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**CONTROL SYSTEM OF BUILDING USING MODELLING AND
SIMULATION**

ŘÍDICÍ SYSTÉM BUDOVY S VYUŽITÍM MODELOVÁNÍ A SIMULACE

(SUMMARY OF DOCTORAL THESIS)

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1 INTRODUCTION

Heating, ventilating and air-conditioning (HVAC) systems are multi-variables systems, which are one of the largest consumer of energy in buildings. These systems provide warmth and cooling, humidity control, indoor air quality, and provide comfort for the occupants.

Because HVAC systems consume so much energy, buildings must have the potential to achieve significant savings by improving control strategy of processes being done by HVAC systems so that improves the efficiency.

Modelling and simulation HVAC systems and their control systems are becoming increasingly important steadily, because the dynamic simulation using special software is the most efficient way to investigate controllability and to control performance of these systems. It is well known that the dynamic performance of a HVAC system has a great impact on energy consumption, as well as on indoor environment. In this thesis, some methods of modelling and simulation using the computer have been designed to obtain the appropriate indoor conditions, with lower costs resulting from energy consumption.

1.1 Defining the objectives dissertation

In this work, an integrated model of controlling indoor climatic conditions within a building has been designed. These parameters are basically temperature, relative humidity and CO₂ concentration.

The goal of the work can be summarized by the following main points:

- 1 Design a computer model by using MATLAB/SIMULINK software and TRNSYS software to simulate and control the optimal indoor climate conditions in a building (office, library, school, theatre). This model achieves the following tasks:
 - a. Modelling the outdoor climatic conditions, and achieving the possibility of interaction with their changes. The model of solar radiation data has been designed by using TRNSYS software which can provide a suitable simulation environment to model climate change. While the other conditions (outdoor temperature and relative humidity have been simulated by exporting the real data taken from meteorological station in Brno (TUBO station) to MATLAB/SIMULINK, so that they can be used as outdoor conditions of the model. The building considered in this thesis is a lecture room at the Faculty of Mechanical Engineering at the Brno University of Technology.
 - b. Modelling the indoor temperature, with the possibility to control it according to the requirements of the occupants.
 - c. Modelling the indoor relative humidity, with the possibility to control it according to the requirements of the occupants.
 - d. Modelling the indoor concentration of carbon dioxide, CO₂, with the possibility to control it according to the requirements of the occupants.
- 2 Optimize indoor conditions in order to reduce their changes as much as possible by means of suitable control strategies which can also reduce energy consumption.

2 INDOOR ENVIRONMENT

It is well known that the human body generates constantly heat by a range from about 75 W during sleeping, to about 1000 W during extreme exercise [1], where excess amounts of heat should be transferred to the surrounding environment by radiation, convection, conduction and evaporation in an accurate and carefully controlled way, so that the internal organs of a human must remain at a constant temperature in order to maintain comfort, health and survival. This value is about 37.0 ± 0.5 °C. The maximum deviation of the temperature from the normal level is about 2 °C [2].

- Thermal comfort describes the synthesis of feeling about thermal conditions in human body. The definition by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) is “the condition of mind in which satisfaction is expressed with the thermal environment” (ASHRAE 2004). There is no comprehensive definition within a specific range of temperatures acceptable for all occupants. But, based on personal experience depends on a large number of factors, where, can be different from one person to another within the same space.
- Breathing produces carbon dioxide. Breathing for average adult contains about 35,000 to 50,000 ppm of CO₂ [3].

Epidemiological research has found that indoor CO₂ concentration is an acceptable indicator to predict human health and performance. Many studies have found that higher CO₂ concentrations in schools are associated with increased student absence [4]. Some studies have found that poorer student performance is associated with increased CO₂ in classrooms [5]. Some searches have confirmed that students performed their tasks at school less effectively when CO₂ concentration was higher [6].

- Relative humidity is a measure refers to the water vapour in the gaseous mixture consisting of water and air. It is expressed as the ratio between the amount of water present in the air at a given temperature to the maximum amount that can be present in the air at that temperature.

Maintain the relative humidity in the range of 40-60 % is the ideal area for occupants [7]. Traditional buildings deal with moisture in the air through the control of ventilation and moisture management. Any changes to the heating or ventilation strategy in a building can affect the ability of the building to deal with the humidity, and this is critical.

Humans have difficulties to feel changes in relative humidity (RH), due to the lack of sensory receptors to moisture [8]. The concept of "dry air" is associated with the irritation of the mucous membrane of the eyes (such as dry eye) and upper airways (sensory irritation) [9], which is a major issue in the classic “sick building syndrome” in non-industrialized buildings [10].

- Whenever there is a temperature difference between the conditioned indoor space of a building and outdoor air, heat transfer takes place through the building structure (walls, roof, floor, etc). This is known as heat gains or losses, based on if heat transfer is to the building or from the building.

The rate of heat exchange (\dot{Q}) through some parts such as roof, wall or floor under steady state can be calculated as follows [11]:

$$\dot{Q} = AU\Delta T \tag{1}$$

Where:

\dot{Q} [W]: heat transfer rate.

A [m²]: surface area.

U [W/ m² K]: the overall heat transfer coefficient.

ΔT [K]: temperature difference between inside and outside air.

U is calculated by the relation [11]:

$$U = \frac{1}{R_{total}} \quad (2)$$

Where:

R_{total} [m² K/W]: total thermal resistance, it can be calculated as follows [12]:

$$R_{total} = \frac{1}{h_{inside}} + \left(\sum_{j=1}^m l_j / k_j \right) + \frac{1}{h_{outside}} \quad (3)$$

Where:

$h_{inside}, h_{outside}$ [W/m².K]: inside and outside heat transfer coefficients, respectively.

l_j [m]: thickness of the j_{th} layer.

k_j [W/m.K]: thermal conductivity of j_{th} material.

U [W/m² .K]: the total amount of heat transmitted from outdoor air to indoor air through a wall or roof per unit area per unit time.

If the surface is also exposed to solar radiation, then [13]:

$$\Delta T = T_{so} - T_{indoor} \quad (4)$$

Where:

T_{indoor} [K]: indoor temperature.

T_{so} [K]: sol-air temperature.

To calculate the effect of solar radiation, sol-air temperature is used, which is an equivalent outdoor temperature combines the effects of convection and radiation. Solar radiation on walls warms the surfaces and affects the rate of conduction heat transfer through the wall. It is calculated using the relation [13]:

$$T_{so} = T_{outdoor} + \frac{\alpha \cdot I}{h_{outside}} \quad (5)$$

Where:

$T_{outdoor}$ [K]: outdoor air temperature.

I [W/m²]: the total solar heat flux on the wall.

α [-]: absorptance of surface for solar radiation.

2 OUTDOOR CLIMATE DATA

2.1 Meteorological station TUBO

In the frame of EUREF permanent network (Regional Reference Frame Sub-Commission for Europe) [14], the meteorological station is identified by four-character code TUBO [15]. The CERGOP (Central European Reference Geodynamic Project) Campaigns were performed in 1999 and 2001 years at this station for geodynamical investigation in the states of central Europe.

In this work, climate data from the station TUBO have been recorded for the period from September 2012 until August 2013. Where, the model has been applied for cool days, hot days, and mild days.

2.2 Processing of weather data by using MATLAB/SIMULINK software

SIMULINK is a program that runs as a companion to MATLAB. These programs are developed and marketed by the MathWorks, Inc [16]. SIMULINK and MATLAB form a package that serves as a tool for modelling dynamic systems. SIMULINK provides a graphical user interface (GUI) that is used in building block diagrams, performing simulations, as well as analysing results. In addition to the outdoor temperature, data of relative humidity of ambient air and data of sun radiation incident on the horizontal surface can be obtained through the site TUBO. These data can be obtained as *text documents*. In order to use these data, they must be converted into a format readable in the designed model as MAT files.

2.3 Processing of weather data by using TRNSYS software

TRNSYS, a transient systems simulation program that has been commercially available since 1975 [17], continues to develop by the international collaboration from the United States (Thermal Energy System Specialists and the University of Wisconsin-Solar Energy Laboratory), France (Centre Scientifique et Technique du Bâtiment), and Germany (TRANSSOLAR Energietechnik).

Weather data concerning solar radiation taken from TUBO station represent the intensity of solar radiation on horizontal surfaces. But in this work, there are vertical walls with different orientations. Therefore, a model has been designed to calculate the intensity of solar radiation on each wall using TRNSYS software. Where, by using total solar radiation on horizontal surface, air temperature and relative humidity, the solar radiation incident on all walls can be obtained for the given geographic location. The designed model is shown in Figure 1, where, the Solar Radiation Processor of this model includes: Total solar radiation on horizontal surface, Temperature and Relative Humidity.

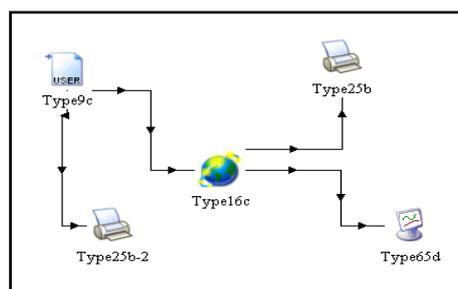


Figure 1: TRNSYS model

3 MODELLING INDOOR THERMAL PROCESSES

It is needed for a better knowledge of the whole building Heat, Air & Moisture (HAM) balance [18] and its impact on the indoor environment, as well as energy consumption for heating cooling, air (de)humidification, in order to provide thermal comfort for occupants while reducing pollution and energy consumption.

A lot of computer applications already exist to deal with these issues. There is no one simulation tool can covers all issues [19]. But there is an option is the coupling of tools [20]. The MATLAB environment has advanced capabilities to simulate indoor thermal processes. A whole building model has already been developed in MATLAB. This model, called HAMBBase (Heat, Air and Moisture model for Building and Systems Evaluation). This model has continuously been improved and implemented in MATLAB. Important features for this work are: multi-zone modelling, solar and shadow calculations and multi climate conditions.

