CONTROL OF CONCRETE CORE CONDITIONING SYSTEMS

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ABSTRACT

A research project on the control of concrete core conditioning systems has been started in May 2004. The paper will show some of the results after one year of work: A state-of-the art analysis has been done. Several kinds of models to analyze the performance of the concrete core conditioning system and to test and evaluate control solutions were developed. A test room for model validation and tests was set up. An unknown-but-bounded approach to cope with the uncertainties in the heat gains during the design phase has been outlined. This approach has lead to a new algorithm for switching between heating, neutral and cooling. The consequences of water flow on/off control on the pump energy consumption, on the spatial distribution of the heat flow between concrete and room and on the self-regulating effect are analyzed. A heating curve algorithm for outside temperature dependant on/off control as alternative to the shift of the flow temperature in partial load operation has been developed. Performance bounds have been determined by calculating the system behavior over one year under the assumption that the controller has full information on present and future inputs.

KEYWORDS: control, concrete core conditioning, thermally activated building systems (TABS), predictive control

INTRODUCTION

A joint research project between Siemens Building Technologies, Empa (Swiss Federal Laboratories for Materials Testing and Research) and HTA Lucerne (School of Engineering + Architecture) on the control of concrete core conditioning has been started in May 2004. The project will last three and a half years inclusive an alpha test in a real building. It is financially supported by the KTI/CTI of the OPET (Swiss Federal Office for Professional Education and Technology). The project has the following goals:

- Develop control strategies for concrete core conditioning systems which are energy efficient and meet the comfort requirements.
- Develop efficient methods to choose and tune control strategies for a concrete core conditioning system of a given building; the method should also include the decision on whether additional cooling and heating facilities are necessary in the rooms. How to cope with uncertain information, e.g. in the internal and solar gains?
- Acquire a position in the controversial discussions on the control of concrete core conditioning systems

The project is organized as follows. Project lead: Jürg Tödtli. Management team: Jürg Tödtli and Viktor Dorer (originally Markus Koschenz). Project team: Markus Gwerder, Franz Renggli, Jürg Tödtli (Siemens); Michael Hediger, Werner Güntensperger (Siemens HVAC Laboratory); Viktor Dorer, Anne Haas, Beat Lehmann (Empa); Kurt Hildebrand (HTA Lucerne). Accompanying team: Kurt Hildebrand, Tobias Kalb, Markus Koschenz, Robert Meierhans, Erich Schadegg, Hans Jörg Schwarz, Esfandiar Shafai, Daniel Stadler.
In the following 6 sections it is reported on some of the findings of the project in the first year. The last section gives an outlook.

STATE OF THE ART

Within the project, different existing control strategies for concrete core conditioning systems (both strategies destined for certain buildings and general strategies) were gathered, described in a standard format, and evaluated (see e.g. [1],[2]). This state of the art analysis serves to pinpoint weaknesses and strengths and to identify possible potential improvements of new solutions. Figure 1 shows a schematic diagram of a typical concrete core conditioning system: At the bottom simplified plant hydraulics and at the top the simplified control action diagram is given. Most of the existing control solutions have the following properties:

1. A main part of the control is an outside temperature compensated flow temperature control, where the set-point of the flow temperature is shifted with varying outside temperature according to the heating curve (HC) or the cooling curve (CC). The cooling curve is typically a constant flow temperature set-point.
2. No feed-back variable form the zones (return temperature, concrete core temperature or room temperature) is used for the control. Self-regulation of the concrete core conditioning system is assumed to be sufficient.
3. The enabling and activation of the heat and cold generation (heating, cooling or neutral) is done dependant on the season and/or the outside temperature.
4. Free cooling is accounted for in a heuristic way.

Some control solutions take additional sensor information into account, e.g. the return temperature, the concrete core temperature or the room temperature. All these solutions can be interpreted as attempt to introduce an influence of the heat gains on the control action, to increase the self-regulation or to go towards closed-loop control of the room temperature.
The evaluation of the control strategies includes also criteria which are not focusing on control itself. Particularly important for a promising control solution is – besides good control performance – a simple commissioning and operability as well as a straightforward explanation.

