Building Simulation 2009

Eleventh International IBPSA Conference
Glasgow, Scotland
July 27-30, 2009

INTEGRATED CALCULATIONS OF THERMAL BEHAVIOUR OF BUILDINGS AND PROCESSES IN AHU - THE TOOL FOR ASSESSMENT OF ENERGY PERFORMANCE OF COMPLEX BUILDINGS

Maciej Mijakowski[1], Piotr Narowski[2], and Jerzy Sowa[3]
Faculty of Environmental Engineering, Warsaw University of Technology, Poland
[1]e-mail: maciej.mijakowski@is.pw.edu.pl
[2]e-mail: piotr.narowski@is.pw.edu.pl
[3]e-mail: jerzy.sowa@is.pw.edu.pl

ABSTRACT

The paper presents the concept of integrated calculations of both thermal behaviour of buildings and processes of air treatment that take place in air handling units – AHU. The model of thermal behaviour of building is based on simplified hourly method described in EN ISO 13790:2007. Standard EN 15241:2007 was the basis for submodels describing higrothermal processes in ventilation and air-conditioning systems. Integration resulted in conversion of 5R1C schema to 6R1C and further in introduction of optional equations for different types of HVAC systems. Presented method is both: simply enough to be implemented to spread sheets (eg. Excel) and accurate enough for assessment of annual energy use in real complex buildings. The example of simulation for an office building confirmed that type of HVAC system (mechanical exhaust ventilation, water-air air conditioning system and all-air constant air volume CAV air conditioning system) has essential influence on energy consumption as in some cases energy use in AHU may be much higher than energy loads themselves.

INTRODUCTION

Overview

Implementation of EU Directive on Energy Performance of Building (EPBD) requires that each EU member state has to develop methodology for assessment of energy performance of different types of buildings, including those equipped with advanced systems of control of both thermal comfort and indoor air quality. These methodologies have to pay special attention to ventilation and air conditioning systems. First reason is due to the fact that they deal not only with control of temperature but also control of humidity. Although CEN standards related to Energy Performance of Buildings calculations suggest to avoid control of humidity, in Polish climate with variation of humidity ratio from 0.6 g/kg in winter time to 12 g/kg in summer some control of humidity is necessary. Otherwise relative humidity can vary from 15 % to 85 % (exceeding acceptable 30-70% range). Second reason is because air systems in comparison with some other building systems has low inertia and fast respond to disturbances. Moreover in some cases (e.g. variable air volume systems - VAV and demand controlled ventilation - DCV) performance of these systems is closely related to behaviour of building.

Taking all this into consideration authors are convinced that not monthly but at least hourly simulation of both building behaviour and system performance can properly assess energy use in complex buildings with advanced air systems.

Lumped Capacitance method and its electric analogue

One of most popular procedures of determining the time dependence of the temperature distribution within solid during transient process is a comparatively simple approach termed lumped capacitance method. The essence of this method is assumption that the temperature of the solid is spatially uniform at any instant during the transient process. This assumption implies that temperature gradients within the solid are negligible. The solid may be as small as the stone or as big as whole building.

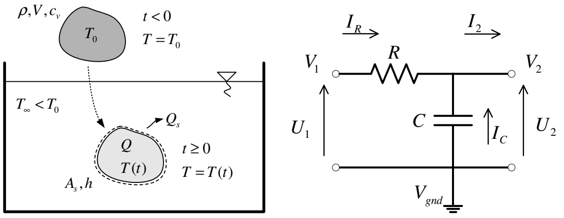

Figure 1 Sudden change of solid environment parameters and its analogue low-pass RC filter

The common example of application of the lumped capacitance method in the heat exchange is description of solid cooling during sudden change of its environment. The governing equation of this process is ordinary differential equation (1), where C is the heat capacitance, H is the heat transfer coefficient from the surface of the solid and θ is the temperature difference between internal solid temperature and environment temperature.

$$\begin{gathered}\rho V c_v \frac{d\Theta(t)}{dt} = -hA_s\Theta(t), \\ C\frac{d\Theta(t)}{dt} = -H\Theta(t),\end{gathered} \tag{1}$$

There is analogue equation in the electric circuits' theory describing RC filter composed of resistors and capacitors driven by a voltage or current source.

$$\frac{dV_2(t)}{dt} = -\frac{1}{RC} V_2(t). \tag{2}$$

Natural response of the simplest RC circuit, capacitor and a resistor connected in series is governed by linear differential equation (2). Circuit composed of only a charged capacitor and a resistor, discharge capacitor energy into the resistor. This voltage across the capacitor over time could be found through *Kirchhoff's* current law, where the current coming out of the capacitor must equal the current going through the resistor. The lumped capacitance method is useful to create the 2R1C building heat exchange model (Fig.2).