Figure 2 shows a diagram of the building, where, the main dimensions in mm are clarified.

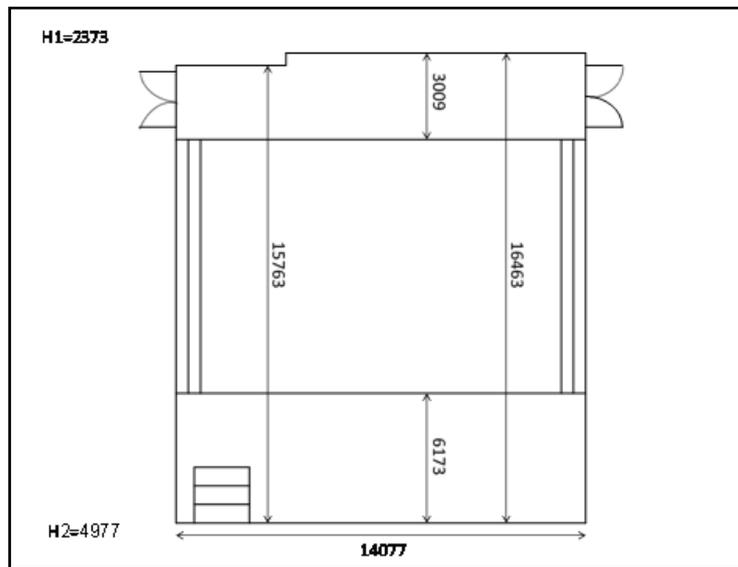


Figure 2: Dimensions of the building

The volume of indoor space is 910 m^3 . There are two external walls with the same dimensions. One of them in north-northwest orientation, while the other in south-southeast orientation. Each wall is covered partially with a wood layer. The area of the wood-covered part is 28.63 m^2 , while the area of concrete part is 14.65 m^2 . Further data are in Table 1.

Table 1: Dimensions and properties of materials of all layers in external wall

External wall from inside to outside direction	Thickness [mm]	Thermal conductivity [W/m.K]	Specific heat capacity [J/kg.K]	Density [kg/m^3]
Wood	5	0.17	2000	700
Concrete	25	1.7	920	2300
Brick	450	0.8	800	1700
Concrete	25	1.7	920	2300

There is a steel frame for the window in each wall. The area of glass is 9.64 m², while area of frame is 4.35 m². Further data are in Table 2.

Table 2: Properties of window frame material

Window frame	Thermal conductivity [W/m.K]	Specific heat capacity [J/kg.K]	Density [kg/m ³]
Steel	16	490	7820

There is another external wall with east-northeast orientation, is covered partially with a wood layer too, with the same layers exactly. The area of the wood-covered part is 36.65 m², while area of concrete part is 33.40 m².

With regard to roof, there is an air gap with thickness 300 mm, is assumed that has the same indoor temperature, connected with a concrete layer. Above roof, there is a room containing equipment for HVAC system. Its temperature changes between the indoor and outdoor temperatures, and it has been obtained by direct measurement. Table 3 includes the dimensions and properties of the concrete layer.

Table 3: Dimensions and properties of materials of roof

Roof	Area [m ²]	Thickness [mm]	Thermal conductivity [W/m.K]	Specific heat capacity [J/kg.K]	Density [kg/m ³]
Concrete	231.75	150	1.7	920	2300

There is an inner wall connected with conditioned indoor space, while under the floor there is another classroom conditioned too. Since the air temperature in the adjacent indoor spaces (hallways, classroom) is the almost the same as in the lecture hall, the heat transfer through internal walls has been neglected in the model.

3.1 Modelling heat transfer indoors

Energy balance indoors can be expressed by the following equation [21]:

$$(\rho_{air} \cdot c_{p\ air} \cdot V_{indoor} + C_{internal}) \frac{dT_{indoor}}{dt} = Q_{ventilation} + Q_{envelops} + Q_{windows} + Q_{gains} \quad (6)$$

Where:

ρ_{air} [kg/m³]: density of air.

$c_{p\ air}$ [J/kg.K]: specific heat capacity of air.

V_{indoor} [m³]: indoor space volume.

$C_{internal}$ [J/K]: lumped thermal capacity of the building, which is the sum of the internal capacities of all internal layers, where, it is assumed that indoor air temperature and the temperature of all internal layers are the same

T_{indoor} [K]: temperature indoor.

$Q_{ventilation}$ [W]: heat loss/gain due to ventilation.

$Q_{envelops}$ [W]: heat exchange through building envelopes.

$Q_{windows}$ [W]: heat exchange through windows.

Q_{gain} [W]: internal gains (occupants and equipments, etc).

Heat transfer through the building envelopes can be expressed by the following equation [22]:

$$Q_{envelope} = \frac{1}{\frac{1}{h_{inside}} + \frac{l_1}{2k_1}} A_1 (T_1 - T_{indoor}) + \frac{1}{\frac{1}{h_{inside}} + \frac{l_{frame}}{2k_{frame}}} A_{frame} (T_{frame} - T_{indoor}) + \frac{1}{\frac{1}{h_{inside}} + \frac{l_{roof}}{2k_{roof}}} A_{roof} (T_{roof} - T_{indoor}) \quad (7)$$

Where:

h_{inside} [W/m².K]: heat transfer coefficient inside. In this model, is set to be 8 W/m².K.

l_1 [m]: thickness of wood layer (first layer).

k_1 [W/m.K]: thermal conductivity of wood layer (first layer inside).

A_1 [m²]: area of wood layer (first layer inside).

T_1 [°C]: temperature of wood layer (first layer inside).

l_{frame} [m]: thickness of windows frame.

k_{frame} [W/m.K]: thermal conductivity of windows frame.

A_{frame} [m²]: area of windows frame.

T_{frame} [°C]: temperature of windows frame.

l_{roof} [m]: thickness of concrete layer of roof.

k_{roof} [W/m.K]: thermal conductivity of concrete layer of roof.

A_{roof} [m²]: area of concrete layer of roof.

T_{roof} [°C]: temperature of concrete layer of roof.

Heat Transferred through the window can be expressed by the following equation [23]:

$$Q_{windows} = A_{windows} U_{windows} (T_{so, windows} - T_{indoor}) + I \cdot SC \cdot A_{windows} \quad (8)$$

Where:

$Q_{windows}$ [W]: heat exchange through windows.

$A_{windows}$ [m²]: windows area.

$U_{windows}$ [W/m².K]: overall heat transfer coefficient of windows.

$T_{so, windows}$ [°C]: sol-air temperature for windows.

T_{indoor} [°C]: temperature indoor.

I [W/m²]: solar radiation incident on the window.

SC : solar heat gain coefficient.

Ventilation heat loss/gain can be calculated as follows [24]:

$$Q_{ventilation} = \frac{N \cdot \rho_{air} \cdot V_{indoor} \cdot c_{p_{air}}}{3600} (T_{outdoor} - T_{indoor}) \quad (9)$$

Where:

$Q_{ventilation}$ [W]: heat loss/gain due to ventilation.

N [1/h]: air change rate = (air change rate due to infiltration + air change rate due to ventilation). Where, infiltration rate is assumed approximately in the lecture room (no occupancy) to be around 0.2 1/h.

V_{indoor} [m³]: indoor space volume.

$c_{p\ air}$ [J/kg.K]: specific heat capacity of air.

$T_{outdoor}$ [K]: outdoor temperature.

T_{indoor} [K]: indoor temperature.

The average amount of heat given off by a person depends on the level of activity. Hence, *total internal gains=constant gains (no occupancy), if any + scheduled gains (occupancy), if any + heat gain from people, if any.*

3.2 Control strategy

ON-OFF controller has been used to control temperature indoor, so that it works as controller for heating process in the direct direction of control signal, as follows:

If: $T_{set}-T_{indoor}$ is out of allowed interval, thus $Q_{heating/cooling} = \dot{m} \cdot c_p \cdot (T_{heater/cooler} - T_{indoor})$ will be provided to classroom until the difference ($T_{set}-T_{indoor}$) return to the allowed interval.

On the other hand, after reversing of control signal, the controller controls the cooling process, as follows: In the direct direction, the difference ($T_{set}-T_{indoor}$) for cooling process is negative because $T_{set} < T_{indoor}$, so relay must work as follows: (switch on point) is (-value) not (+value), and (switch off point) is (+value) not (-value). That means: if $T_{set}-T_{indoor} = -value$, relay will send signal to switch cooling on. Conversely: if $T_{set}-T_{indoor} = +value$, relay will send signal to switch cooling off. Hence, signal relay should be inversed. That means when relay signal is 1, cooling process is off. When Relay signal is 0, cooling process is on. This process can be achieved as follows: When Relay signal is (1), control signal in direct direction is (1), and it is controlling heating process, while the reversed signal is (0), so there is no controlling of cooling process. While, when Relay signal is (0), control signal in direct direction is (0), so there is no controlling of heating process, while reversed signal is (1), and it is controlling cooling process.

Where, the control signal in the process of heating and cooling begins only when the temperature indoor after supplying of air from the air conditioning system without heating or cooling, is out of the allowed range of temperature indoor, as shown in Figure 3.

