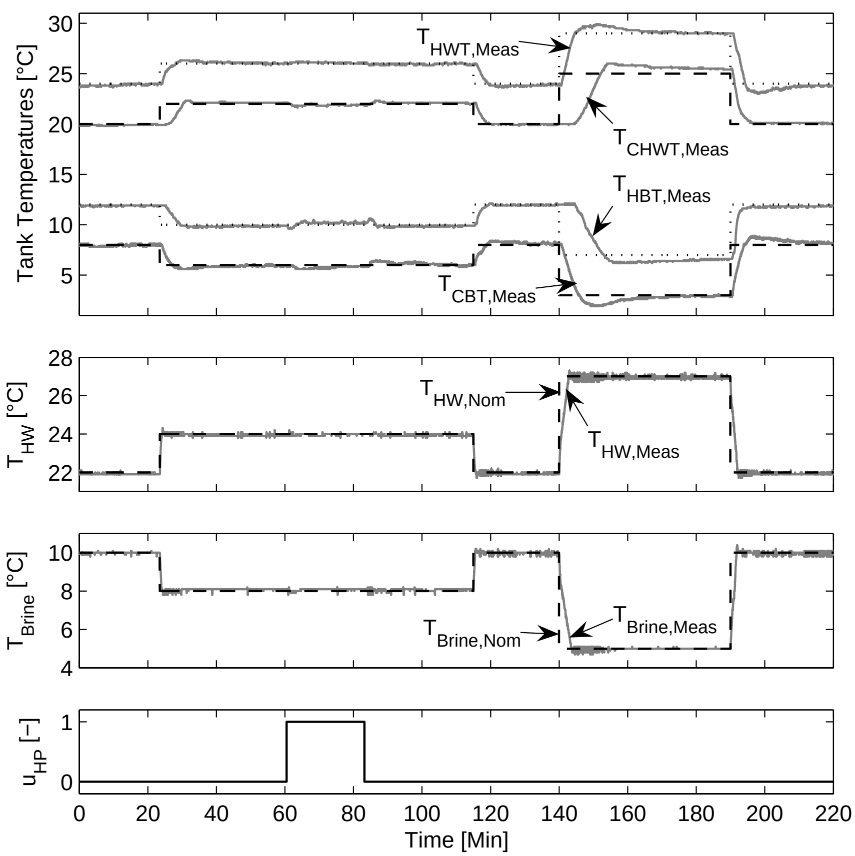

Fig. 5. Response of the test bench to excitations.

2.2 Dynamic Emulation

A correct dynamic emulation at the heat pump test bench requires a real-time communication between controller, heat pump, and simulation models. A meaningful comparison among controllers requires the data acquisition of the important signals at the test bench. This is made possible by the real-time XPC-target operating system. The models can be implemented in a Simulink file, with the Simulink blocks, or with a C/C++ function. The real-time communication with the sensors and actors of the test bench as well as the data acquisition are made possible with specific XPC-target blocks that are available in Simulink. To perform the dynamic emulation, the overall Simulink model is compiled in a stand-alone real-time device.

The simulation models of the house and the heat extraction borehole dynamics are coupled with the test heat pump. These models are provided with the measured signals such as the temperatures at the outlet and the heat flows of the heat pump. As a result, the new values for the room temperature and the set-point temperatures at the inlet of the heat pump can be simulated. The controller of the hydraulic installation (Section 2.1) ensures the tracking of these set-points.

The test heat pump operates with a single-speed compressor. The built-in controller box is provided with the internal temperature and pressure data of the heat pump as well as with the emulated weather data from the simulations. The new controller algorithm for the heat pump can be implemented in the heat pump controller box. Alternatively, the heat pump can be switched on and off by an external device or by implementing the controller algorithm directly in the model of the XPC-target computer.