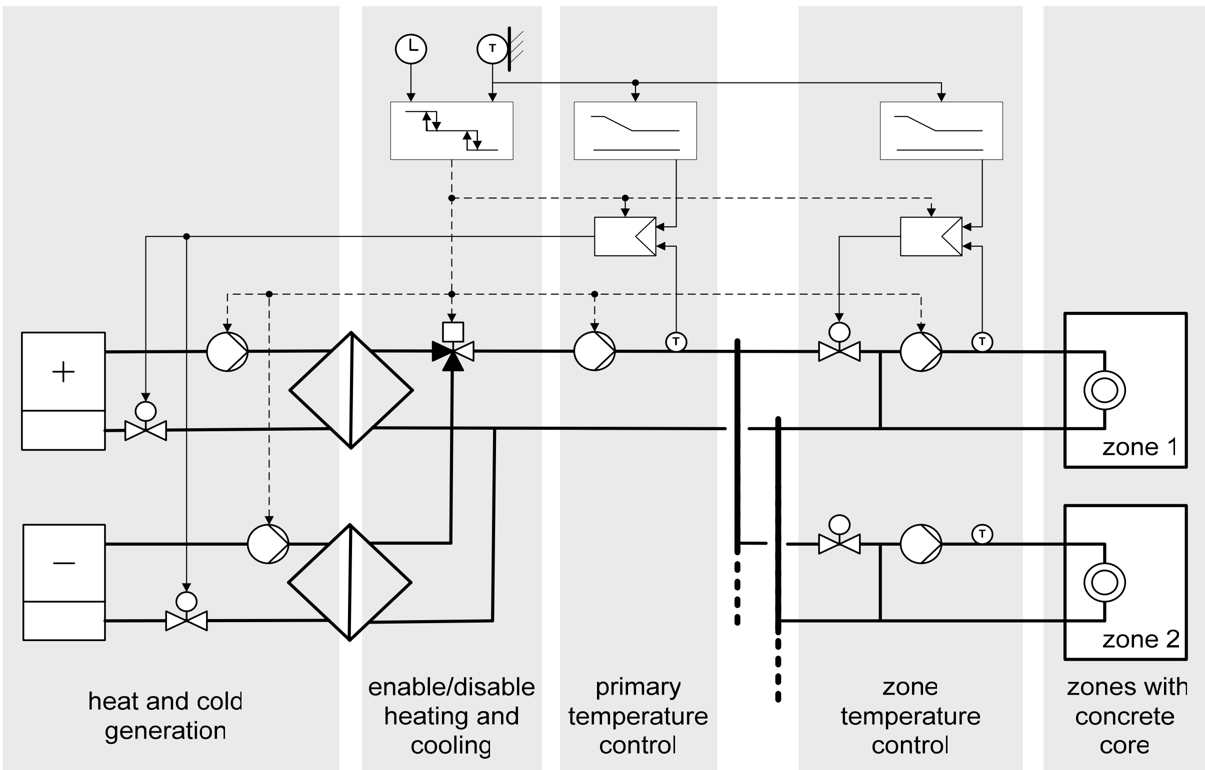

Figure 1. Schematic diagram of a concrete core conditioning system.

LABORATORY SET-UP AND MEASUREMENTS

The HVAC-Laboratory of Siemens has the possibility to test room automation control equipment on realistic and up to date test facilities. One test room is especially designed to meet the thermal behavior of offices in modern commercial buildings equipped with concrete core conditioning and different types of floors and ceilings (Figure 2). Special attention has been taken on the test room boundaries. In assumed office building with all identical offices, there is no heat transfer from one room to the next on one level. Therefore it is sufficient to just insulate these boundaries of the test room well. As there is an inevitable temperature gradient in room height there will be heat transfer form the office room to its neighbors above and below. For this reason these boundaries of the test room can be heated or cooled according to the actual surface temperatures in the test room. The thermal influences of outside temperature on the test room can be simulated by a weather zone built in front of the test room's facade. As an example, Figure 3 shows the test room temperature ϑ_r and floor and ceiling surface temperatures (ϑ_{fs} , ϑ_{cs}) on a step change of the weather zone temperature (+20°C to –20°C) and of the concrete core conditioning flow temperature (20°C to 27.4°C). After the step changes, water flow is on/off controlled with 1h on and 4h off.

