Harmonization of Thermal and Daylight Flows with Modelling, Simulation and Control System Design in Buildings

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Abstract. The paper deals with a specific problem in the wide area of intelligent buildings – with the harmonization of thermal and daylight flows. The first part describes some aspects of modelling and simulation of thermal phenomena. A complex simulator in Matlab Simulink environment was developed. A real process – a test chamber was also built for validation of mathematical modelling and control design. Different control algorithms were tested in simulation environment and on the real process-test chamber. Finally the illumination control by the aid of changeable properties in the chamber envelope – roller blind positioning, was also studied.

Keywords. Modelling, simulation, control system design, intelligent building, temperature, illumination.

1. Introduction

Modelling and simulation is a valuable approach when designing control systems in different areas. The very attractive area is also the area of intelligent building which deals with various approaches which enable the comfort feeling conditions inside buildings. Among them thermal and (day)light conditions are of course very important so the attention must be paid also to the design of corresponding control systems. Control system design which is illustrated in Fig.1 is a very complex procedure which demands also the modelling and simulation in the overall iterative approach [8]. The control design approach and especially the modelling and simulation itself have several important features:

- They have features of cyclic and iterative procedures.
- Designers experiences have an important role.
- In all phases the final goal or the purpose of the model must be considered.
- The modeller must be aware of presumptions, simplifications and constraints.
- There are no universal solutions.

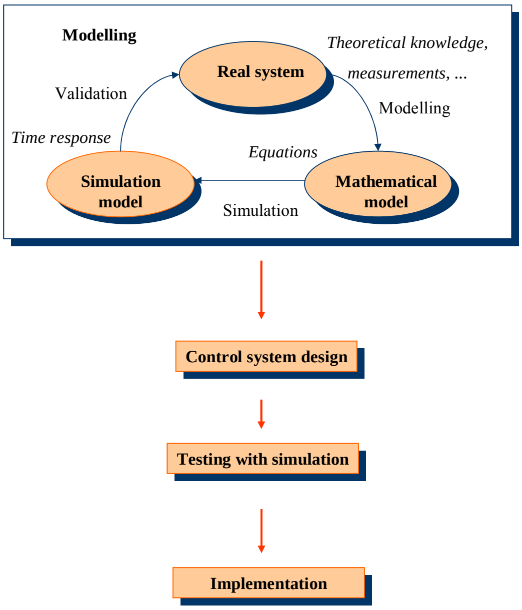


Figure 1. Control system design includes modelling and simulation cyclic procedure

Our goal was to use the described procedure for the design of system which controls the thermal and daylight flows inside the building.

For the validation of mathematical model and control strategies as well a test chamber (see Fig.2) was built on the roof platform of the Faculty of Civil and Geodetic Engineering, University of Ljubljana (46.0° latitude, 300m altitude). It has dimensions 1m x 1m x 1m and is designed especially for control design purposes. The cell is shifted off the ground and the roof is ventilated in order to avoid the overheating caused by direct radiation on the roof. Walls, floor and ceiling are built of lightweight brick blocks. The south wall is completely glazed with double-glazing composed of two layers of standard clear glass and air fill, and the thickness of wooden frame is 5 cm. The alternating geometry of the window is made with the automatically moveable roller blind. The roller blind is an external PVC blind and its position can be controlled. The measured values are: inside and outside temperatures, temperature of the ground, direct and reflected solar radiation, indoor illumination and the position of the roller blind.

Figure 2. The test chamber

Our goal is to achieve the desired indoor temperature $T_{c\ ref}$ and indoor illumination $j'_{c\ ref}$ with appropriate heating, ventilation, and blind positioning. The emphasize was given to the usage of passive energy resources, i.e. how to use the roller blind positioning to achieve pleasant conditions in the room and of course to make some energy savings.

The test chamber was modelled as a block with inputs (control variables) for heater, ventilator and roller blind positioning and the indoor temperature and indoor illumination as output (controlled) variables. The changeable external temperature T_e and global solar radiation j_e were treated as external disturbances. The skeleton of the control strategy is depicted in Fig.3.

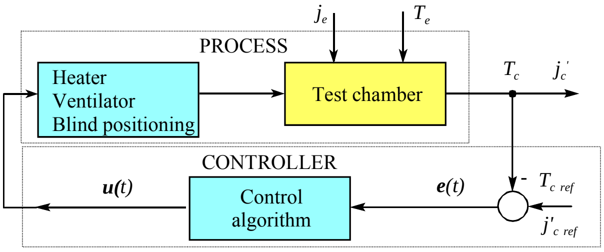


Figure 3. The skeleton of the chamber control system

2. Modelling

Up to now mathematical model of the thermal part of the mentioned process was derived [9], i.e. the influence of the heating, ventilating and blind positioning to the internal temperature in the presence of global solar radiation and external temperature as two disturbances. The modelling is a complex and complicated procedure and we shall emphasise only some more important issues. In the modelling the following phenomena were considered: thermal conduction, thermal convection, radiation and long wave radiation.