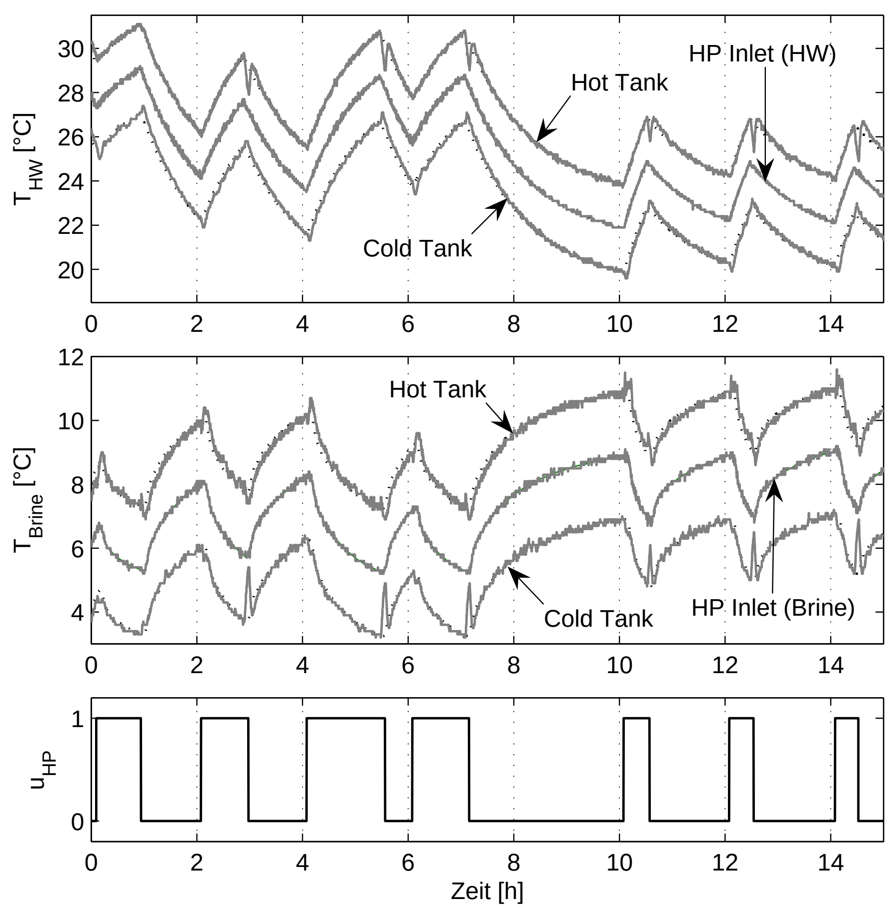

Fig. 6. Short test of a dynamic emulation.

2.2.1 Results of the dynamic emulation

The final step is to conduct a dynamic emulation to examine the coupling among simulation models and the test heat pump. A sample emulation is shown in Fig. 6, the house model used is a simple third-order model (Shafai et al. 2002) that has been validated with a real single-family house. The heat pump controller utilized is the PWM-MPC controller described in Section 3. Its parameters are adjusted to the characteristic curve of the house model. Fig. 6 shows that the tank temperatures and the heat pump inlet temperatures are tracked correctly.

3 PULSE-WIDTH MODULATION WITH A MODEL-BASED CONTROLLER

The new controller calculates the optimal heat distribution over one day, taking into account the weather forecasts, the dynamics of the house, as well as any low-tariff periods and power cut-off periods. A quadratic cost function (quality index) is defined, whose minimum represents the optimal solution:

$$J(\dot{Q}_{req}) = \sum_{k=0}^{N} \left\{ \dot{Q}_{req,k}^{T} \cdot R_k \cdot \dot{Q}_{req,k} + \left(T_{R,k} - T_{ref,k}\right)^{T} \cdot Q_k \cdot \left(T_{R,k} - T_{ref,k}\right) \right\}. \qquad \text{(Eq. 2)}$$

The quality index J is a function of the required heat energy flow $\dot{Q}_{req}$. The optimization includes the N future time steps of the period T_S. The signals $T_{R,k}$ and $T_{ref,k}$ are the predicted and reference room temperatures, respectively. The relation between $\dot{Q}_{req}$ and the room temperature T_R is given by a linear differential equation of second order:

$$\begin{bmatrix} \dot{T}_{HW,In}(t) \\ \dot{T}_R(t) \end{bmatrix} = \begin{bmatrix} \frac{k_{WR}}{c_W \cdot \rho_W \cdot V_W} & -\frac{k_{WR}}{c_W \cdot \rho_W \cdot V_W} \\ \frac{k_{WR}}{c_r \cdot \rho_r \cdot V_r} & \frac{k_{loss} - k_{WR}}{c_r \cdot \rho_r \cdot V_r} \end{bmatrix} \cdot \begin{bmatrix} T_{HW,In}(t) \\ T_R(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{c_W \cdot \rho_W \cdot V_W} & 0 \\ 0 & -\frac{k_{loss}}{c_r \cdot \rho_r \cdot V_r} \end{bmatrix} \cdot \begin{bmatrix} \dot{Q}_{HP}(t) \\ T_A(t) \end{bmatrix}$$