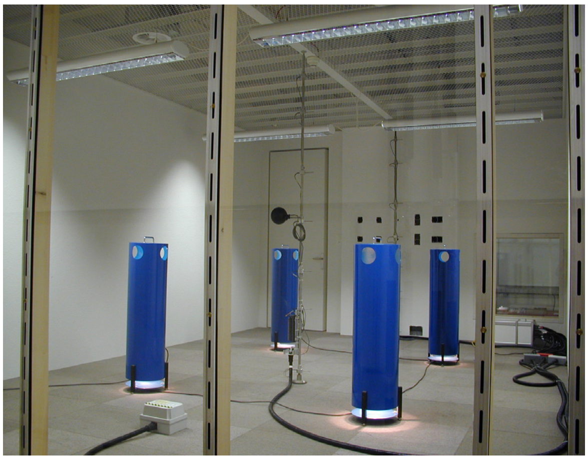

Figure 2: Laboratory test room.

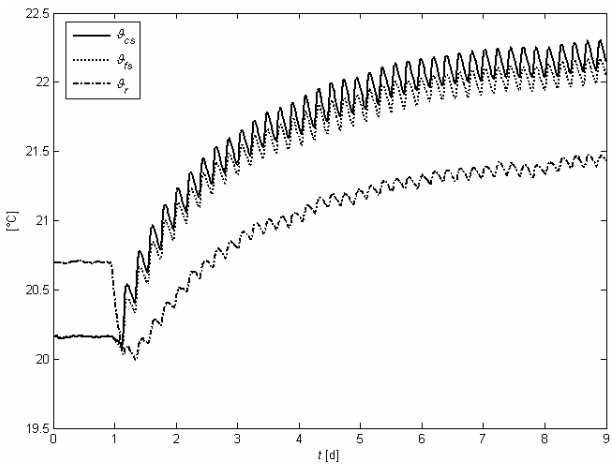

Figure 3: Example of laboratory measurements.

MODELS

Overview over models

Several kinds of models are used in the project:

- A first order differential equation model coming from [3] (M1)
- MATLAB/SIMULINK simulation and optimization models (M2)
- TRNSYS models (M3)
- A finite element method (FEM) model (M4)

(M1) is applied for calculations in water flow on/off control (see section water flow on/off control). Models (M2), (M3) are used as simulation models: Preliminary simulation studies are performed using 1-zone building models; to investigate the interaction between different zones and the influence of various orientations and building parameters also multizone building models are developed. By implementing the newly developed control strategies their performance in terms of comfort, energy consumption etc. can be compared. (M2) is also adopted for performance bound calculations (see section performance bounds for the control of concrete core conditioning). (M4) serves as validation model for water flow on/off operation.

Validation of models

Up to present, design and simulation of concrete core conditioning could be done by using the existing 1-dimensional tabs-model described in [3]. This "basic" tabs-model initially was designed for constant operation, being valid for slow temperature oscillations down to a time period of about 10 hours. In order to be able to correctly model also faster dynamic changes the basic model had to be improved which was reported by Weber et. al. [4]. This "enhanced" concrete core conditioning model was validated using harmonic temperature oscillations, proving to give good results down to time periods of half an hour.
As within intermittent operation (on-off control step function) even higher frequencies are encountered, the enhanced model was validated against calculations with the FEM Model (M4, cf. following paragraph).

FEM model of a room with concrete core conditioning system

The model (M4) has been designed to study the influence of water flow on/off control with different on and off periods on the thermal behavior of the room and the concrete slab. The model is thought to represent a room being part of a larger building.
The model consists of a concrete slab with concrete core conditioning system with air spaces of about half a typical room height above and below. Other walls (apart from the concrete slab) are not included in the model. The spaces above and below the concrete slab are connected via air spaces at two opposite sides, see Figure 4. High insulation layers at these two sides of the slab are applied to avoid heat flows through these sides to the air. The boundaries of the simulation area (the whole air space) are adiabatic, apart from two parts of the surface used to model the heat losses to ambient.