The problem of thermal conduction through the wall or window is treated as one-dimensional as it is assumed that changes perpendicular to the wall/window are much greater than the changes within the surface area. Another simplification was obtained by the assumption that one can calculate with an average temperature within one material layer. So partial diffusive equation of heat conduction becomes an ordinary one. Introducing the thermal resistance R_i and thermal capacity C_i we obtain for five layers material (Fig. 4) the following differential equation:

$$\frac{d}{dt}\begin{bmatrix}T_1\\T_2\\T_3\\T_4\\T_5\end{bmatrix}=\begin{bmatrix}\frac{1}{C_1(R_1+R_2)} & \frac{1}{C_1(R_1+R_2)} & 0 & 0 & 0\\ \frac{1}{C_2(R_1+R_2)} & -\frac{R_1+R_2+R_3}{C_2(R_1+R_2)(R_2+R_3)} & \frac{1}{C_2(R_2+R_3)} & 0 & 0\\ 0 & \frac{1}{C_3(R_2+R_3)} & -\frac{R_2+R_3+R_4}{C_3(R_2+R_3)(R_3+R_4)} & \frac{1}{C_3(R_3+R_4)} & 0\\ 0 & 0 & \frac{1}{C_4(R_3+R_4)} & -\frac{R_3+R_4+R_5}{C_4(R_3+R_4)(R_4+R_5)} & \frac{1}{C_4(R_4+R_5)}\\ 0 & 0 & 0 & \frac{1}{C_5(R_4+R_5)} & \frac{1}{C_1(R_4+R_5)}\end{bmatrix}\begin{bmatrix}T_1\\T_2\\T_3\\T_4\\T_5\end{bmatrix}+\begin{bmatrix}\frac{q_i}{C_1}\\0\\0\\0\\-\frac{q_e}{C_5}\end{bmatrix} \tag{1}$$

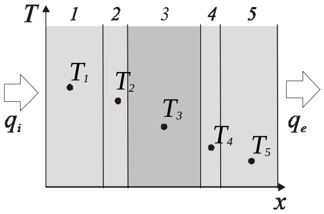


Figure 4. Heat conduction through five layers material

q_i and q_o are appropriate heat flows. Eq.2 describes the dynamics of heat transfer through the window (Fig.5), where T_1 stands for the temperature of the inner crownglass of the window and T_2 for outside glass pane. α_{wn} is conduction coefficient of air fill between inside and outside crownglass surface. The solar radiant flows on the inside and outside crownglass are described by q_{i_wn} and q_{e_wn}. The capacities of the inner and outside glass are C_1 and C_2, respectively.

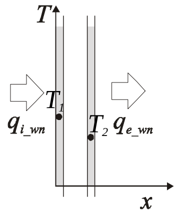


Figure 5. Heat conduction through window

$$\frac{d}{dt}\begin{bmatrix}T_1\\ T_2\end{bmatrix}=\begin{bmatrix}-\frac{\alpha_{wn}}{C_1} & \frac{\alpha_{wn}}{C_1}\\ \frac{\alpha_{wn}}{C_2} & -\frac{\alpha_{wn}}{C_2}\end{bmatrix}\begin{bmatrix}T_1\\ T_2\end{bmatrix}+\begin{bmatrix}\frac{q_{i\_wn}}{C_1}\\ \frac{-q_{e\_wn}}{C_2}\end{bmatrix} \tag{2}$$

3. Simulation

Mathematical model was implemented in the simulation environment MATLAB Simulink, which is widely used on Universities but also more in more in Industry. It enables the development of modular and transparent models. High accuracy and fast simulation can be obtained. It is very easy to program also complex experiments with simulation runs. The user interface enables a good interaction possibilities, the results can easily and efficiently be presented in different ways (time responses, animation, …). It is also very important that one can use many toolboxes for control system design. Fig. 6 shows the highest hierarchical level of the modularly constructed simulation model, which is already prepared to serve as a test cell for control system development and validation.