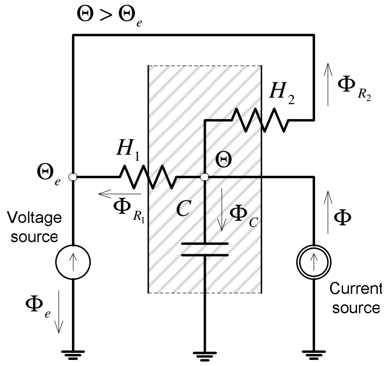

Figure 2 The building 2R1C heat exchange model

Solving the linear ordinary differential equation with modified *Euler* method leads to linear equation (3). The temperature of building construction in current instant depends on its temperature in previous moment. The constants in this equation are the building capacitance C, heat transfer coefficients H_1, H_2 and time step τ. The energy flux Φ can be transient during calculation.

$$\Theta_n = \frac{\Theta_{n-1}\left(\frac{C}{\tau} - \frac{1}{2}\left(H_1 + H_2\right)\right) + \Phi}{\frac{C}{\tau} + \frac{1}{2}\left(H_1 + H_2\right)}. \tag{3}$$

Increase of stability and accuracy of calculation is achieved with *Crank-Nicholson* method. This technique approximates the temperature of building construction in current time step as mean value of temperature calculated for current and previous time interval.

$$\bar{\Theta}_n = \frac{1}{2}\left(\Theta_n + \Theta_{n-1}\right) \tag{4}$$

The 6R1C model of building heat dynamic

Simplified hourly method for estimation of annual energy use in building presented in standard EN ISO 13790:2007 is based on the lumped capacitance method. The 5R1C model specified in this standard does not contain separated ventilation air flux with a controlled supply temperature and infiltration flux of external air. Modified 6R1C model presented on Figure 3 has two streams of air coming into building – controlled ventilation and uncontrolled infiltration. This model has still many similarities with the 2R1C model (fig. 2). In 6R1C model heat resistance R_2 is replaced by five heat resistances, which allows user to determine additional temperatures of internal surface temperature of building construction and internal building air temperature. The model allows to supply the heat energy to three nodes – to interior of building construction, to the internal surface of building construction and to indoor air.

The potentials θ in the nodes are θ_e – the external air temperature, θ_v – the ventilation air temperature, θ_m – the building construction temperature in lumped capacitance method, θ_s – the temperature of internal surface of building contracture, θ_i – internal air temperature.

Resistances of the electric 6R1C circuit are equivalent of heat resistances in building: R_{Tr1} – heat transfer resistance of outside construction building part, R_{Tr2} – heat transfer resistance of internal part of construction, R_S – heat convection resistance of internal surface of building construction, R_W – external windows and doors heat transfer resistance, R_{Ve} – heat transfer resistance of controlled ventilation air stream, R_{Vi} – heat transfer resistance of uncontrolled infiltration air stream.

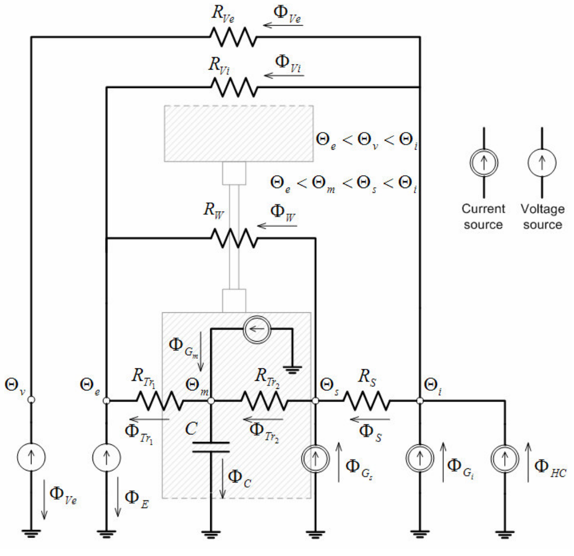

Figure 3 The building 6R1C heat exchange model

Electric currents supplying the circuit of the 6R1C model are equivalent of internal heat gains and energy delivered by building heating or cooling system. The energy streams Φ are: Φ_{Tr1} – heat flow through the external surface of building opaque envelope, Φ_{Tr2} – heat flow through the internal surface of building opaque envelope, Φ_C – heat flow accumulated in building construction, Φ_S – convection heat flow from internal surface of building construction to internal air, Φ_W – heat flow transferred through external windows and doors, Φ_{Ve} – heat flux carried with controlled ventilation air, Φ_{Vi} – heat carried with infiltration air.