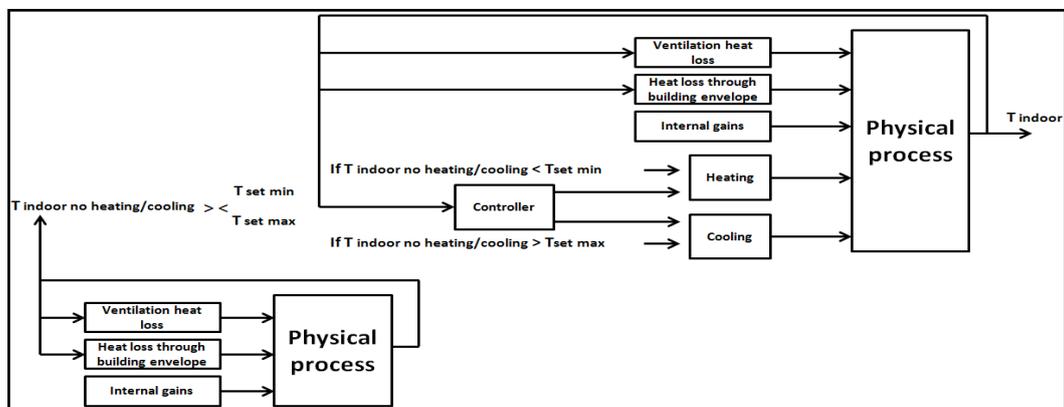


Figure 3: Temperature control algorithm

After calculating all terms on the right side of equation (7), temperature indoor can be calculated

3.3 Calculate heat removed/added

To control temperature inside the classroom, a certain amount of heat must be added or removed. But, considering that the indoor temperature is changing depending on the changing in outdoor temperature, as well as the changing in internal gains, controllers must be used to keep indoor temperature within the allowed range.

The amount of added heat must be greater than a minimum value, so that heating leads to achieving the minimum temperature in the allowed range, as shown in Figure 4.

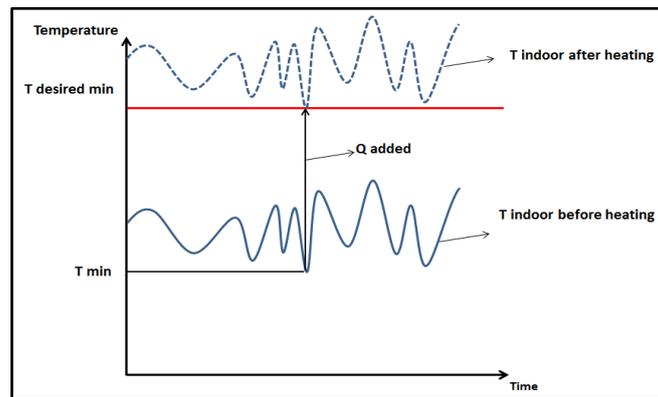


Figure 4: Added heat

It is necessary to calculate the minimum indoor heat gain ($Q_{sumheatmin}$), in order to determine the extreme conditions indoors in winter (the allowed coldest indoor temperature).

Where: $Q_{sumheatmin}$ is the minimum value of the following sum:

(ventilation heat exchange if $T_{indoor}=T_{set, min}$) + (heat exchange through the building envelope if $T_{indoor}=T_{set, min}$) + (internal heat gains)

This value represents the extreme conditions allowed indoors in winter, where, there should be a maximum supplying of heat.

There is a specific range, where, within it, indoor temperature can change without the need for any supplying or removing heat to/from indoor space. Hence, the minimum value in this range is called $T_{set, min}$, while the maximum value in this range is called $T_{set, max}$.

Hence, the minimum heat indoor without heating must be calculated, as follows:

$Q_{sumheatmin} = \text{Min (ventilation heat Min + heat through the building envelope Min + internal heat gain)}$

Where: *ventilation heat Min* can be calculated as follows:

$$\text{Ventilation heat Min} = \frac{N \cdot \rho_{air} \cdot V_{indoor} \cdot c_{pair}}{3600} (T_{outdoor} - T_{setmin}) \quad (10)$$

While, *heat through the building envelope Min = heat exchange through building envelope if $T_{indoor}=T_{set, min}$*

Where: $T_{set, min}$ is the minimum allowed indoor temperature. Hence, conditioner temperature (supply air temperature) can be calculated as follows:

$$T_{conditione} = T_{set\ min} - \frac{Q_{sumheatmin}}{m \cdot c_{p\ air}} \quad (11)$$

Where:

m [kg/s]: mass flow of supply air.

c_{pair} [J/kg.K]: specific heat capacity of supply air.

On the other hand, the amount of removed heat must be greater than a minimum value, so that cooling leads to achieving the maximum temperature in the allowed range, as shown in Figure 5.

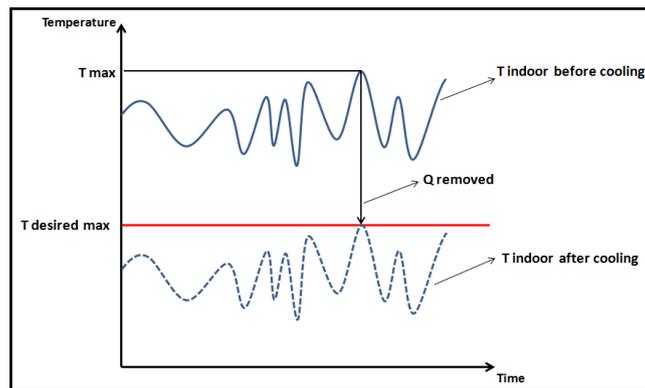


Figure 5: Removed heat

It is necessary to calculate the maximum indoor heat gain ($Q_{sumheatmax}$), in order to determine the extreme conditions indoors in summer (the allowed hottest indoor temperature).

Where: $Q_{sumheatmax}$ is the maximum value of the following sum:

(ventilation heat exchange at $T_{indoor}=T_{set, max}$) + (heat exchange through the building envelope at $T_{indoor}=T_{set, max}$) + (internal heat gains)

This value represents the extreme conditions allowed indoors in summer, where, there should be a maximum removing of heat.

So, the maximum heat indoor without cooling must be calculated, as follows:

$Q_{sumheatmax} = \text{Max (ventilation heat Max + heat through the building envelope Max + internal heat gain)}$

Where: *ventilation heat Max* can be calculated as follows:

$$\text{Ventilation heat Max} = \frac{N \cdot \rho_{air} \cdot V_{indoor} \cdot c_{pair}}{3600} (T_{outdoor} - T_{set, max}) \quad (12)$$

While, *heat through the building envelope Max = heat exchange through building envelope if $T_{indoor}=T_{set, max}$*

Where: $T_{set, max}$ is the maximum allowed indoor temperature. Hence, conditioner temperature (supply air temperature) can be calculated as follows:

$$T_{conditione} = T_{set\ max} - \frac{Q_{sumheatmax}}{m \cdot c_{p\ air}} \quad (13)$$

4.3 Demand controlled ventilation (DCV) model

The average of target indoor CO₂ concentration (set point) used in this model is 800 ppm. This strategy has been applied by using ON-OFF controller, which operates as follows: When the differential between indoor CO₂ concentration measured and set point is in the range [-50→50], there is no signal control. In this case, switch (2) allows only the constant rate to pass, as shown in Figure 7. On the other hand, when the differential between indoor CO₂ concentration measured and set point exceeds this range, there will be a feedback signal. In this case, switch (2) allows the forced rate to pass until the differential becomes again within the range.

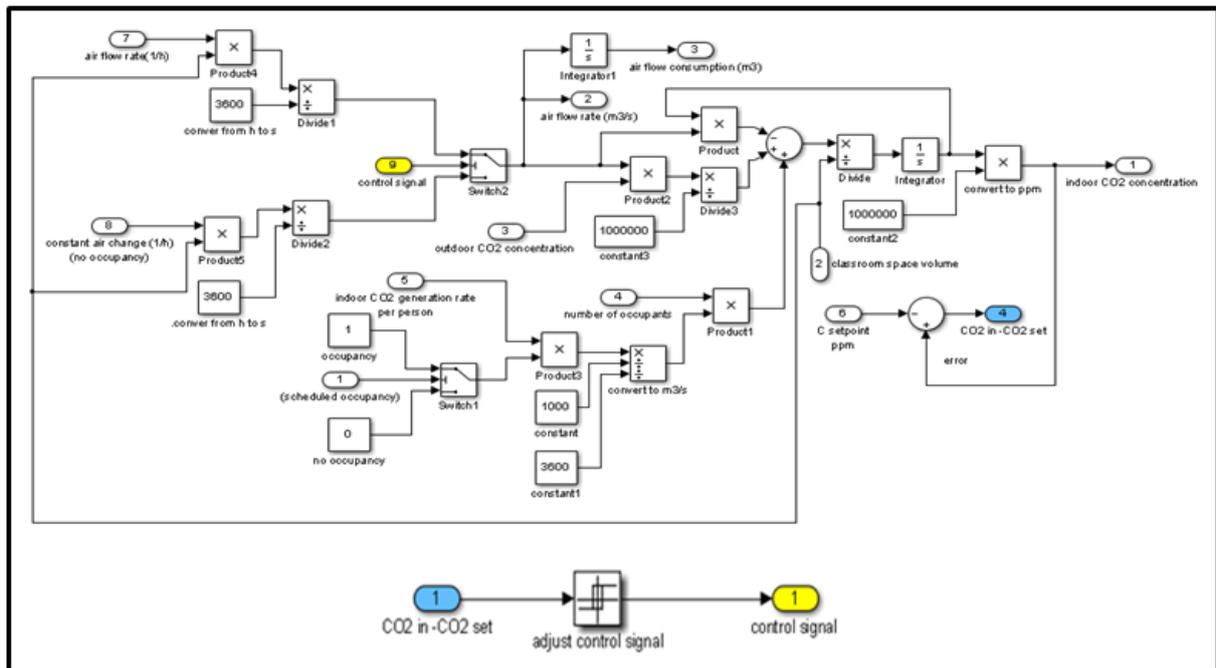


Figure 7: Demand controlled ventilation (DCV) with ON-OFF controller

By the imposition that amount of air savings must be heated or cooled by the different between indoor and outdoor temperatures during winter or summer, respectively, the energy needed for this process can be calculated as follows [26]:

$$E = \rho_{air} \cdot c_{p\ air} \cdot V_{air} \cdot |\Delta T| \quad (16)$$

Where:

E [J]: heat (energy).