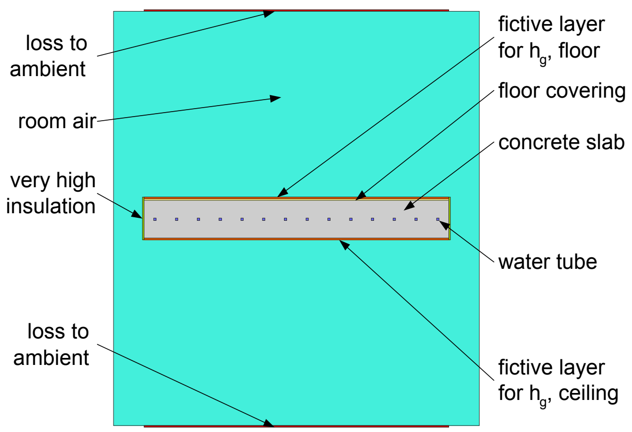

Figure 4. Simulation area in the FEM-Model; section in a plane perpendicular to concrete slab and tubes.

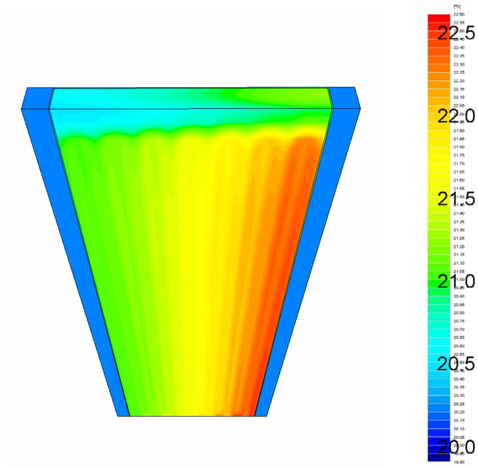

Figure 5. Temperature distribution on ceiling at the time of maximum average temperature.

The room model may be very simple, but must allow for study of dynamic behaviour of the system including room air. Therefore:

- The room air is modeled as material block with very high heat conductance (to emulate "mixing" of the room air) to allow for the room air temperature being a simulation result.
- The combined (radiative and convective) heat transfer coefficients h_g from slab to air are modeled introducing thin fictive layers with appropriate heat conductance between floor and air and ceiling and air, respectively, and with a low heat capacity (resistance only).
- The steady state heat flow per temperature difference between room air and ambient air is modeled using boundary condition ambient temperature and an appropriate heat transfer coefficient and loss area.

Different configurations concerning floor covering, position of the tube layer, and on/off periods have been studied. The simulation results show that

- the temperature levels (i.e. the temporal and spatial average) of core and surfaces are mainly determined by the type the covering and the position of the tube layer,
- the temperature distribution and variation is mainly determined by the length of a cycle, and the ratio of on/off periods. The longer the cycle and the smaller the on/off ratio, the larger are the temperature differences encountered,
- even long cycles with small on/off ratios meet all comfort requirements.

Figure 5 shows the temperature distribution on the ceiling at the time of the maximum average ceiling temperature, for the tube layer close to the ceiling and an on/off period of 1 h/4 h. Flow and return are on the far end of the slab, on the right and the left side, respectively.

AN UNKNOWN-BUT BOUNDED APPROACH TO COPE WITH UNCERTAINTIES IN THE KNOWLEDGE OF THE HEAT GAIN

An unknown-but-bounded approach to cope with the uncertainties in the (internal and solar) heat gains during the design phase has been developed. It is assumed that the designer of the control scheme knows lower and upper bounds of the heat gains $\dot{q}_{glb}, \dot{q}_{ghb}$. The difference between the lower and upper bounds is defined as the uncertainty in the knowledge of the gains. Figure 6, which illustrates the basic idea of the approach, shows that depending on the uncertainty in the heat gains there are three different cases for open-loop room temperature control, i.e. for the so called outside temperature compensated flow temperature control, where the set-point of the flow temperature is shifted with varying outside temperature according to the heating curve HC or the cooling curve CC.