There are six ideal energy sources in the scheme of the building model. The potential θ_e modelled by the ideal voltage source is the equivalent of varying external temperature. The temperature of ventilation air supplied to buildings rooms is modelled by ideal voltage source of potential θ_v. Another energy streams feeding the circuit are ideal current sources. They represent solar and internal heat gains and heat delivered by heating or cooling system to building. The source current Φ_{HC} corresponds to system heat. The currents Φ_{Gi}, Φ_{Gs} and Φ_{Gm} represents energy of solar and internal heat gains divided into three parts and balanced in the internal air, the internal surface of building construction and the mass of building.

The determination of transient potentials and branch currents in the circuit is possible after transformation of the circuit of five resistors to get the substitute of H_2 conductance. Introducing replacing conductance of the resistors in the circuit:

$$H_{Z_1} = \frac{H_S H_{Ve}}{H_S + H_{Ve} + H_{Vi}}, \tag{5}$$

$$H_{Z_2} = \frac{H_S H_{Vi}}{H_S + H_{Ve} + H_{Vi}}, \tag{6}$$

$$H_{Z_3} = H_{Z_1} + H_{Z_2} \quad \text{and} \tag{7}$$

$$H_{Z_4} = H_{Z_3} + H_W, \tag{8}$$

it is possible to calculate the replacing conductance $H_2 \equiv H_{Z5}$:

$$H_{Z_5} = \frac{H_{Tr_2} H_{Z_4}}{H_{Tr_2} + H_{Z_4}}. \tag{9}$$

The reduction of the 6R1C circuit to 2R1C scheme is possible with superposition principle. The current $\Phi \equiv \Phi_{mtot}$ generated by all energy sources except the capacitor must be determined to use the equation 3.

Calculation of Φ_{mtot} current is possible assuming that the circuit is a DC circuit (Fig. 4) in one time step powered by all ideal energy sources Φ_{HC}, Φ_{Gi}, Φ_{Gs}, Φ_{Gm} and θ_v, θ_e except the capacitor energy. In accordance with superposition principle if the circuit is powered by one source, other voltage sources must be short-circuited and current sources must be cut off. The potential of $\theta_{m,n}$ in present time is calculated from formula:

$$\Theta_{m,n} = \frac{\Theta_{m,n-1}\left(C/3600 - 0,5\left(H_{Tr_1} + H_{Z_5}\right)\right) + \Phi_{mtot}}{C/3600 + 0,5\left(H_{Tr_1} + H_{Z_5}\right)}. \tag{10}$$

This potential represents the temperature of building construction calculated with one hour time step.

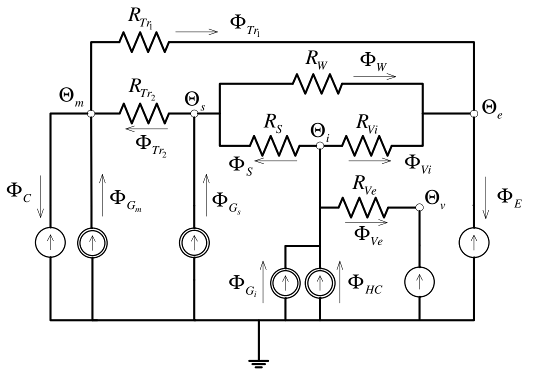

Figure 4 Substitute 6R1C DC circuit for one time step

Total current Φ_{mtot} in the θ_m node generated by Φ_{HC}, Φ_{Gi}, Φ_{Gs}, Φ_{Gm} and θ_v, θ_e ideal current and voltage energy sources in the DC circuit presented on Figure 4 equals:

$$\Phi_{mtot} = \Phi_{G_m} + H_{Tr_1}\Theta_e + \frac{H_{Z_5}}{H_{Z_4}}\left(\begin{array}{l}\Phi_{G_s} + H_{Z_1}\left(\dfrac{\Phi_{HC} + \Phi_{G_i}}{H_{Ve}} + \Theta_v\right) + \\ + \left(H_{Z_2} + H_W\right)\Theta_e\end{array}\right) \tag{11}$$

After determining all branch currents in that circuit, it is possible to calculate the potential θ_s with first *Kirchhoff's* current law.

$$\Theta_s = \frac{H_{Tr_2}\Theta_m + \left(H_{Z_2} + H_W\right)\Theta_e + H_{Z_1}\Theta_v + \Phi_{G_s} + \dfrac{H_{Z_1}}{H_{Ve}}\left(\Phi_{HC} + \Phi_{G_i}\right)}{H_{Tr_2} + H_{Z_4}} \tag{12}$$