ρ_{air} [kg/m³]: density of air.

$c_{p\ air}$ [J/kg.K]: specific heat capacity of the air.

V_{air} [m³]: air volume.

$|\Delta T|$: the difference between indoor and outdoor temperatures in absolute value.

5 MODELLING HUMIDITY INDOORS

5.1 Relative humidity model

Moisture balance in conditioned indoor space is shown in Figure 8.

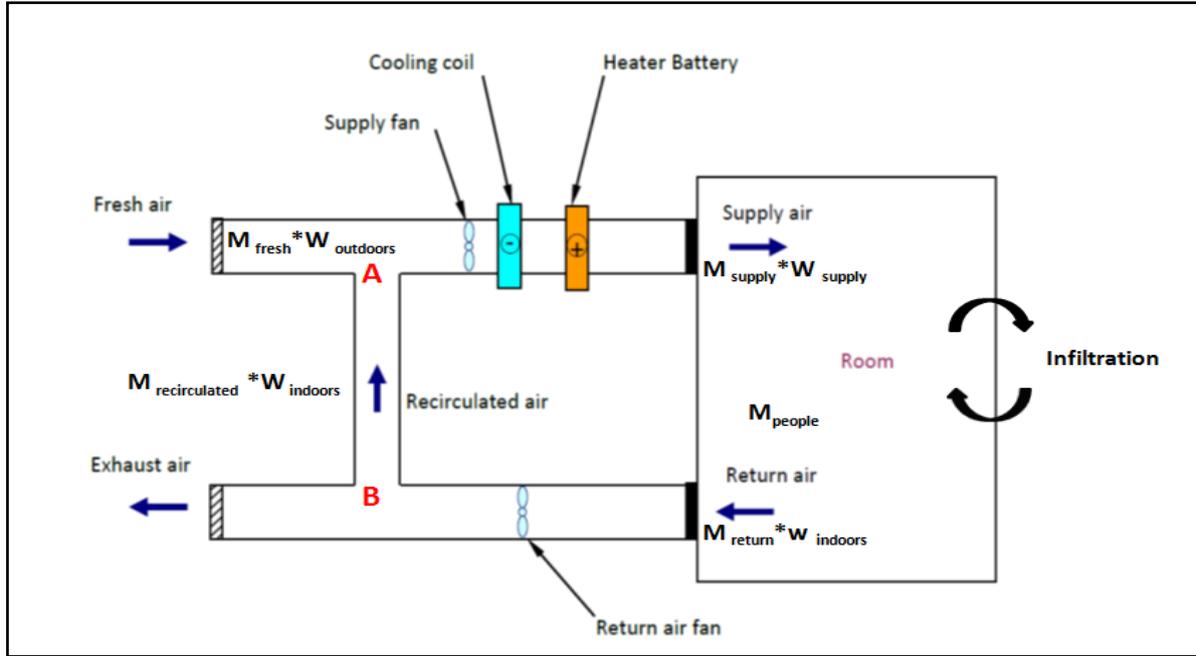


Figure 8: Schematic diagram of moisture balance in room with central plant air conditioning system

Mass balance indoors can be expressed by the relation [27]:

$$M_{supply} \cdot W_{supply} - M_{return} \cdot W_{indoors} + M_{infiltration} \cdot W_{outdoors} - M_{infiltration} \cdot W_{indoors} + M_{people} + M_{added/removed} = \rho_{air} V_{indoor} \frac{dW_{indoors}}{dt} \quad (17)$$

Where:

M_{supply} [kg/s]: mass flow of supply air.

W_{supply} [kg/kg]: specific humidity of supply air.

M_{return} [kg/s]: mass flow of return air.

$W_{indoors}$ [kg/kg]: specific humidity of air in the room.

$M_{infiltration}$ [kg/s]: mass flow of infiltration air.

$W_{outdoors}$ [kg/kg]: specific humidity of air outdoors.

M_{people} [kg/s]: moisture generated from people, normally is (0.01157/1000 kg/s per person) [28]

$M_{added/removed}$ [kg/s]: moisture generated by conditioning.

Depending on mass balance at point **A**:

$$M_{supply} \cdot W_{supply} = M_{fresh} \cdot W_{outdoors} + M_{recirculated} \cdot W_{indoors} \quad (18)$$

Depending on mass balance at point **B**:

$$M_{return} = M_{fresh} + M_{recirculated} \quad (19)$$

Where:

M_{fresh} [kg/s]: mass flow of fresh air.

$M_{recirculated}$ [kg/s]: mass flow of recirculated air.

By substitution equations (18) and (19) in equation (17):

$$W_{indoors} = \int \frac{(M_{fresh} + M_{infiltration}) \cdot (W_{outdoors} - W_{indoors}) + M_{people} + M_{added/removed}}{\rho_{air} \cdot V_{indoor}} \quad (20)$$

Outdoor humidity can be calculated by the relation [29]:

$$W_{outdoors} = \frac{0.622 \cdot RH_{outdoors} \cdot P_{s,outdoors}}{P_{outdoors} - (RH_{outdoors} \cdot P_{s,outdoors})} \quad (21)$$

After calculating $W_{indoors}$, relative humidity indoors $RH_{indoors}$ can be calculated as follows [29]:

$$W_{indoors} = \frac{0.622 \cdot RH_{indoors} \cdot P_{s,indoors}}{P_{indoors} - (RH_{indoors} \cdot P_{s,indoors})} \quad (22)$$

Where:

- a) $P_{s,indoors}$ [Pa]: saturation pressure of air indoors, can be calculated by the equation [30]:

$$P_{s,indoors} = \frac{e^{\left(\frac{77.3450 + 0.005 T_{indoor} - 7235}{T_{indoor}} \right)}}{T_{indoor}^{8.2}} \quad (23)$$

Where: T_{indoor} [K]: is temperature of air indoors.

- b) $P_{indoors}$ [Pa]: pressure air indoors.

Then, relative humidity indoors $RH_{indoors}$ can be calculated by the relation [29]:

$$P_{indoors} = \frac{T_{indoor} \cdot R_{air,indoor} \cdot m}{Q_v} \quad (24)$$

5.2 Control humidity model

There is a specific range, where, within it, indoor relative humidity can change without the need for supplying or removing humidity (water) from the indoor space. Hence, the minimum value in this range is called RH_{min} and corresponding humidity is $W_{in(min)}$. While the maximum value in this range is called RH_{max} and corresponding humidity is $W_{in(max)}$.

From equation (20), if assumed that:

$$M_{fresh} + M_{infiltration} = a$$

$$M_{people} = b$$

$$\rho \cdot V = c$$

If not, add or remove water:

$$c \cdot W_{indoors} = \int a \cdot (W_{outdoors} - W_{indoors}) + \int b \quad (25)$$

- If $W_{indoors} < W_{in(min)}$, there must be a process of adding water.

Where:

$$W_{in(min)} = \frac{0.622 \cdot RH_{min} \cdot P_{s,indoors}}{P_{indoors} - (RH_{min} \cdot P_{s,indoors})} \quad (26)$$

In this case, equation (25) must become as follows:

$$c \cdot W_{in(min)} = \int a \cdot (W_{outdoors} - W_{in(min)}) + \int b + \int M_{added} \quad (27)$$

- If $W_{indoors} > W_{in(max)}$, there must be a process of removing water.

Where:

$$W_{in(max)} = \frac{0.622 \cdot RH_{max} \cdot P_{s,indoors}}{P_{indoors} - (RH_{max} \cdot P_{s,indoors})} \quad (28)$$

In this case equation (25) must become as follows:

$$c \cdot W_{in(max)} = \int a \cdot (W_{outdoors} - W_{in(max)}) + \int b - \int M_{removed} \quad (29)$$

By subtracting equation (25) from equation (27):

$$\int M_{added} = c(W_{in(min)} - W_{indoors}) + a \int (W_{in(min)} - W_{indoors}) \quad (30)$$

By subtracting equation (25) from equation (29):

$$\int M_{removed} = c(W_{indoors} - W_{in(max)}) + a \int (W_{indoors} - W_{in(max)}) \quad (31)$$

After calculating $\int M_{added}$ and $\int M_{removed}$, as shown in Figure 9, adding and removing water rates can be calculated as follows:

$M_{added} = \int M_{added} / (\text{time integration of adding water})$, as shown in Figure 10.

Where: time integration of adding water is the interval time where $RH_{indoors} < RH_{min}$.

$M_{removed} = \int M_{removed} / (\text{time integration of removing water})$, as shown in Figure 10.

Where: time integration of removing water is the interval time where $RH_{indoors} > RH_{max}$.