In the block Initialization all parameters about materials, geometry of window, orientation, geographic location and starting simulation time are given. So the simulation of the behaviour in the case of different materials, orientations, geographic locations, position and number of windows and period of the year can be performed. Outdoor temperature and Global solar radiation are defined with appropriate data files obtained from real measurements. They can easily be defined by some other signals from Simulink library. Temperature of terrain, Direct radiation and Cloudiness are prepared as constants or step signals. However in the presented model Direct radiation and Cloudiness are not independent (e.g. if the parameter of direct radiation changes from 0 to 1, the parameter of cloudiness changes from 1 to 0). The mentioned signals are treated as disturbance inputs. The last three inputs signed with Heater, Ventilator and Blind are control inputs as they will be fed by controller signals in order to assure the appropriate indoor temperature. Indoor temperature is the model output or from the point of control system the controlled variable. Of course the simulator can be easily modified so that also other variables of the model can be influenced or monitored.

Several measurements were used for appropriate final parameters tuning of the theoretical model of the test chamber. Another set of measurements was used for simulator validation. Simulations were obtained with the measured outdoor temperature and global solar radiation as input variables taken from the experiments as well as with the signal for blind moving regime (see Fig. 7). The comparison of the simulated indoor temperature and the measured one is presented in Fig. 8. The error between calculated and measured values is acceptable and is in the range of 5-20%. Mainly it is caused by unexpected ventilation heat-losses through some cracks in the dry wall panels and by the influence of wind.

Fig. 9. shows the measurements (chamber temperature (T_c) and external temperature(T_e)) that were obtained on the real process –chamber. After the steady state the heating power was increased at 7^{35} and again at 15^{10}. The external temperature did not change significantly. Fig. 10 shows the measured (T_{cm}) and the simulated (T_{cs}) temperature in the chamber.

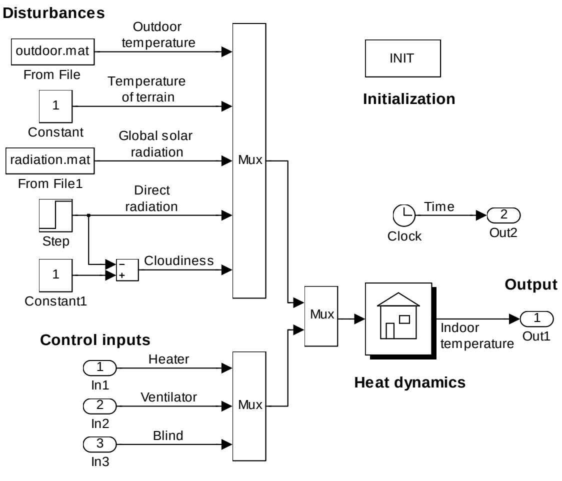


Figure 6. Scheme of the simulator in MATLAB-Simulink environment

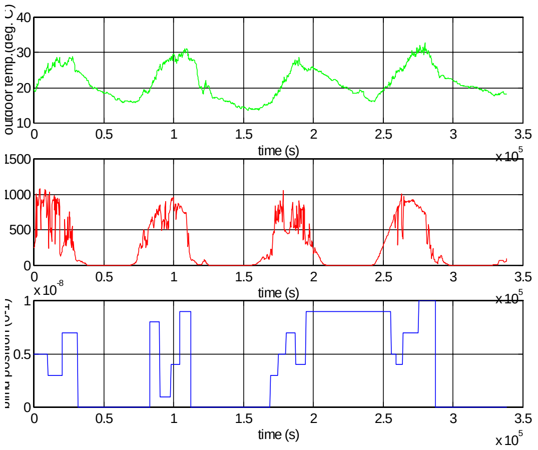


Figure 7. Input signals: outdoor temperature, global solar radiation and blind position

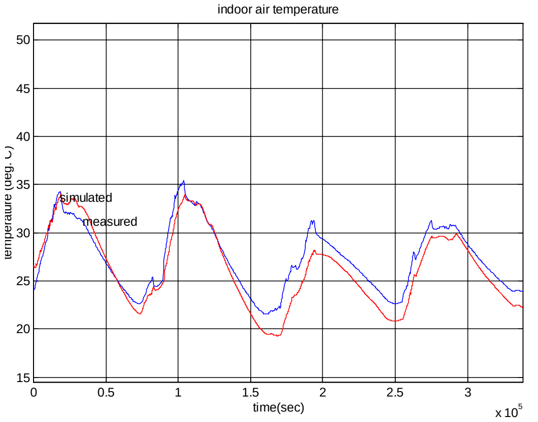


Figure 8. Comparison of the measured and simulated indoor temperature

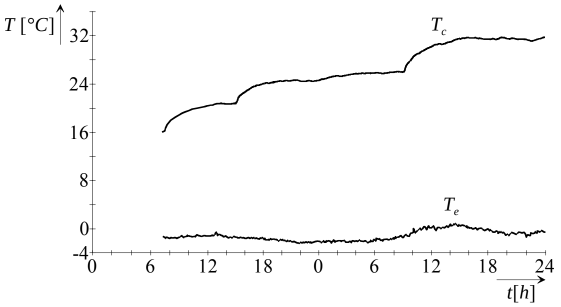


Fig. 9. Measurements: chamber temperature (T_c) and external temperature (T_e)