The calculated potential θ_s is necessary to determine the potential θ_i representing the internal air temperature.

$$\Theta_i = \frac{H_S\Theta_s + H_{Vi}\Theta_e + H_{Ve}\Theta_v + \Phi_{HC} + \Phi_{G_i}}{H_S + H_{Vi} + H_{Ve}} \tag{13}$$

Concept of AHU calculation's method

Behaviour of ventilation and air-conditioning systems and calculations of energy use for preparation of outside air in AHU are based on EN 15241 "Ventilation for buildings – Calculation methods for energy losses due to ventilation and infiltration in commercial buildings". The main idea is to calculate the energy needed for transferring the air parameters from outdoor conditions to required values at supply (fig. 5).

The following processes were taken into account:

- heat recovery (sensible and latent) during winter and summer,
- heating,
- humidifying,
- cooling,
- dehumidifying,
- preheating and precooling of air in ground heat exchanger.

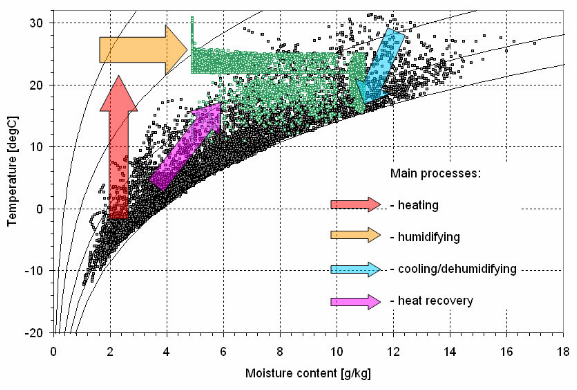

Figure 5 The main idea of AHU calculation's method

Submodels of air treatment processes provide energy consumption (if any, for example heat recovery does not need energy – the additional energy for fans etc. is calculated separately) and air parameters modified by the process. Although the equations describing processes are simple and well know (for example from EN 15241) the annual behaviour of AHU may be quite complex. The advanced logical analysis (the substitution of control system modelling) is often necessary. The quantitative and qualitative changes of processes can be forced by both weather changes and variations of building loads. At the same time the available processes are limited by the level of functionality of HVAC system.

SIMULATIONS

The simulation of annual energy consumption in office was used to present the usability of developed model. Selected building located in Warsaw (Poland) has a heavy construction (big thermal capacitance). Building occupied by 400 persons has total area of 3640 m^2 and volume of 10920 m^3.

Heating and cooling loads were calculated assuming technologies (construction materials, windows etc.) commonly used in Poland, typical office equipment and typical profiles of operation (from 7.00 a.m. to 8 p.m.). The set point for heating was assumed as 21°C (16°C when building is not used) while set point for cooling was assumed as 26°C. For systems that can control humidity following set points were used: for humidification 30%, for dehumidification 65%.

The calculations were made for several variants of HVAC systems. Three presented in this paper are:

- variant 1 (NO AHU) constant exhaust mechanical ventilation (20 000 m^3/h) only during operating hours, control of indoor temperature depends on heating/cooling systems (water or direct expansion),
- variant 2 (HIG AHU) balanced mechanical ventilation with full option of air treatment in AHU, constant air flow rate based on hygienic needs (20 000 m^3/h) only during operating hours, control of indoor temperature depends on heating/cooling systems (water or direct expansion) while AHU provides control of humidity,
- variant 3 (FULL AHU) all air constant air volume (CAV) air conditioning system, airflow rate (60 000 m^3/h) during operating hours, control of indoor temperature during operation hours depends fully on AHU, but in winter time when the building is not used minimal temperature of 16°C is kept with help of additional hydronic heating system.

Air handling units in variants 2 and 3 include option of heat recovery (rotary heat exchanger) with nominal efficiency 90%. To avoid problems with frost control system does not allow to cool down exhaust air below -5 °C. Humidity is not recovered from exhaust air. During hot period heat exchanger is not used.

Additionally it is assumed that air infiltration is ~ 0,1 h^{-1} (only for variants with AHU).

The indoor temperature for each variant of HVAC is presented on fig. 6. The energy consumption during a typical year is presented in table 1 and on fig. 7.