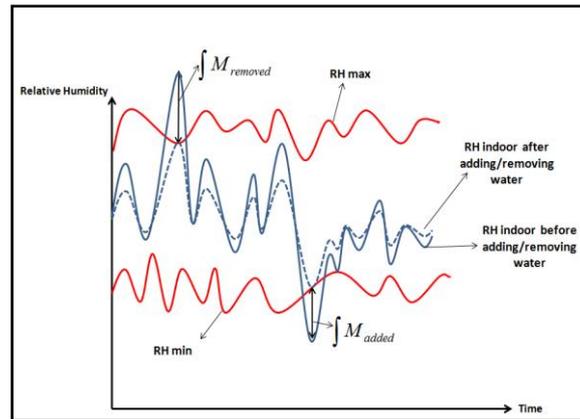


Figure 9: Control of indoor relative humidity

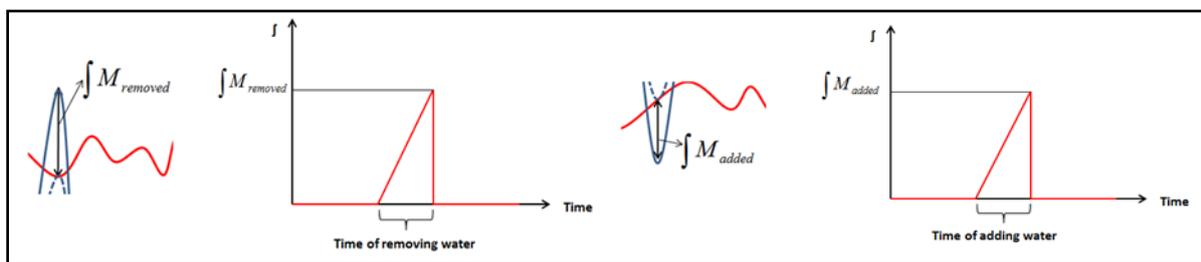


Figure 10: Calculate $M_{removed}$, M_{added}

Control indoor relative humidity $RH_{indoors}$ can be done by the quantity $M_{added/removed}$ which determines the amount of water must be added/removed to/from indoor air, so that maintain the desired indoor relative humidity.

If *relative humidity indoor no conditioning* < *minimum level*, signal control must be sent so that adding water process begins.

If *relative humidity indoor no conditioning* > *maximum level*, signal control must be sent so that removing water process begins.

If *maximum level* > *relative humidity no conditioning* > *minimum level*, there is no signal control.

This strategy is shown in Figure 11.

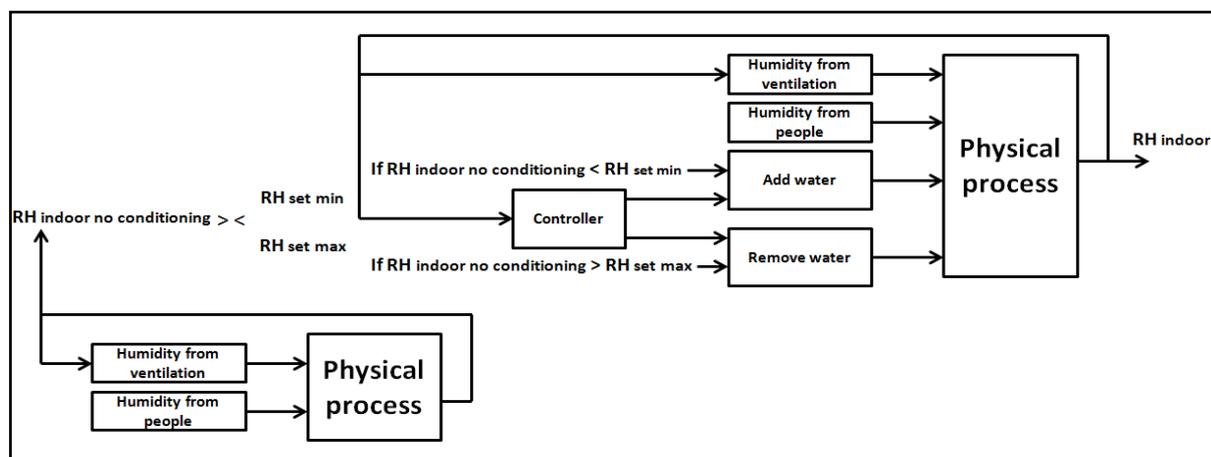


Figure 11: Scheme proposed strategy to control humidity indoor

7 VALIDATION AND RESULTS

The results have been compared with the results recorded by a monitoring system installed in the building “Honeywell Enterprise Buildings Integrator (EBI)” [31].

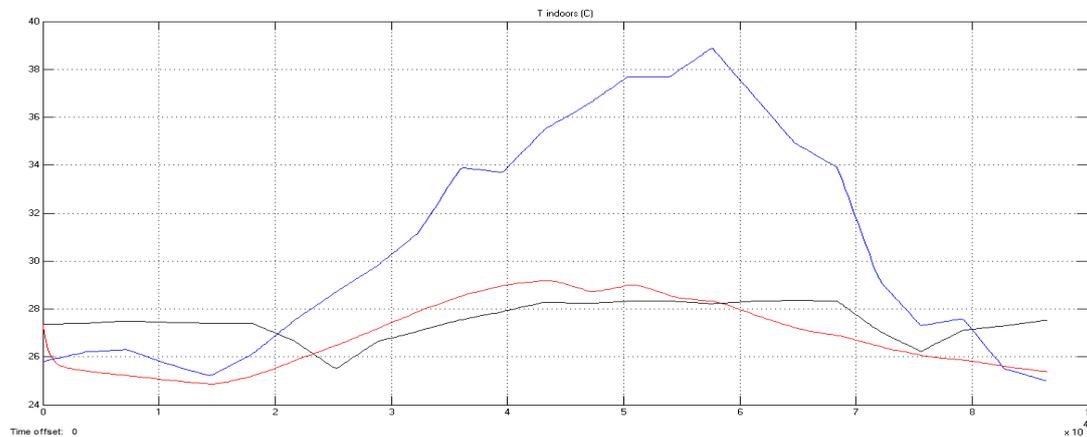
The results are as follows:

First, results will be displayed for a day of non-air-conditioned, and without occupancy.

August 8/8/2013

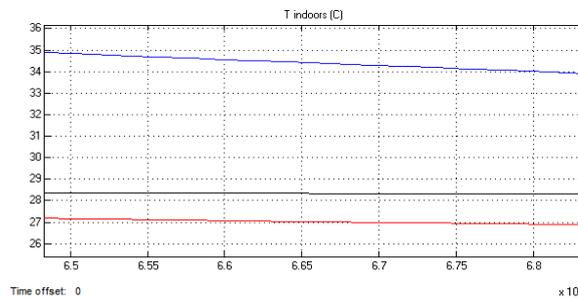
Period	16:00:00-18:40:00
mass flow of supply air	0kg/s
mass flow of fresh air (base rate)	0kg/s
maximum conditioner temperature	-
number of occupants	0

Results of the whole day



Red: simulation result
 Black: values monitored by Honeywell system
 Blue: outdoor temperature obtained by TUBO station

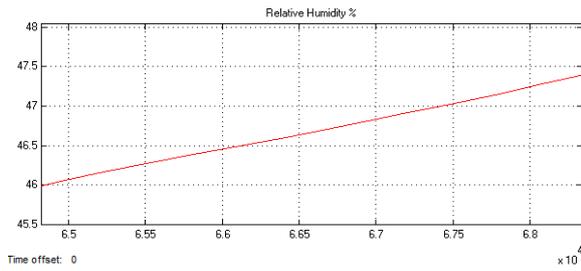
Results of the period specified above in the table (It is the method which will be used in all results)



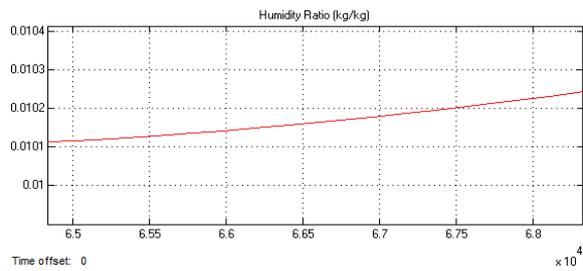
Red: simulation result
 Black: values monitored by Honeywell system
 Blue: outdoor temperature obtained by TUBO station

Modelling temperature

Relative humidity

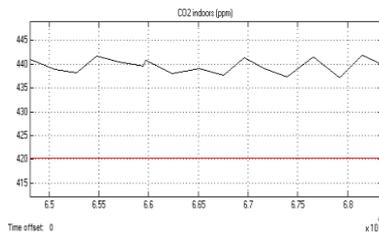


Humidity ratio



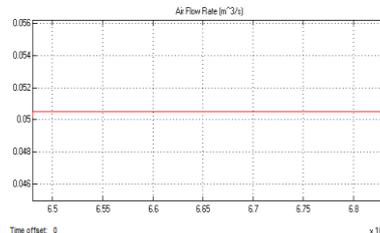
Modelling humidity

CO₂ concentration [ppm]



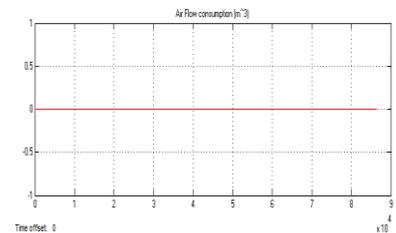
Red: simulation result
Black: values monitored by Honeywell system

Air flow rate [m³/s]



Red: simulation results

The total amount of fresh air supplied into the classroom [m³]



Red: simulation results

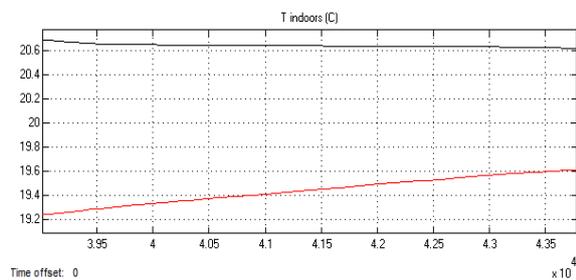
Modelling ventilation

Mild day, with occupancy 37%

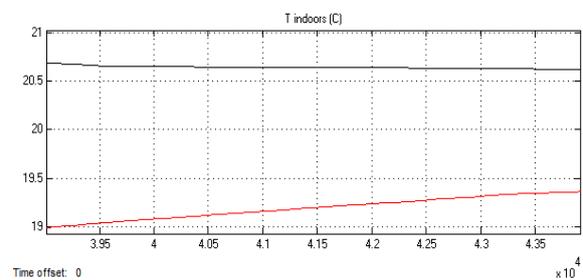
October 22/10/2012

Period	10:50:00-12:13:00
mass flow of supply air	3 kg/s
mass flow of fresh air	1.5 kg/s
maximum heater temperature	21 °C
occupancy	70