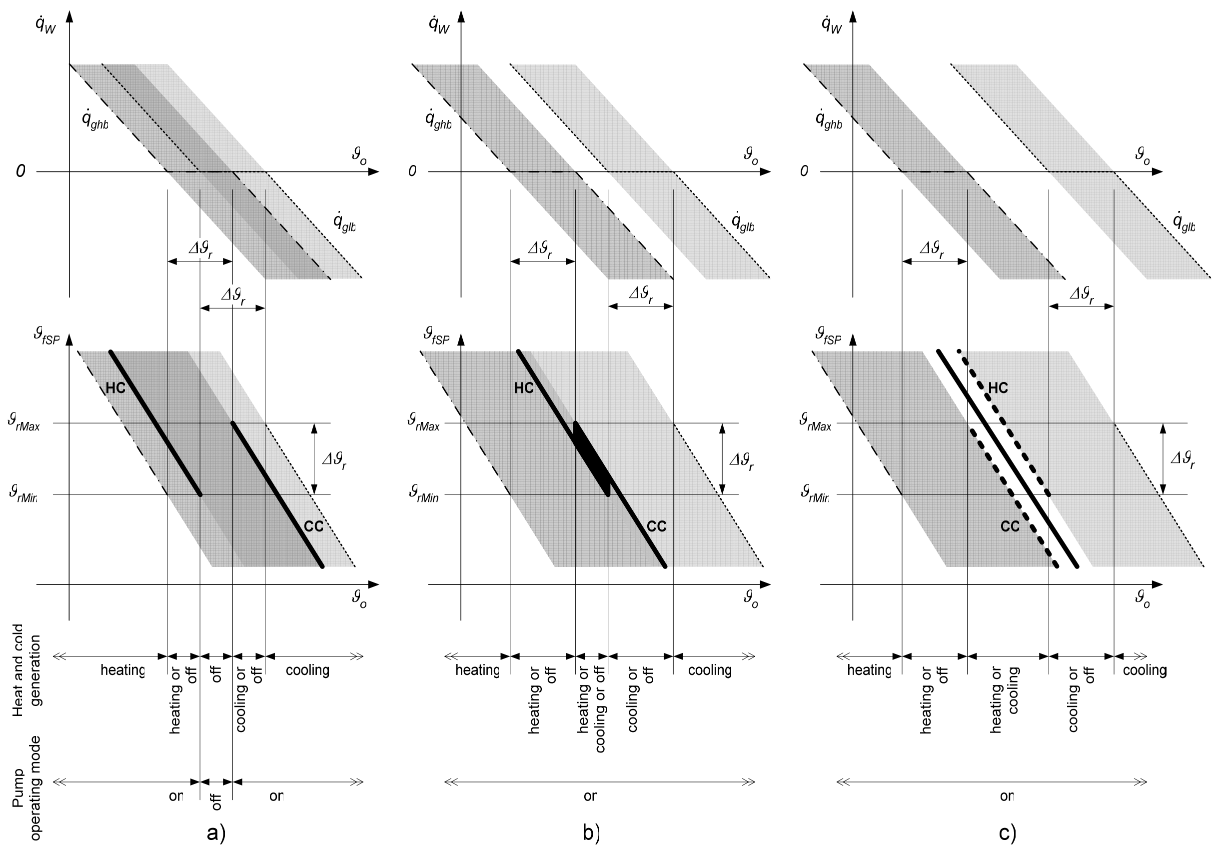

Figure 6. Different uncertainties in heat gains: a) Low, b) Medium, c) High.