Table 1
Energy consumption for analysed variants

	NO_AHU	**HIG_AHU**	**FULL_AHU**
Energy delivered to rooms directly by heating/cooling system [kWh/year]			
Heating	635612	35126	6199
Cooling	-49405	-65077	0
Energy delivered to AHU [kWh/year]			
Heating	0	81235	270318
Humidifying	0	54682	181223
Cooling and dehumidifying	0	-50049	-111648
Total energy consumption [kWh/year]			
Heating	635612	171042	457739
Cooling	-49405	-115126	-111648
Specific total energy consumption [kWh/(m^{2}year)]			
Heating and cooling	188,2	78,6	156,4

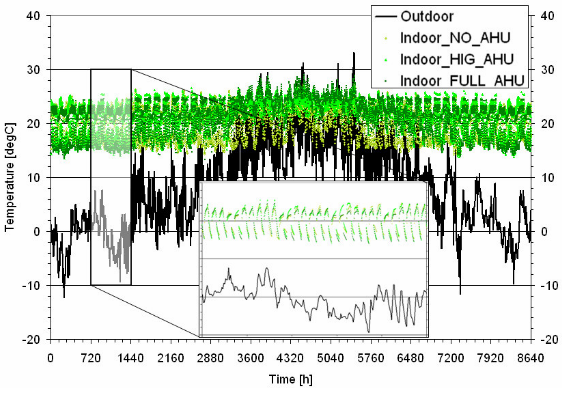

Figure 6 Indoor and outdoor temperature

a)

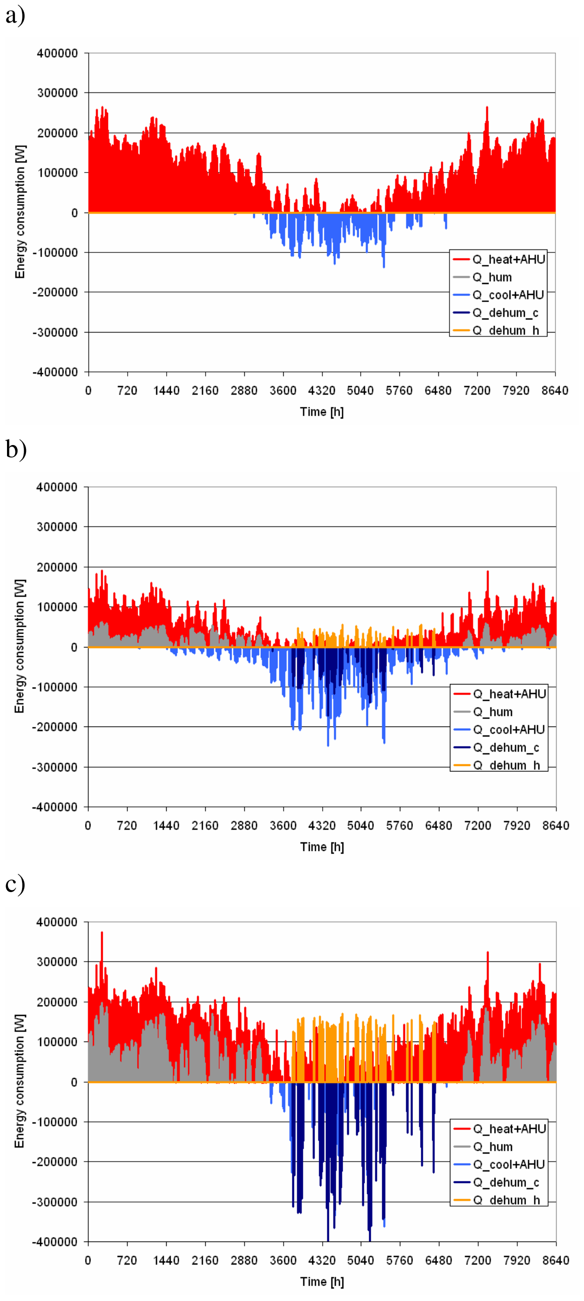

Figure 7 Energy consumption during a typical year for variants: NO AHU (a); HIG AHU (b); FULL AHU (c)

Analysis of hourly power needs for heating and cooling presented on figure 7 shows that analysed variants behave differently during a year. Differences refer not only to peak values but also to duration of heating/cooling periods. It can be observed that the highest heating and cooling needs are in FULL_AHU variant, while the longest cooling period is observed for HIG_AHU.

Charts shows also other specific properties of each system. For instance in FULL_AHU variant it can be observed that extensive cooling resulting form setpoints for dehumidification is accompanied with additional reheating of air supplied to rooms.

RESULT ANALYSIS

The simulations confirmed that type of HVAC system has essential influence of energy consumption and in some cases may be more important than energy loads themselves. Specific total energy consumption varies from 78,6 kWh/(m^{2}year) to 188,2 kWh/(m^{2}year). Huge differences relate not only to total energy use but also to relative amount of energy devoted for different processes.