Simulation result for the actual strategy used in building

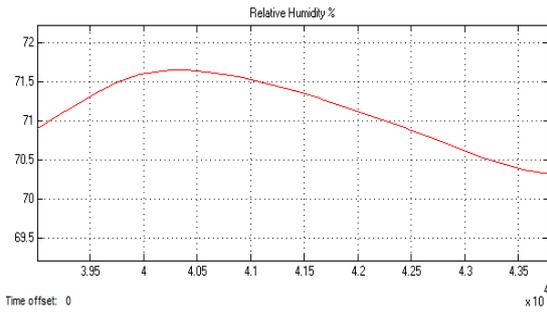


Modelling T_{conditioner}: T_{conditioner} = 20.5 °C

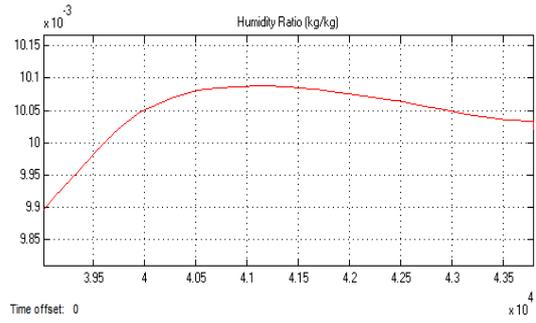


Red: simulation result for the actual strategy used in building
Black: values monitored by Honeywell system

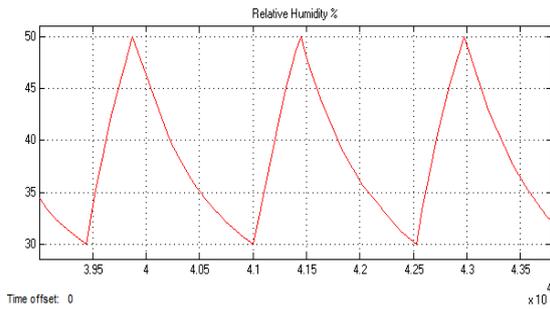
Relative humidity before conditioning



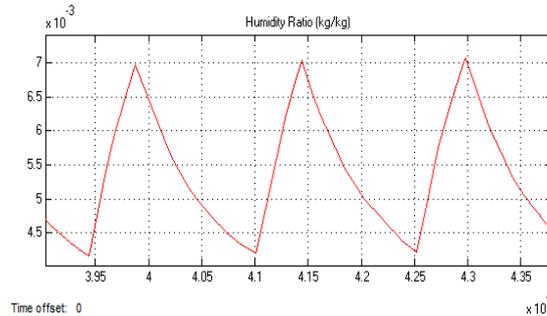
Humidity ratio before conditioning



After conditioning: 0.0053 kg/s removed water

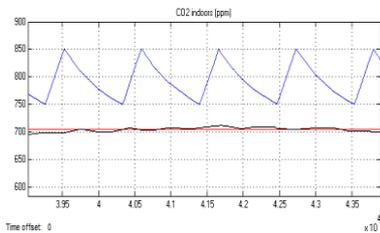


After conditioning: 0.0053 kg/s removed water

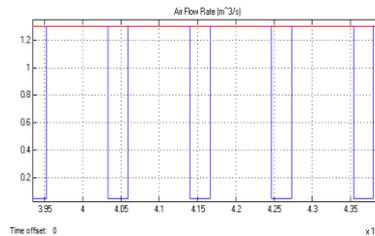


Modelling humidity

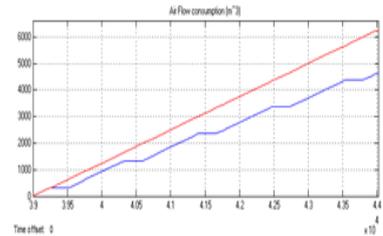
CO₂ concentration [ppm]



Air flow rate [m³/s]



The total amount of fresh air supplied into the classroom [m³]

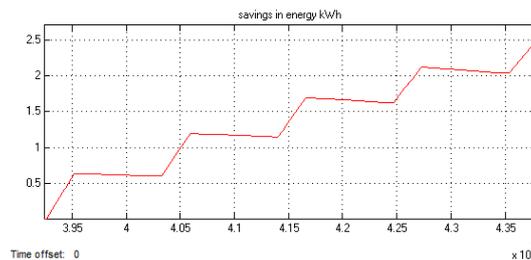


Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
 Red: simulation results for the actual strategy used in building
 Black: Measured values monitored by Honeywell system

Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
 Red: simulation results for the actual strategy used in building

Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
 Red: simulation results for the actual strategy used in building

Modelling ventilation



Savings in energy for heating/cooling by using DCV

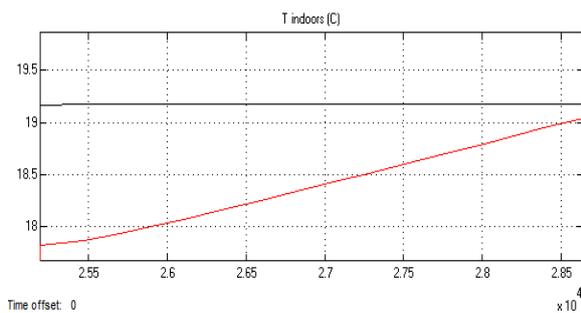
Although the outdoor temperature is mild, but there is a saving in energy, because the size of occupancy is significant. Therefore, there will be a clear impact due to controlling the flow of air based on demand (Demand controlled ventilation), so that the air quality remains within the allowable values.

Cold day and no occupancy, where, fresh air is just the base rate (no need to use DCV)

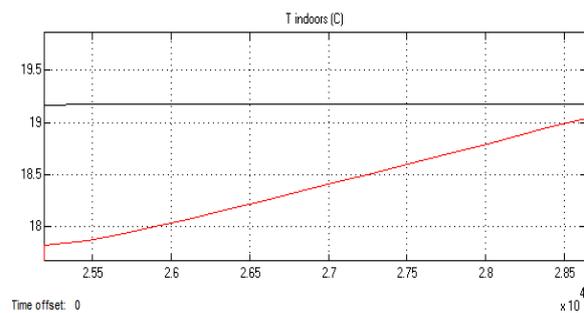
February 21/2/2013

Period	7:00-8:00
mass flow of supply air	0.75 kg/s
mass flow of fresh air (base rate)	0.225 kg/s
maximum heater temperature	46 °C
occupancy	0

Simulation result for the actual strategy used in building



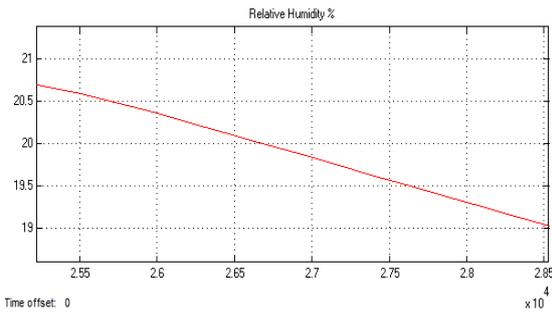
Modelling $T_{\text{conditioner}}: T_{\text{conditioner}} = 46 \text{ } ^\circ\text{C}$



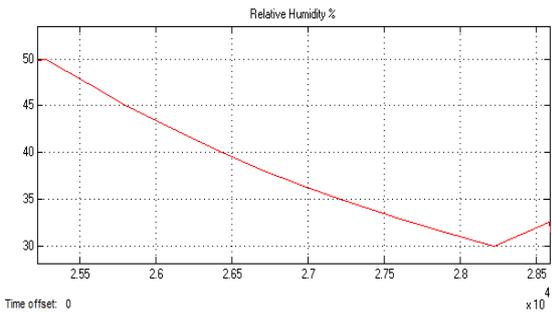
Red: simulation result for the actual strategy used in building
 Black: values monitored by Honeywell system

Modelling temperature

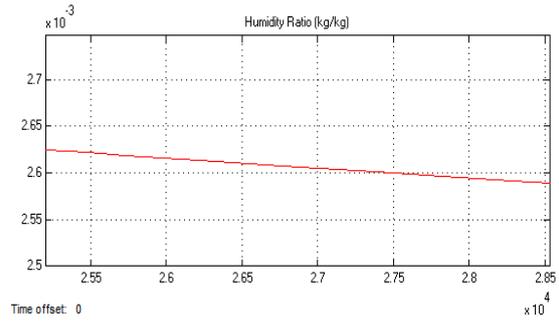
Relative humidity before conditioning



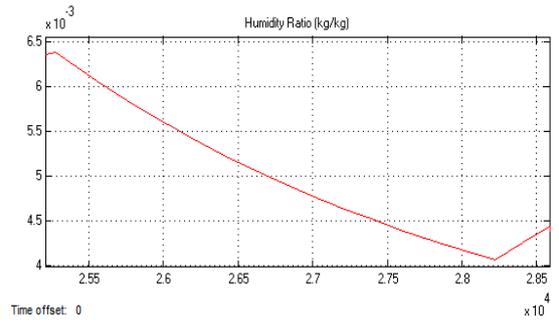
After conditioning: 0.00086 kg/s added water



Humidity ratio before conditioning

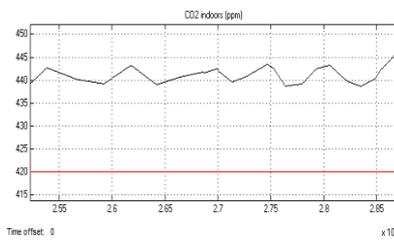


After conditioning: 0.00086 kg/s added water



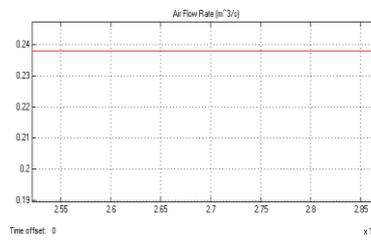
Modelling humidity

CO₂ concentration [ppm]