If the uncertainty is low (Figure 6a), then there exists a range in the outside air temperature ϑ_o where there is definitely no heating and no cooling required. If the uncertainty is medium (Figure 6b), then there exist a range in ϑ_o where depending on the heat gains heating, cooling or no action (neutral, off) is required. It is the flow temperature controller which is able to do the correct action, knowing only the flow temperature ϑ_f and the valve position. This outside temperature range is usually quite broad. If the uncertainty is high (Figure 6c), it is not possible to maintain the room temperature ϑ_r in the comfort region (ϑ_{rMin} to ϑ_{rMax}) for all heat gains between the lower and the upper bounds with open-loop room temperature control. It is the case where the control scheme needs additional information, e.g. the return temperature, the concrete core temperature ϑ_r.
The approach can also be used to cope with room to room variations of heat gains if there is no possibility to control the rooms individually.

WATER FLOW ON/OFF CONTROL

Water flow on/off control is a possible alternative to the shift of the flow temperature setpoint in partial load operation. The consequences of water flow on/off control on the pump energy consumption, on the spatial distribution of the heat flow between concrete and room and on the self-regulating effect are analyzed. Moreover, a heating curve algorithm for outside air temperature dependant on/off control has been developed based on [5].
In Figure 7 results calculated with model (M1) for a pulse wide modulation (PWM) with period 5 hours are shown for a given zone with ϑ_{rMin} = 21 °C, ϑ_{rMax} = 26 °C. The heat gains are uncertain but bounded ($\dot{q}_{glb}$ = 5 W/m^2, $\dot{q}_{ghb}$ = 20 W/m^2).

