PROPOSAL OF SIMPLIFIED CALCULATION 6R1C METHOD OF BULDINGS ENERGY PERFORMANCE ADOPTED TO POLISH CONDITIONS

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Summary

This paper presents proposal of simplified calculation 6r1c method of buldings energy performance adopted to polish conditions. The lumped capacitance method is utilized to define equations of building heat exchange 6R1C model. The model is the modification of simple hourly method described in EN ISO 13790:2007 standard. It should be pointed out that the 6R1C model additionally incorporates the air handling unit model (AHU model) based on EN 15241 standard. The ventilation heat transfer coefficient was split into controlled ventilation heat transfer coefficient and infiltration heat transfer coefficient. This extended method can be used for more precise calculation of heat and cool demand and can be adopted for fast and simple determining of buildings energy performance. The integrated 6R1C method was validated with the Bestest procedure. Validated method was used for calculations of energy performance of several nonresidential buildings. The calculation results published confirmed that the integrated 6R1C hourly method with simple AHU model can be used to calculate the annual energy consumption for buildings. The calculation results (verified with the Bestest) as well as pilot applications for nonresidential buildings confirmed that developed 6R1C model integrated with AHU model (after small adjustments) can be used for fast calculation of energy demand of buildings. The proposed simulation method has open structure and can be used for energy performance estimation of different HVAC systems in buildings.

Keywords: energy performance certificate, building energy simulations, 6R1C method

1 Introduction

Implementation of Energy Performance of Buildings Directive (EPBD) requires that each EU member state 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. Special attention has to be paid to ventilation and air conditioning systems in buildings, often responsible for more than 50% of energy delivered to the buildings. This paper presents the assumptions, method, verification and application of simple hourly 6R1C energy simulation method for buildings equipped with advanced ventilation and air conditioning systems adopted to polish conditions.

2 Methods

Lumped heat capacitance and resistance method and its electrical analogy

One of the most common transient conduction problems deals with a solid body exposed to a sudden change of its thermal environment. One can consider a stone that is initially at a uniform temperature and is rapidly immersed in huge amount of water. Another example is solid, concrete wall at constant uniform temperature which is exposed to sudden change of surrounding air temperature. Lumped capacitance method makes assumption that the solid has high thermal conductivity and the surface heat transfer is low comparatively to the conductance. The essence of the lumped capacitance method is assumption that the solid internal temperature is spatially uniform at any instant during the transient process of heat exchange with the surrounding. It means that the temperature gradient within the solid is neglected at any time in the transient process. In the example, the initial temperature of the solid is assumed to be T_0 and is spatially uniform. The temperature of water T_∞ in which the solid is immersed is lower than the solid initial temperature T_0 at the initial instant $t = 0$. After immersing the solid temperature will decrease for time $t > 0$, until it eventually reaches T_∞. This reduction is due to convection heat transfer at the solid-liquid interface.

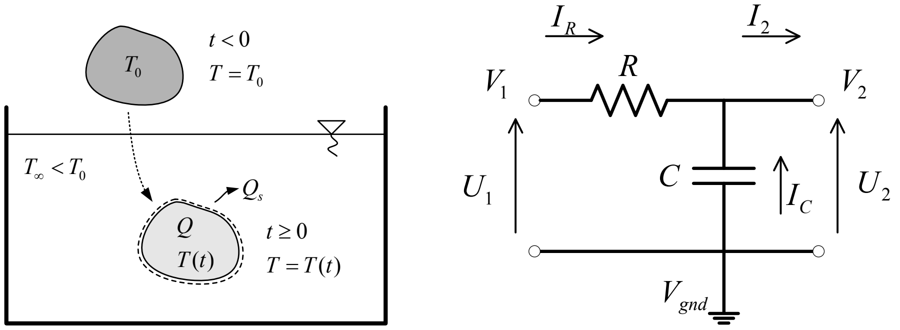


Fig. 1 Cooling down hot solid (left) and discharging of capacitor C through resistor R (right) - two different phenomena described by the same differential equation.

The process of transient heat transfer in the lumped capacitance method is described by the ordinary differential equation (1) or (2):

$$C\frac{d\Theta}{dt} = -H\Theta, \tag{1}$$

$$\frac{d\Theta}{dt} = -\frac{1}{RC}\Theta. \tag{2}$$

There is analogous equation in the electric circuits' theory to the equation (2). The equivalent of transient heat transfer in the lumped capacitance method in the circuits' theory is the electric current flow in the circuit composed with electric capacitor and resistor known as four-terminal RC network or RC quadripole shown on fig. 1. This quadripole is a filter that passes low-frequency signals but attenuates (reduces the amplitude) of signals with frequencies higher than the cutoff frequency $f_c = 1/(2\pi RC)$:

$$\frac{dV_2(t)}{dt} = -\frac{1}{RC}V_2(t). \tag{3}$$

So the two different phenomena – discharging of capacitor *C* through resistor *R* and cooling down hot solid are described by the same differential equation (fig. 1). This observation allows modeling the lumped capacitance heat exchange process with electrical circuits consisting of capacitor and resistors. Many models of heat exchange were build on that base starting with simple one node 2R1C lumped capacitance building model (model depends only on the building heat capacity, envelope external surface heat resistance and heat flux delivered to the building construction). Modifications of the 2R1C model can lead to more sophisticated models (e.g. the 5R1C model presented in ISO-FDIS 13790 [3] makes it possible to calculate additionally: transient internal air temperature in building, masonry temperature and internal surface temperature).

6R1C method of estimation of annual energy use in building

The 6R1C model method of estimation of annual energy use in building is further development of 5R1C model. The basic reason for modification was fact that 5R1C model does not contain separated ventilation air flux with a controlled supply temperature and infiltration flux of external air. Modified model presented at figure 2 describes two ways of air coming into building – controlled ventilation and uncontrolled infiltration. The model, similarly as 5R1C, allows supplying the heat to three nodes – the building construction, the internal surface of building construction and the 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 external walls, θ_i – internal air temperature. Resistances of the electric 6R1C circuit are equivalent to heat resistances in building: R_{Tr1} – heat transfer resistance of outside construction 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, R_{Vi} – heat transfer resistance of uncontrolled infiltration. Electric currents supplying the circuit of the 6R1C model are equivalent of internal heat gains and energy delivered by building heating or cooling system.

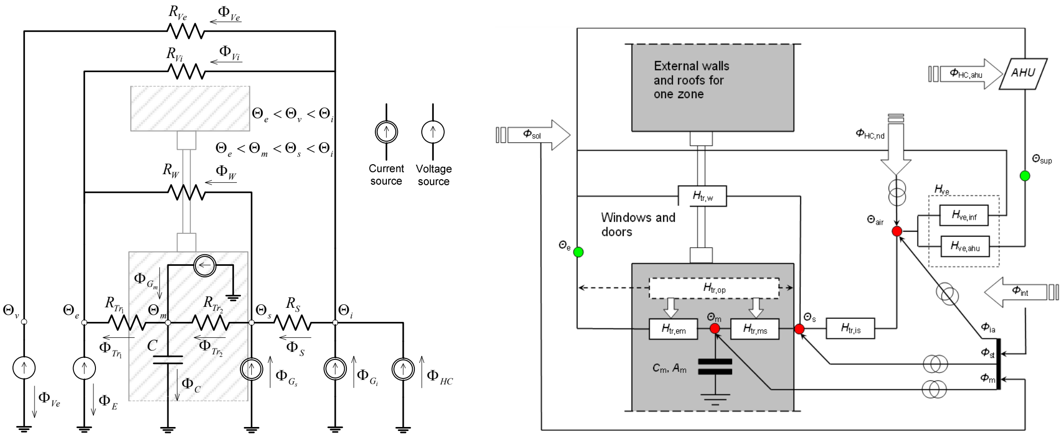


Fig. 2 Lumped capacitance heat exchange6R1C building model

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 replacing conductivity H_2 of the 2R1C circuit can be represented as the circuit of five resistors of the 6R1C circuit. The conductivity of this replacing resistor can be calculated using the partial conductance of serial and parallel connected resistors:

$$H_{Z_1} = \frac{H_S H_{Ve}}{H_S + H_{Ve} + H_{Vi}}, \qquad H_{Z_2} = \frac{H_S H_{Vi}}{H_S + H_{Ve} + H_{Vi}}, \tag{4,5}$$

$$H_{Z_3} = H_{Z_1} + H_{Z_2} \text{ and } H_{Z_4} = H_{Z_3} + H_W \tag{6,7}$$

with the formula:

$$H_{Z_5} = \frac{H_{Tr_2} H_{Z_4}}{H_{Tr_2} + H_{Z_4}} \tag{8}$$

The replacing conductance H_{Z5} in the 6R1C model can be treated as conductance H_2 of the 2R1C model, then it can be noticed that $H_2 \equiv H_{Z5}$. The replacing current source $\Phi \equiv \Phi_{mtot}$ supplying the capacitor with the potential θ for circuit 2R1C can be calculated as the sum of currents in that node supplied by for current sources Φ_{HC}, Φ_{Gi}, Φ_{Gs}, Φ_{Gm} two voltage sources with potential θ_v i θ_e with short circuit of capacitor C. The potential $\theta_{m,n+1}$ in the current instant of time ($n+1$) depending on potential in previous instant of time (n) can be calculated with modified *Euler's* method as:

$$\Theta_{m,n+1} = \frac{\Theta_{m,n}\left(C/3600 - 0{,}5\left(H_{Tr_1} + H_{Z_5}\right)\right) + \Phi_{mtot}}{C/3600 + 0{,}5\left(H_{Tr_1} + H_{Z_5}\right)}. \tag{9}$$