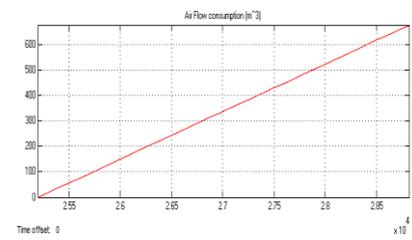
Red: simulation result for the actual strategy used in building
Black: values monitored by Honeywell system

Air flow rate [m³/s]



Red: simulation results for the actual strategy used in building

The total amount of fresh air supplied into the classroom [m³]



Red: simulation results for the actual strategy used in building

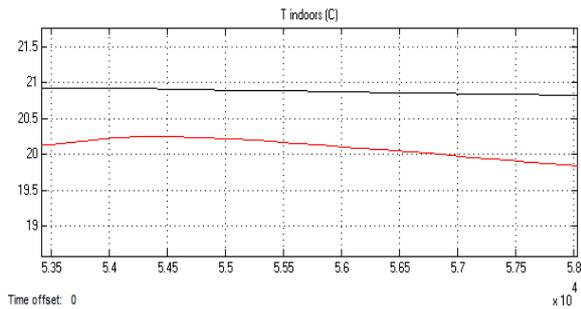
Modelling ventilation

Mild day, with occupancy 2%

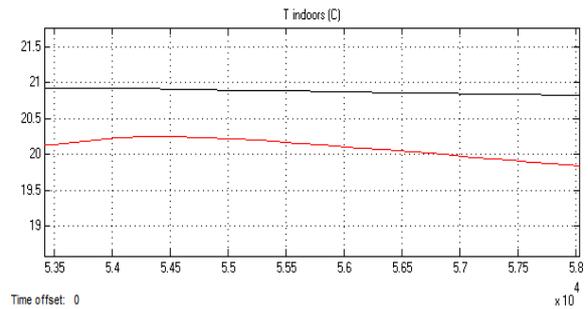
May 7/5/2013

Period	14:51:00-16:13:00
mass flow of supply air	0.75kg/s
mass flow of fresh air	0.225 kg/s
maximum heater temperature	21 C (no heating nor cooling)
occupancy	4

Simulation result for the actual strategy used in building



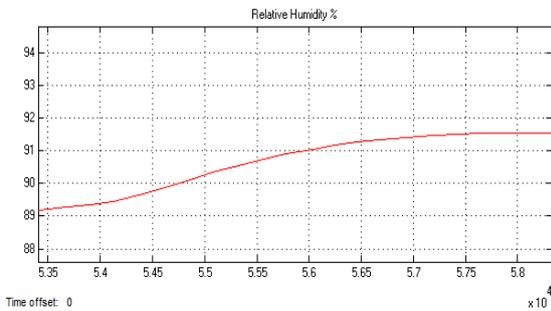
Modelling $T_{conditioner}$: $T_{conditioner} = 21^{\circ}C$



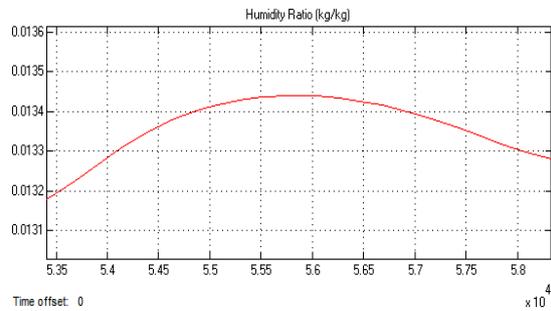
Red: simulation result for the actual strategy used in building
Black: values monitored by Honeywell system

Modelling temperature

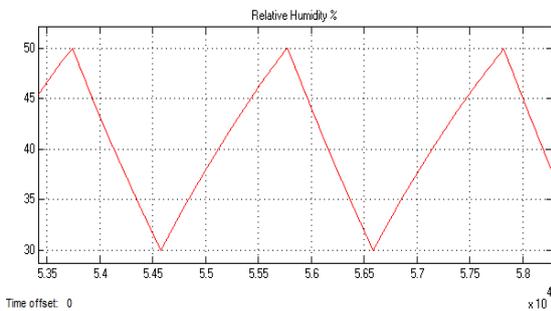
Relative humidity before conditioning



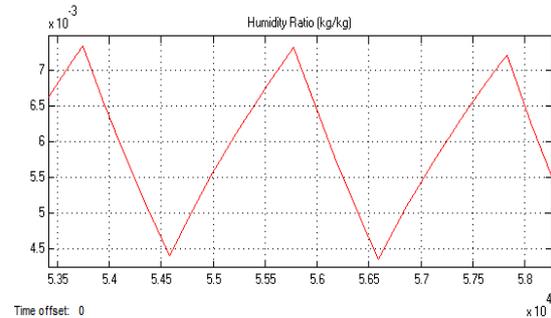
Humidity ratio before conditioning



After conditioning: 0.0033 kg/s removed water

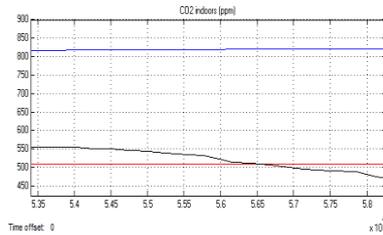


After conditioning: 0.0033 kg/s removed water



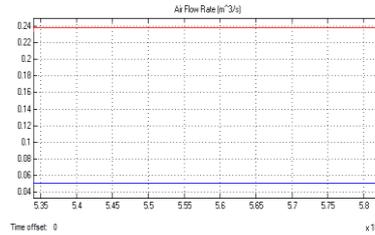
Modelling humidity

CO₂ concentration
[ppm]



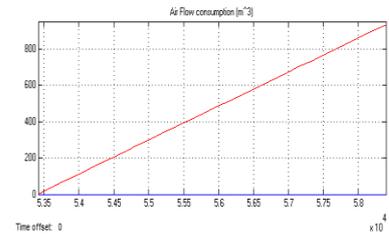
Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
Red: simulation results for the actual strategy used in building
Black: Measured values monitored by Honeywell system

Air flow rate
[m³/s]



Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
Red: simulation results for the actual strategy used in building

The total amount of fresh air supplied into the classroom
[m³]



Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
Red: simulation results for the actual strategy used in building

Modelling ventilation

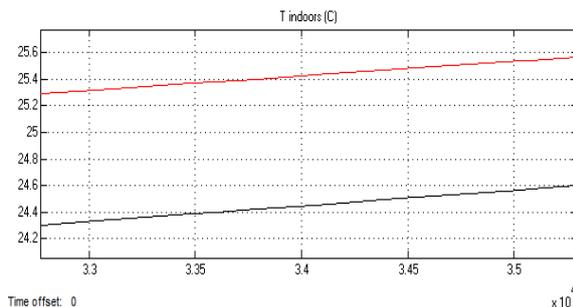
As long as there is no air conditioning, the use of DCV strategy has no effect on energy consumption, although there are savings in air consumption.

Hot day, with occupancy 18%

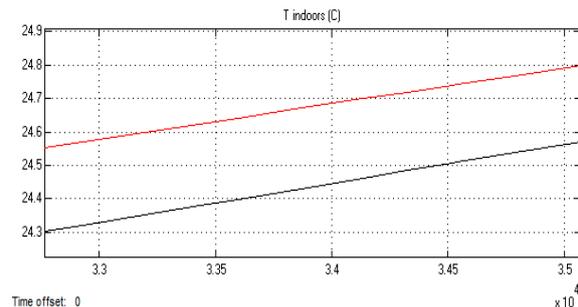
June 20/6/2013

Period	9:06:00- 9:50:00
mass flow of supply air	3 kg/s
mass flow of fresh air	1.26 kg/s
conditioner temperature	19 °C
number of occupants	34

Simulation result for the actual strategy used in building



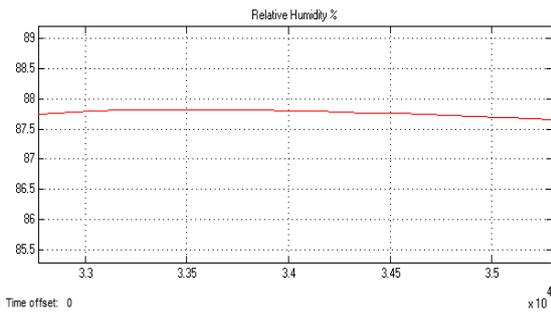
Modelling T_{conditioner}: T_{conditioner} = 17.5 °C



Red: simulation result for the actual strategy used in building
Black: values monitored by Honeywell system

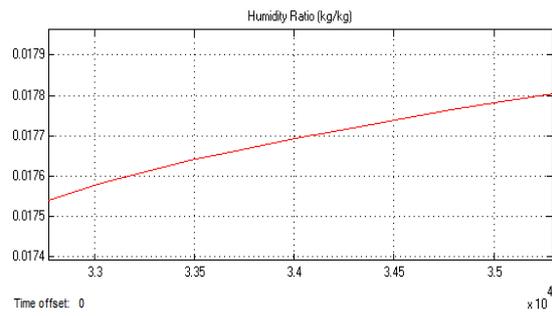
Modelling temperature

Relative humidity before conditioning

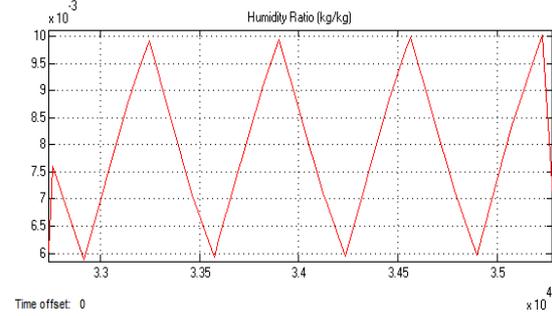
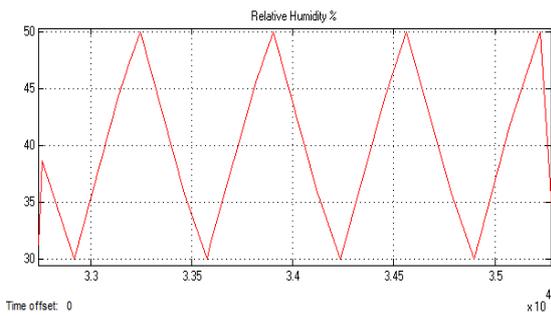