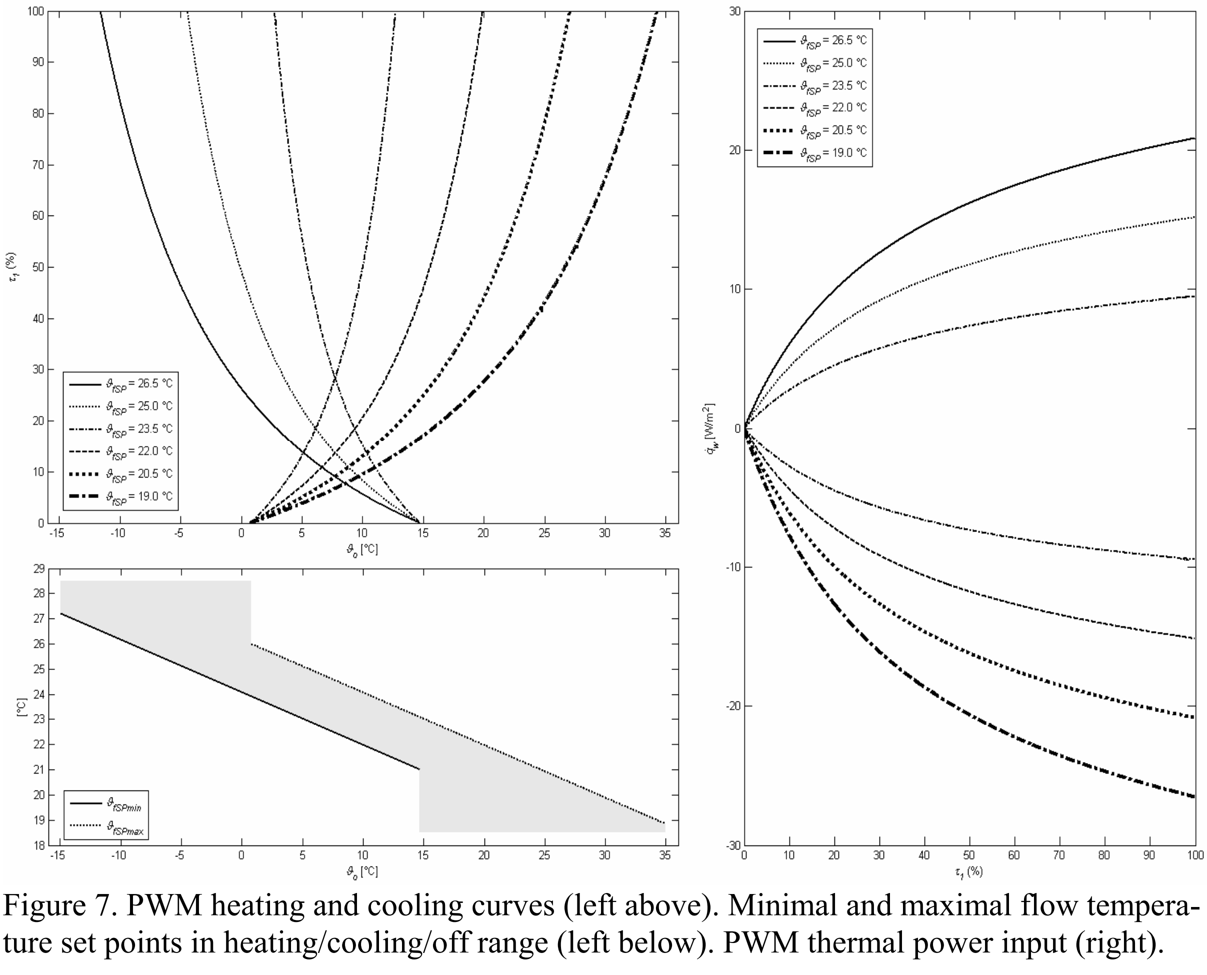

Figure 7. PWM heating and cooling curves (left above). Minimal and maximal flow temperature set points in heating/cooling/off range (left below). PWM thermal power input (right).

On the left side above turn-on ratios τ_I for different flow temperature set points ϑ_{fSP} are given. Due to the uncertain heat gains, there exists an outside air temperature range where heating or cooling can be demanded (see also Figure 6b). Minimal and maximal flow temperatures for this range are printed left below. The right side of Figure 7 shows the thermal power input $\dot{q}_w$ dependent on the turn on ratio for different flow temperature set points ϑ_{fSP} . Because the turn-on ratio is proportional to pump power, it can be seen that PWM leads to super-proportional pump energy savings.

PERFORMANCE BOUNDS FOR THE CONTROL OF CONCRETE CORE CONDITIONING SYSTEMS

Ideal model based predictive open-loop controllers are used to determine performance bounds for concrete core conditioning control strategies. There the predictive controllers solve periodically an optimization problem in which a given cost function is minimized. The optimization problem can be formulated so that comfort criteria are kept with minimal energy costs (additional constraints may exist). Ideality means that the concrete core conditioning system under control is exactly the same as the model used for the controllers' optimization and that in addition the future disturbances for the whole optimization horizon are known (ideal prediction). Models (M2) were developed as optimization and simulation models to identify performance bounds. The basic algorithm used is derived from [6],[7].
Below a performance bound for a two zone concrete core conditioning control problem is discussed as an example (see Figure 8): A primary temperature (and water flow on/off) control task has to be solved for two physically identical zones with different heat gains while no zone temperature and mass flow control is succeeded (situation as in Figure 1, but without zone pumps and zone valves).