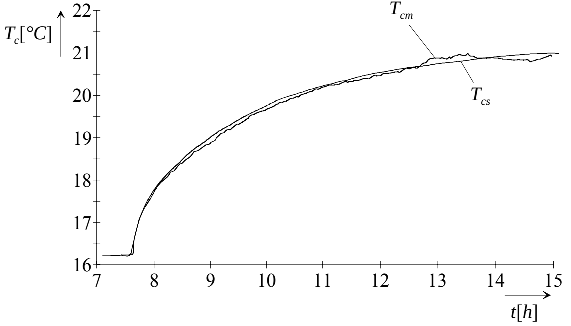


Figure 10. The measured and the simulated temperature in the chamber

4. Temperature control

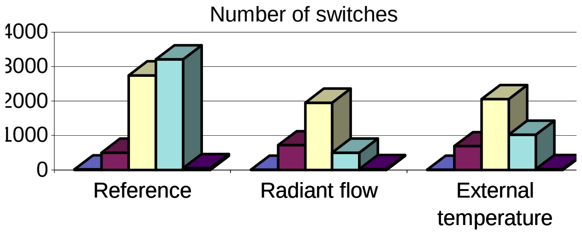
Different control strategies with different aims were studied with simulation and with experiments on test chamber. One of the studies was the following: the temperature T_c (see Fig. 3) was measured and the control system fed the eight stage heating system [10]. A special expert control system, on-off controller, PID controller [3], fuzzy controller [1] and deadbeat controller [4] were designed and tested. They were compared and validated using the following criteria during transient responses:

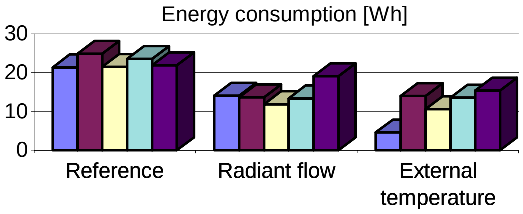
- Number of switches of heaters stages. It was determined by the appropriate counting during simulation on the same time interval 3 hours.
- Energy consumption: $W = \int_0^{t_{\max}} P_{heat}(t)dt$
- Integral square error: $ISE = \int_0^{t_{\max}} e^2(t)dt$

The conditions for experiments were the following:

- step change in the reference signal T_{ref} from 20°C to 22°C ,
- step change in radiant flow j_e for 40W/m2,
- step change in external temperature T_e for 2°C with simultaneous change in radiant flow j_e for 10W/m2.

The appropriate comparison is shown in Fig. 11. Different criteria for all three step changes for designed algorithms are shown.





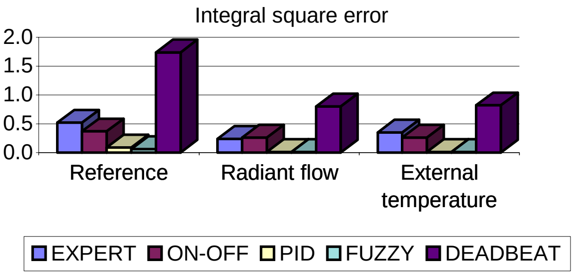


Figure 11. The comparison of the defined criteria

Number of switches Expert control algorithm has the smallest number of switches what is expected as it is designed so that it does not react very frequently. It is also clear, that the deadbeat controller has also a small number of switches as it is discrete with quite a large sampling interval within which a heater can not be switched on or off. It would be very easy to reduce the number of switches with PID and FUZZY algorithms without significant aggravation of other criteria.

Energy consumption The algorithms are more or less equivalent. The expert algorithm seems to be superior in the case of external temperature change.

Integral square error The FUZZY and PID are superior in this case. Deadbeat algorithm is perfect when using linear mathematical model with the continuous control signal. However using non-linear process model and discrete controller the control systems performance was very bad also with regard to some other criteria (e.g. changes of control signal are intensive also after transient response).