(Eq. 3)

The model is the same as in (Shafai et al. 2002), but here the dynamics of the floor are neglected. Since the required heat energy of the house under the same conditions (outdoor and room temperatures) is constant and cannot be optimized, the minimization of the electrical energy consumption, i.e. cost, makes more sense. A variable cost term is thus introduced and the quadratic heat energy term is changed to a quadratic electric consumption or cost term:

$$R_k = R_0 \cdot \left(\frac{Cost_k}{COP_k} \right)^2, \qquad \text{(Eq. 4)}$$

where R_0 is a nominal weighting factor, $Cost_k$ is the cost of the energy, and COP_k is the coefficient of performance of the heat pump at the time k. The coefficient of performance for the N time steps can be estimated using the characteristic curve of the heat pump. Since the COP of air-water heat pumps is directly dependent on the outdoor temperature, R_k can be evaluated on the basis of the predicted outdoor temperature. In contrast, the COP for brine-water heat pumps depends on the brine temperature, which is more difficult to predict because it depends on the state of the heat pump. The brine temperature prediction method used is the same as for the outdoor temperature prediction, i.e., the course of the brine temperature predicted for the next day is the same as that of the previous day, except that it is shifted by the difference between the actual temperature and the temperature of the day before (Shafai et al. 2002).

The parameter Q_k can be set to 1 without any loss of generality of the problem solution. The minimization problem of (Eq. 2) with the constraint in (Eq. 3) leads to an analytic recursive solution, which is reported in (Shafai et al. 2002).

The commonly used heat pumps in single-family houses are provided with a single-speed compressor that is unable to deliver a variable heat flow. Thus the heat energy has to be delivered in heat energy packets. The incentive for using pulse-width modulation in the MPC controller is the optimization of the energy ratio of the heat pump (Shafai et al. 2002). For this optimization, the required heat energy over a fixed on/off period (e.g., two hours) is calculated by integrating the required heating energy flow. The heat pump is switched on at the beginning of each period and remains on until the required heating energy has been delivered. Using a fixed on/off period for the pulse-width modulation is justifiable since the energy ratio does not vary much with respect to the outdoor temperature and the "on" cycle duration of the heat pump.

4 COMPARISON OF CONTROLLERS ON THE TEST BENCH

The test bench was used within the scope of the project "Pulse-width modulation for heat pump heating systems". The new controller algorithm using the MPC-PWM concept was compared with the conventional relay-type controller. Using the house model of third order described in (Shafai et al. 2002) and the outdoor temperature course shown in Fig. 7, the heating of the house was emulated for two weeks. The outdoor temperature during the first week of the emulation was characterized by temperature steps which allow the reaction of the controllers to be analyzed precisely. For the second week, an oscillating temperature course was selected in order to reproduce the temperature fluctuations over the course of one day. The electrical energy costs were set to 0.1 cents/kW during the day (from 7.00 to 22.00 hours) and to 0.05 cents/kW during the night. In Switzerland, the period from 11.00 to 12.00 noon is a peak period. Since the electric power providers usually cut off power to heating units during that time, the emulation includes a power cut-off period from 11.00 to 12.00. The objectives for each controller were to ensure the mean room temperature of 21°C and to place approximately 70% of the heat energy in the low-tariff interval, i.e. at night. The controllers were fed with the same information, i.e. the measured brine and heat-circuit water temperatures and the outdoor temperature. The characteristic curve of the controllers was adjusted with the aid of the known house dynamics and the results of a test week.