Of course basic reason is that different HVAC systems offers different levels of functionality. Variant 1 does not offer the possibility of intentional humidification and dehumidification of air. Moreover air is supplied to rooms directly through envelope without preheating that creates potential risk of draught. In variant 2 ~ 57,8% of cooling energy has been delivered to AHU when the setpoint for dehumidification was dominating over setpoint for cooling. In variant 3 this ratio reached 81,4 %. In both variants dehumidification creates also additional needs for heating air before supply to rooms.

Other very important difference is associated with different ventilation rates. Variants 1 and 2 assume 50 m^3/h of outdoor air per person (13,9 l/s per person) while variant 3 assumes 150 m^3/h per person (41,7 l/s per person). This situation results in substantial differences in energy use. On the other hand higher ventilation rates offer a chance to create more productive indoor environment.

Having differences motioned above in mind it is worth to analyze relative energy consumption presented in table 2. Total energy consumption for heating and cooling for variant 2 (HIG_AHU) was selected as reference (100%).

Due to lack of heat recovery variant NO_AHU is characterized by very high energy consumption for heating (~370 % of reference value) and relatively low energy consumption for cooling (~43 % of reference value) due to lack of humidity control. Energy is directly delivered to rooms.

Table 2
Relative energy consumption for analysed variants
(Total energy consumption for variant HIG_AHU =100%)

	NO_AHU	**HIG_AHU**	**FULL_AHU**
Energy delivered to rooms directly by heating/cooling system - relative			
Heating	371,6%	20,5%	3,6%
Cooling	42,9%	56,5%	0,0%
Energy delivered to AHU - relative			
Heating	0,0%	47,5%	158,0%
Humidifying	0,0%	32,0%	106,0%
Cooling and dehumidifying	0,0%	43,5%	97,0%
Total energy consumption -relative			
Heating	371,6%	**100,0%**	267,6%
Cooling	42,9%	**100,0%**	97,0%

Analysis of results for variant 2 (HIG_AHU) indicates that heating energy is basically delivered to AHU. Although set point for humidification was assumed only 30% of relative humidity, ~ 32% of heating energy is used for this purpose. Cooling is realized generally in rooms, while majority of cooling energy delivered to AHU is used for dehumidification.

Variant 3 is characterized by higher energy use for heating (energy used for humidification is higher than total energy use for heating in variant 2). All energy, with small exception for heating rooms in wintertime during breaks in building operation, is delivered to AHU. Total energy use for cooling is lower as higher ventilation rates creates good conditions for “free cooling” during periods of moderate temperatures.

Results can be analysed also from the point of view of total primary energy consumption. However in that case special attention has to be paid to the addition of different types of energies. Buildings generally use more than one energy source (e.g. gas and electricity) and the estimation of total primary energy use has to integrate the losses of the whole energy chain for different types of energy.

In Poland procedures of estimation of the energy performance of buildings introduced due to implementation of EPBD uses the concept of primary energy consumption. Corresponding values of primary resource energy factors used in Poland are (examples): 0 for renewable energies, 1.1 for gas and 3 for electrical power.

Total annual primary energy consumption (calculated using energy factors) for analysed systems vary from 533,5 MWh/year (HIG_AHU) to 847,4 MWh/year (NO_AHU). Variant 3 (FULL_AHU) has similar value 838,5 MWh/year.

These way of calculation leads to values of specific primary energy consumption from 146,6 [kWh/(m^{2}year)] for (HIG_AHU) to 232,8

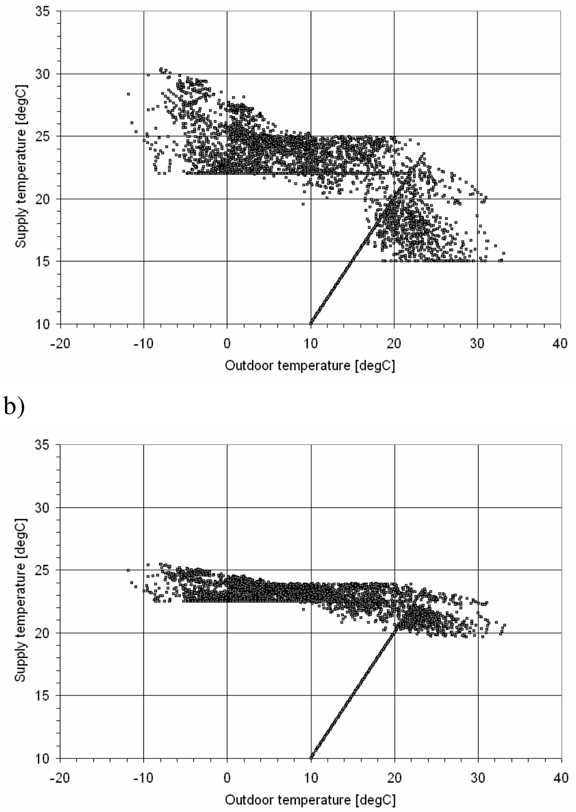

Figure 8 Supply temperature as a function of outdoor temperature for variants: HIG AHU (a); FULL AHU (b)