5. Illumination control

Up to now we developed only the thermal part of the mathematical model. However daylight in buildings is also very important. Daylight can be used to reduce the lighting and heating energy consumption. Besides daylight increases occupants satisfaction and improves also workers productivity.

As described mathematical modelling was efficiently used for temperature control system. The strategy was then validated in real system environment – on model chamber. Later these solutions were further improved also with some different strategies which included also daylight. They were verified only with real experiments on model chamber. One attempt is depicted with Fig.12.

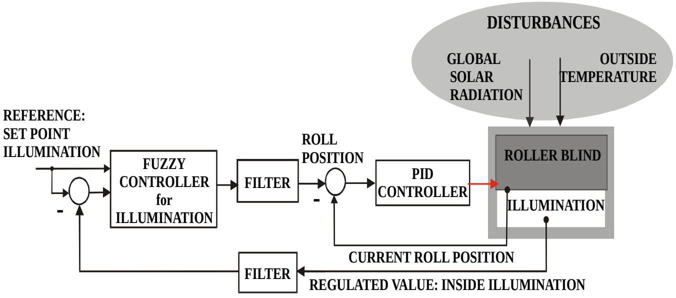


Figure 12. Illumination control system

Controlled external roller blind on the window (Fig. 12) is supposed to harmonize the illumination response. Two signals are measured: the indoor illumination which is the main controlled variable and the position of the roller blind, which is the auxiliary variable of the cascade control system. The main controller is a fuzzy controller and the auxiliary one is a conventional PID controller. The main controller gives the reference value for roller blind position and the auxiliary controller feeds the motor of the roller blind. The results of one experiment are shown in Fig. 13.

The system was influenced by the set point illumination step changes and by the changes of the global solar radiation as disturbances. The deviations of the controlled inside illumination from desired inside illumination profile are small, in the range smaller than ±100 lux. The luminous efficacy which is the ratio between inside illumination and global solar radiation was also studied in different experiments.

The influence of the roller blind position to the inside temperature was also studied. In particular working conditions we also succeeded to harmonize inside temperature and illumination by simultaneously influencing two control loops - thermal and illumination to the roller blind.

Of course, passive energy resources can be used efficiently only in some narrow bands with regard to appropriate reference values. Normally active resources – heating, cooling, electrical lightening must be used to drive the system in the vicinity of reference signals.

6. Conclusion

In the paper we describe some results in our efforts to harmonize thermal and daylight flows with intelligent control approaches. The basis of all control design approaches is the mathematical modelling. Some aspects of theoretical modelling

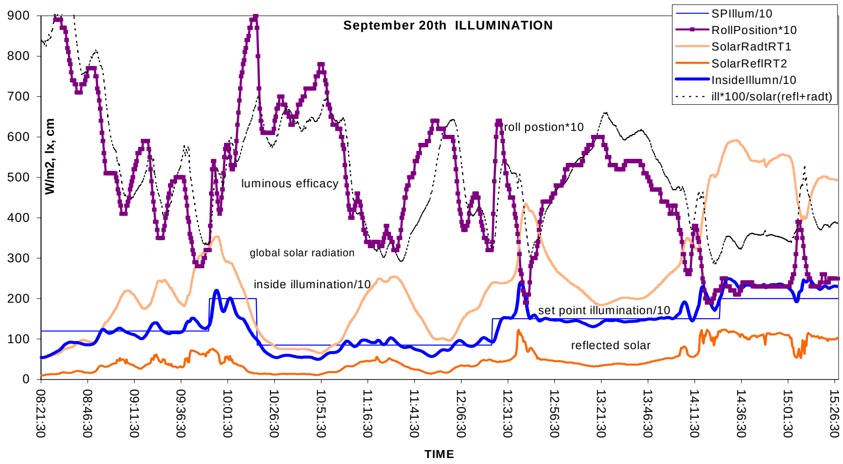


Figure 13. Cascade control of inside illumination

were described. Experimental modelling was also studied and the best results were obtained with fuzzy logic.

Mathematical model was efficiently used for the design of temperature control system. Different strategies were tested in simulation and in real experimental environment as well.

However the main challenge in our study was and will be particularly in the future to use some changeable properties of the building envelope, especially transparent parts for control purposes. The changeable geometry of the window was used for illumination and temperature control. It was shown that it is possible to use such approach when active energy resources drive the system nearby the reference conditions.

In the future the model will be completed with the illumination part so that overall control strategy can be studied in the simulation environment. There are various possibilities to study different control strategies and to include also additional modelling approaches.

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