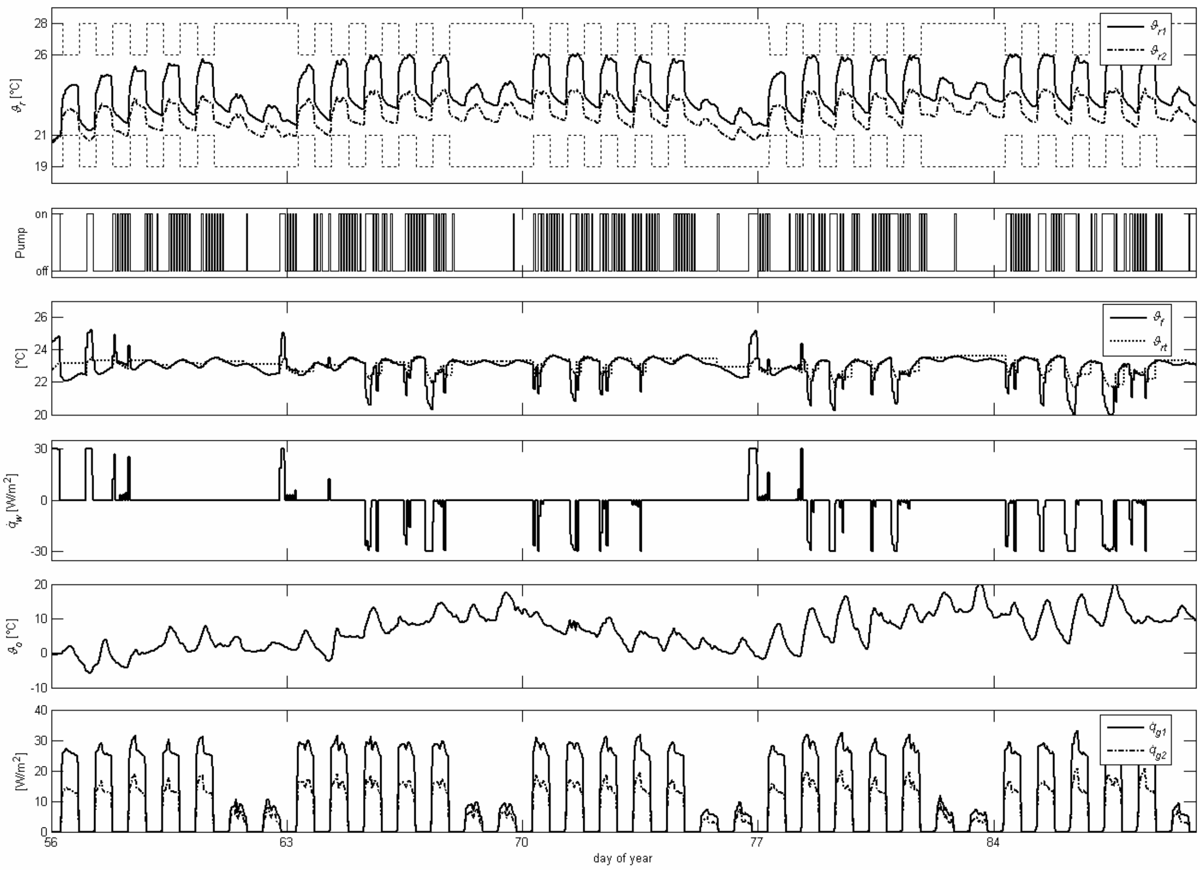

Figure 8. Performance bound for a two zone concrete core conditioning system.

Costs for heating and cooling power are assumed equal and are minimized. The optimization is done with sampling time 1 h and optimization horizon length of 48 h. Constraints are imposed on flow temperature ϑ_f (ϑ_{fMin} = 20 °C, ϑ_{fMax} = 27 °C), on room temperatures ϑ_{r1} and ϑ_{r2} (dotted lines on top axis of Figure 8), and on the heat flow to the concrete core from the water side $\dot{q}_w$ ($\dot{q}_{wMin}$ = –30 W/m^2, $\dot{q}_{wMax}$ = +30 W/m^2).
As can be seen in Figure 8, all the constraints are kept. An interesting result is that the pump is often turned on without heating/cooling the water ($\dot{q}_w$ = 0 W/m^2) to transfer heat from the zone 1 with high heat gains to the zone 2 with low heat gains (this is only done when the heat transfer from zone 1 to zone 2 is more than 5 W/m^2).

OUTLOOK

The development and validation work of the simulation and optimization models will be concluded. The unknown-but-bounded approach – including algorithms for switching between heating, cooling, neutral and cooling operation – will be brought to a practically applicable form. Several closed-loop control algorithms, varying also in the feedback-variable (room temperature, concrete core temperature, return temperature) and in the control variable are currently designed. Further work on the water flow on-off control as alternative to the shift of the flow temperature must be done. How to cope with multi-zone buildings with different kinds of hydraulic systems and the integration of additional cooling and heating devices will be considered.
A final selection of control solutions will be tested and evaluated by simulations, in the laboratory test-room and in an alpha-test. A guideline on how to choose and tune control strategies will be written. It will give also an answer on the controversial questions.

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