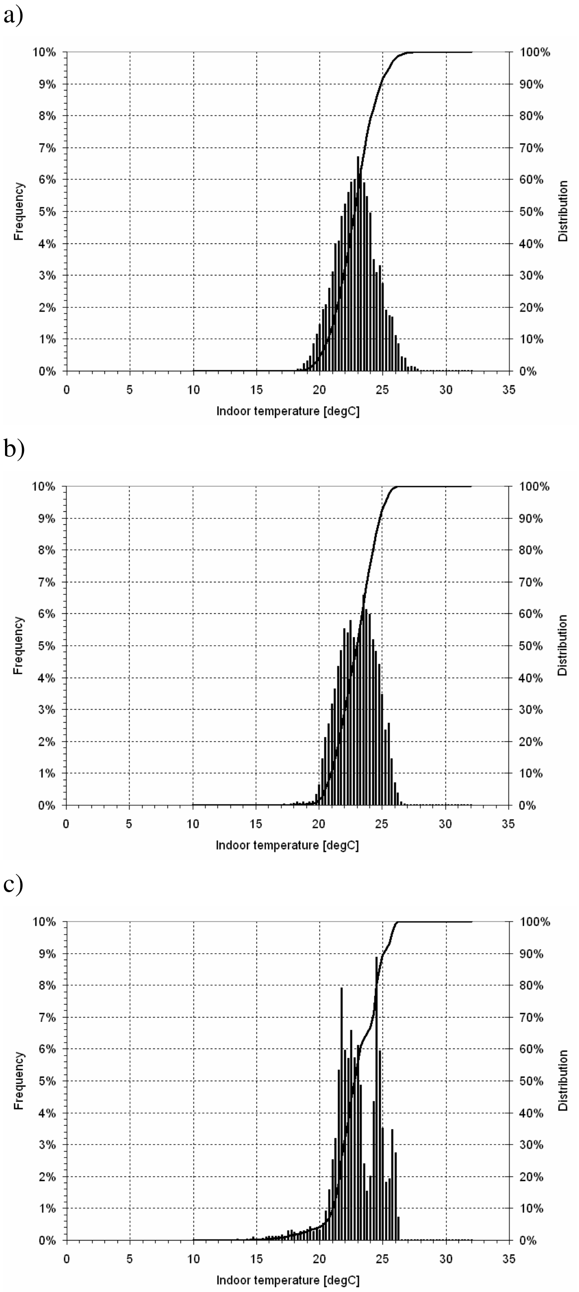

Figure 9 Histograms of indoor temperature variation during operating hours for variants: NO AHU (a); HIG AHU (b); FULL AHU (c)

[kWh/(m^{2}year)] for (NO_AHU). Of course these values are much higher than presented in table 1.

Developed model can be also used for comparison of thermal behaviour of both building and ventilation/air-conditioning system.

The annual performance of AHU may be investigated on charts presenting analysed parameter as a function of outdoor temperature (fig. 8). On this figure one may identify:

- heating/cooling processes
- setpoint for heating/cooling
- free cooling phenomena