After conditioning: 0.0134 kg/s removed water

Humidity ratio before conditioning

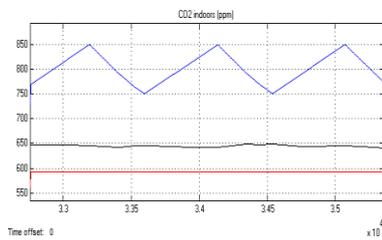


After conditioning: 0.0134 kg/s removed water



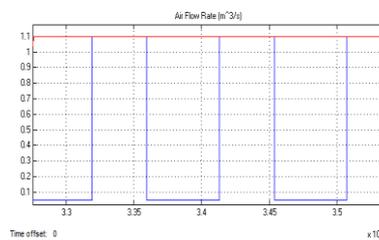
Modelling humidity

CO₂ concentration [ppm]



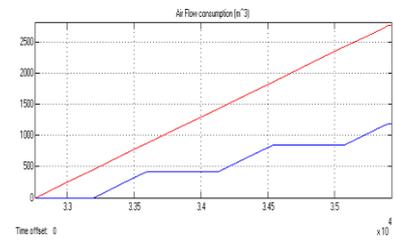
Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
 Red: simulation results for the actual strategy used in building
 Black: Measured values monitored by Honeywell system

Air flow rate [m³/s]



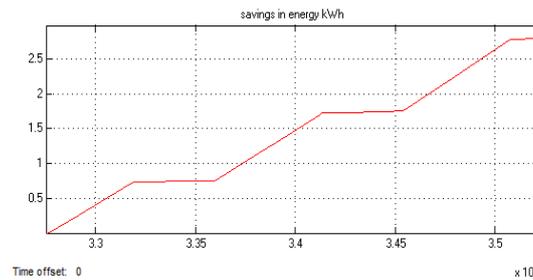
Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
 Red: simulation results for the actual strategy used in building

The total amount of fresh air supplied into the classroom [m³]



Blue: simulation results of DCV for CO₂ setpoint 800 ± 50 ppm
 Red: simulation results for the actual strategy used in building

Modelling ventilation



Savings in energy for heating/cooling by using DCV

The savings in fresh air supplied into the classroom and the savings in energy are significant, because conditioning of hot air requires more energy. Hence, DCV strategy has a significant impact on energy consumption for cooling.

8 CONCLUSION

The basic physical processes within classrooms with different sizes of occupancy have been modelled using MATLAB/SIMULINK software. In order to accomplish this task, the outdoor boundary conditions had to be specified with the used of weather data obtained from the meteorological station in Brno (TUBO). These data have been converted into other form readable in the designed model. The data which have been converted into MAT files are outdoor temperature and relative humidity, so that become ready to be used directly, through exporting them to the model.

With regard to the values of the intensity of solar radiation, a sub-model has been designed by using TRNSYS software to calculate the intensity of solar radiation incident on the walls of the building, with the help of the values of temperature, relative humidity and the intensity of solar radiation taken from the meteorological station.

Modelling the indoor temperature is based on the principle of conservation of energy. The main flows of energy to and from the building through the envelope have been modelled, taking into account the internal thermal loads. Then, control strategy to control temperature using an ON-OFF controller has been designed, so that it works for heating/cooling processes, as it is required, at the same time. In direct signal, it controls heating process. After reversing of control signal, it controls cooling process, taking into account that the criterion to begin to control temperature inside the room are conditions after using supply air, but in absence of heating or cooling.

Modelling the concentration of carbon dioxide is based on the principle of conservation of mass, where, the main flows of air to and from the building have been modelled with the amount of carbon dioxide carried by these flows. Then two different control strategies have been modelled: first is the traditional strategy, while the second is demand controlled ventilation (DCV). DCV strategy uses fresh air only when the concentration of carbon dioxide reaches to the limit values. This way leads to savings in energy needed for air conditioning.

Modelling humidity is based on the principle of conservation of mass, where, the main flows of air to and from the building have been modelled with the amount of water vapour carried by these flows, taking into account the amount of water vapour originating from the people inside. Then depending on the moisture content of the maximum and minimal levels, an approximate method has been modelled to calculate the rate of water which must be added or removed, to keep relative humidity within the allowed range.

To determine the validity of the model, simulation results have been compared with the actual results taken by monitoring system installed inside the classroom known as EBI system (Enterprise Buildings Integrator).

The results have shown that the values of temperature, relative humidity and concentration of carbon dioxide within the classroom are close to the recorded values with variations that do not exceed ten percent of the maximum level. The results have shown that DCV strategy

can save the energy used for heating/cooling. The amount of savings basically depends on the size of occupancy and climatic conditions outdoors. Where, in mild weather, the savings in energy are low, especially for low occupancy. While in hot/cold weather, the savings in energy are significant, even for low occupancy.

References

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- [2] Fu, G. *A Transient 3-D Mathematical Thermal Model for the Clothed Human*. Ph.D. thesis, Kansas State University, 1995.
- [3] Office of Environmental Health. *Public Health Evaluation of Indoor Air Quality, Self-Reported Illnesses, and Tumors Corona del Sol High School, Tempe, Arizona*. Arizona. 2008.
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Abstract

Maintaining of the indoor climate conditions so that they keep compatible with the occupants comfort is a key issue for control of heating, ventilation and air conditioning systems (HVAC systems). Computer modelling offers a virtual environment similar to real climatic conditions indoors and outdoors. It aims basically to devise solutions for control of indoor climatic conditions. This process requires understanding of these environments from physical and mathematical perspective, so that physical processes of these environments can be represented using relationships and equations which can reflect the influence of different environmental parameters. Then simulation process offers the possibility to describe the interaction between these models and their behaviour over time. It gives default representation of those environments and allows understanding of their behaviour before transferring these models to real applications. MATLAB/SIMULINK software has an advanced ability to simulate HVAC systems by creating a wide working environment for the designers depending on the development of mathematical models and simulating them by SIMULINK so that results output could be compatible with the desired conditions. This thesis addresses the process of modelling the indoor environment in buildings in order to understand the behaviour of key parameters which affect the thermal comfort of the occupants. The mathematical models of the indoor environment of a classroom have been designed with three basic indoor parameters: concentration of carbon dioxide, air temperature and relative humidity. Changes of these parameters over time have been simulated. Then, control strategies have been proposed for these parameters in order to keep them under the appropriate conditions of the occupants, although changing of climate outdoors, thermal and mass loads indoors. Through mathematical methods, some optimization methods have been proposed in order to reduce energy consumption without affecting the permissible limits of these parameters. Validation process of the model has been carried out by comparing the results with the real outputs monitoring by Honeywell Enterprise Buildings Integrator system installed in the classroom.

Abstrakt

Udržování vnitřních klimatických podmínek tak, aby byly v souladu s tepelným komfortem lidí, je klíčovou otázkou pro řízení systémů vytápění, větrání a klimatizace (HVAC systémy). Počítačové modelování nabízí virtuální prostředí pro simulaci vnitřních i vnějších podmínek a s jeho pomocí je možné navrhnout řešení pro řízení technických zařízení budov. Tento proces vyžaduje pochopení těchto prostředí z fyzikálního a matematického hlediska tak, aby bylo možné fyzikální procesy daných prostředí reprezentovat pomocí vztahů a rovnic odrážejících jejich různé parametry. Simulační proces dále nabízí možnost popsat interakci mezi těmito modely a jejich chování v čase, dává výchozí reprezentace těchto prostředí, a umožňuje pochopení jejich chování před přenosem těchto modelů do reálných aplikací. Simulace umožňuje respektovat, a ovlivňovat jejich chování přes kontrolu navržených modelů. MATLAB/SIMULINK software má pokročilé schopnosti pro simulace systémů HVAC, a to vytvořením širokého pracovního prostředí pro designéry v závislosti na vývoji matematických modelů a jejich simulace pomocí SIMULINK, aby výsledky mohly být slučitelné s požadovanými výstupy. Tato dizertační práce se zaměřuje na proces modelování vnitřního prostředí v budovách, aby bylo možné pochopit chování klíčových parametrů, které mají vliv

na tepelnou pohodu obyvatel či uživatelů, matematické modely vnitřního prostředí posluchárny byly navrženy speciálně pro tři základní parametry: koncentrace oxidu uhličitého, teplota vzduchu a relativní vlhkost. Změny chování těchto parametrů v průběhu času jsou simulovány a poté strategie kontroly návrhu těchto parametrů může je udržet ve vhodných rozmezích komfortních pro obyvatele či uživatele, i když změny venkovního klimatu, tepelné a hmotnostní zatížení interiéru. Pomocí matematických metod, některé optimalizační metody byly navrženy za účelem snížení spotřeby energie bez vlivu na mezní hodnoty těchto parametrů. Proces validace modelu se provádí porovnáním výsledků s reálnými výstupy monitoringu Honeywell Enterprise Buildings Integrator systémem (EBI) nainstalovaným v areálu univerzity.