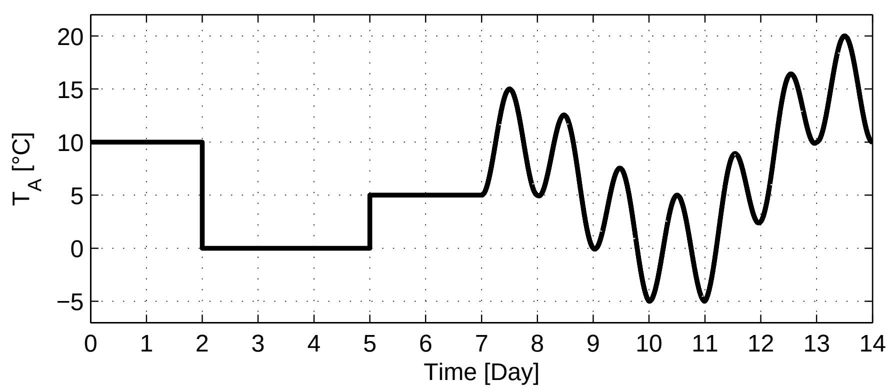

Fig. 7. Outdoor temperature course for the controller comparison.

The purpose of the comparison in the test bench is to observe which controller can extract more information from the measured signals, maximizing the room temperature comfort while optimizing the energy consumption and recognizing disturbances like solar radiation or open windows. The comparison of the controllers focused particularly on the energy costs, the energy consumption, the COP of the heat pump, as well as the mean room temperature. Obviously, since these values are correlated, they have to be analyzed together. The emulated room temperature for both controllers is shown in Fig. 8. Both were able to guarantee the mean room temperature of 21°C. The larger daily temperature fluctuations observed with the MPC-PWM controller may be attributed to the major heating activity occurring during the low-tariff period.

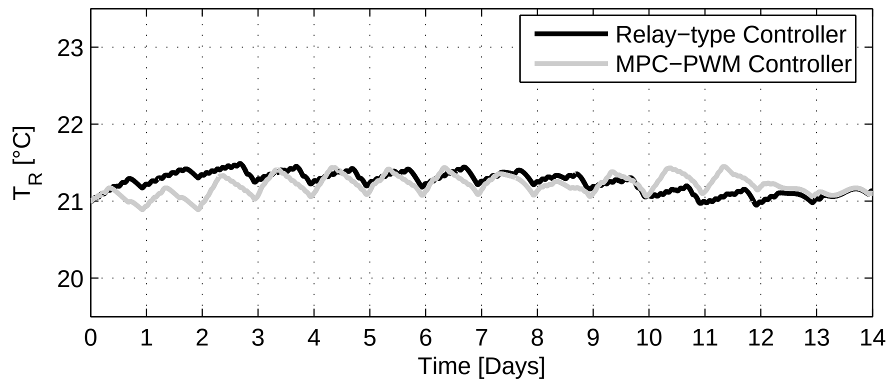

Fig. 8. Emulated room temperature course for the two controllers tested.

Table 1 shows the results of the two-week emulation. They show that the MPC-PWM controller was able to keep the same mean value and standard deviation of the room temperature as the conventional controller, while requiring nearly the same amount of electrical energy. However, the MPC-PWM controller placed considerably more heat energy in the low-tariff period.

Table 1. Comparison of the emulation results of a conventional relay-type controller and the MPC-PWM controller.

	Conventional Relay-Type	**MPC-PWM**
Mean Room Temperature [°C]:	21.24	21.20
Standard Deviation [°C]:	0.13	0.12
Total Heating Energy [kWh]:	1070	1063
Total Electrical Energy [kWh]:	207	204
Coefficient of Performance [-]:	5.17	5.21
Low-Tariff Energy Rate [%]:	57.1	74.03
Total Energy Costs [€]:	14.80	12.85

An additional advantage of using the model-based controller is the fact that the duration of the low-tariff period can be arbitrarily changed without the need to readjust the characteristic curve of the controller. The low-tariff period is not applied in many countries as yet; however, the variable cost term can be used for example to reduce the heating during the night or to assure the floor heating in the morning.

5 CONCLUSIONS

The test bench permits to make a dynamical analysis of the heat pump controller algorithms. The results of the examinations at the test bench show that the set-points given by the simulation models can be tracked. The simulation models can be implemented in a simple way in a real-time system. The new controller algorithms have been implemented and successfully tested in the controller box integrated in the heat pump and in external devices connected to the heat pump. The latter mode permits to test preliminary versions of the controller without the need for a permanent implementation in a controller box.

The results of the emulation with the new controller algorithm have shown that the heat energy can be placed in a desired time interval more easily than with conventional controllers. The optimization algorithm ensures the minimization of the costs and electrical energy.

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