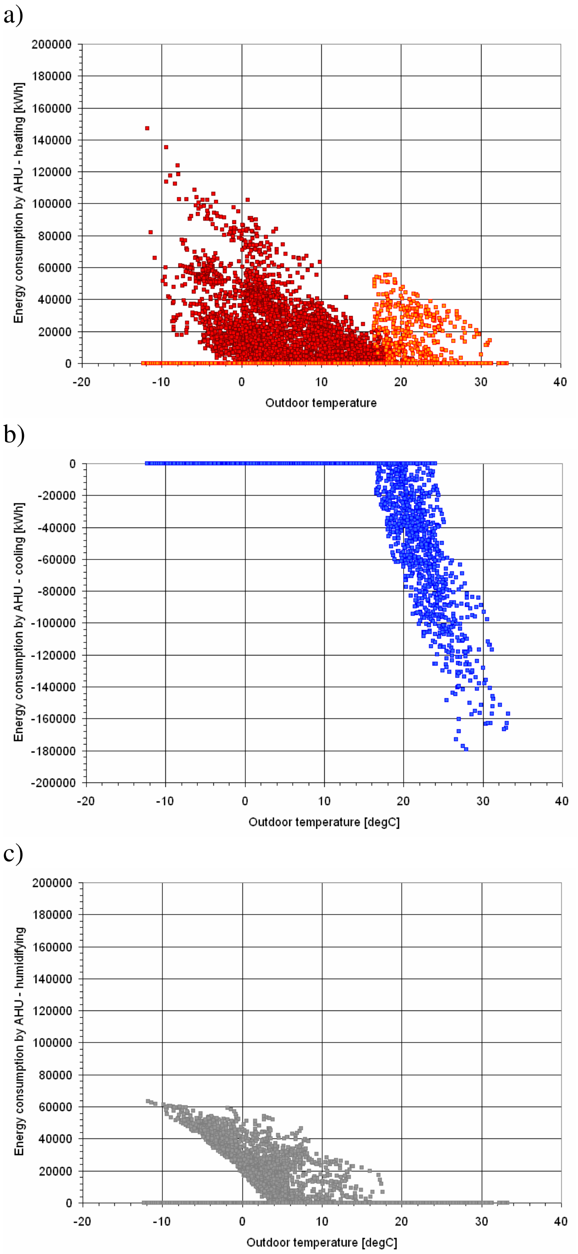

Figure 10 Energy used for different processes in AHU (HIG_AHU) as a function of outdoor temperature: heating energy (a); cooling energy (b); energy used for humidification (c)

On the charts one may easily observe different setpoints for temperature of air supplied to rooms (not setpoints for indoor temperature).

The histograms of indoor temperature variation during operating hours for three variants of HVAC system are presented on fig. 9.

Histograms presented on figure 9 indicate that analysed systems have comparable ability to maintain indoor temperature within assumed range. Thus, presented strong differences in energy consumption are not the consequences of differences in indoor temperature. Of course, systems offer different ranges of indoor humidity (variant NO_AHU does not include humidification or intentional dehumidification).

Presented simulation (just for case study building) underlined strong points of combined water – air systems.

Figure 10 presents relation between energy used for different processes of air treatment for HIG_AHU in relation to outdoor temperature. Because of necessary reheating after dehumidification on cooling coils heating needs are observed during whole year. Cooling needs are observed for temperatures above 16°C. Required intensity of humidification decrease with outdoor temperature. Humidification is not observed for temperatures exceeding 20°C.

Of course, quantitative results obtained in this particular simulation should not be generalised.

CONCLUSION

The integrated calculations of both thermal behaviour of buildings and hygrothermal processes in AHU gives an occasion for very interesting analysis. New 6R1C method offers new possibilities in modelling advanced ventilation systems with variable air supply temperature or with variable air volume systems. Huge differences in different types of air conditioning systems and control algorithms resulted in preparation of optional sets of equations used to calculate supply air temperature or variable air volume. AHU model has an open structure and can be easily modified on demand. If user understands both air treatment processes and control strategy in real AHU there are no limitations in modifying basic CAV or VAV submodels.

Of course case study results presented in the paper cannot be generalized. They were presented just to show the potential of hourly methods. The authors are deeply convinced that presented case study as well as other simulations performed up to now with utilisation of this method provide much more valuable information than monthly methods.

In practice, results of hourly simulations can help investors or architects to properly select type and then optimize sizing of HVAC system.

ACKNOWLEDGEMENT

The paper was written due to the support of STEP Project PL 0077 financed by a grant from Iceland, Liechtenstein and Norway through the EEA Financial Mechanism and the Norwegian Financial Mechanism.

REFERENCES

EN 15241 Ventilation for buildings – Calculation methods for energy losses due to ventilation and infiltration in commercial buildings

Gerald C., Wheatley P. 2004: *Applied Numerical Analysis*, 7th Edition, Pearson Addison Wesley

Incropera F., DeVitt D. 2002. *Fundamentals of Heat and Mass Transfer*, 5th Edition, J. Wiley & Sons

ISO-FDIS 13790: *Energy performance of buildings - Calculation of energy use for space heating and cooling*, ISO/TC 163/SC 2, 2007

Narowski P. 2009. *Uproszczona metoda godzinowa obliczania ilości ciepła do ogrzewania i chłodzenia budynków*, Ciepłownictwo, Ogrzewnictwo, Wentylacja, No 1 (466) 2009, p. 27 (in Polish)

Welty J., Wicks Ch., Wilson R., Rorrer G. 2001. *Fundamentals of Momentum, Heat and Mass Transfer*, 4th Edition, J. Wiley & Sons