The current Φ_{Tr2} can be calculated with replacing ideal current source connected to node with potential θ_s, connected to the ground (short circuit) and with branch currents caused by current sources Φ_{Gi} and Φ_{HC}, and voltage sources θ_v and θ_e. The current supplying the node θ_s from current sources Φ_{HC} and Φ_{Gi} can be calculated from the formula:

$$\Phi_S^{(\Phi_{HC}+\Phi_{G_i})} = \frac{H_S}{H_S + H_{Vi} + H_{Ve}}\left(\Phi_{HC} + \Phi_{G_i}\right) = H_{Z_1}\frac{\Phi_{HC} + \Phi_{G_i}}{H_{Ve}}. \tag{10}$$

The current supplying the node θ_s from voltage source θ_v can be calculated as:

$$\Phi_S^{(\Theta_v)} = \frac{H_S}{H_S + H_{Vi}}\left(\frac{H_{Ve}\cdot\left(H_S + H_{Vi}\right)}{H_{Ve} + \left(H_S + H_{Vi}\right)}\Theta_v\right) = H_{Z_1}\Theta_v \tag{11}$$

The current supplying the node θ_s from The voltage source θ_e generates current in node θ_s which equals:

$$\Phi_S^{(\Theta_e)} = \frac{H_S}{H_S + H_{Ve}} \left(\frac{H_{Vi} \cdot \left(H_S + H_{Ve}\right)}{H_{Vi} + \left(H_S + H_{Ve}\right)} \Theta_e \right) + H_w \Theta_e = \left(H_{Z_2} + H_W\right) \Theta_e. \tag{12}$$

Substitute circuit scheme with the node θ_m shorted to ground and supplied with replacing ideal current source is shown on figure 12. The current supplying the node θ_m in that circuit equals:

$$\Phi_{Tr_2} = \frac{H_{Tr_2}}{H_{Tr_2} + H_{Z_4}} \left(\underbrace{\Phi_{G_s} + \Phi_S^{(\Phi_{HC} + \Phi_{G_i})} + \Phi_S^{(\Theta_v)} + \Phi_S^{(\Theta_e)}}_{\Phi_{S,tot}} \right) = \frac{H_{Z_5}}{H_{Z_4}} \Phi_{S,tot}. \tag{13}$$

The branch current Φ_{Tr1} flowing to node θ_m generated by voltage source with potential θ_e equals:

$$\Phi_{Tr_1}^{(\Theta_e)} = H_{Tr_1} \Theta_e, \tag{14}$$

and with another current and voltage sources equals 0. The total current Φ_{mtot} in node θ_m generated by all sources but the voltage source of capacitor can be calculated as:

$$\Phi_{mtot} = \Phi_{G_m} + H_{Tr_1} \Theta_e + \frac{H_{Z_5}}{H_{Z_4}} \left(\Phi_{G_s} + H_{Z_1} \left(\frac{\Phi_{HC} + \Phi_{G_i}}{H_{Ve}} + \Theta_v \right) + \left(H_{Z_2} + H_W\right) \Theta_e \right) \tag{15}$$

Applying the *Kirchoff's* currents law for the node with potential θ_s allows writing the balance equation for that node of 6R1C circuit and determining its potential:

$$H_{Tr_2}\left(\Theta_s - \Theta_m\right) + \left(H_{Z_2} + H_W\right)\left(\Theta_s - \Theta_e\right) + H_{Z_1}\left(\Theta_s - \Theta_v\right) = \Phi_{G_s} + \frac{H_{Z_1}}{H_{Ve}}\left(\Phi_{HC} + \Phi_{G_i}\right) \tag{16}$$

$$\Theta_s = \frac{H_{Tr_2}\Theta_m + \left(H_{Z_2} + H_W\right)\Theta_e + H_{Z_1}\Theta_v + \Phi_{G_s} + \frac{H_{Z_1}}{H_{Ve}}\left(\Phi_{HC} + \Phi_{G_i}\right)}{H_{Tr_2} + H_{Z_4}} \tag{17}$$

The same procedure can be applied for determining potential θ_i:

$$H_S\left(\Theta_i - \Theta_s\right) + H_{Vi}\left(\Theta_i - \Theta_e\right) + H_{Ve}\left(\Theta_i - \Theta_v\right) = \Phi_{HC} + \Phi_{G_i} \tag{18}$$

$$\Theta_i = \frac{H_S\Theta_s + H_{Vi}\Theta_e + H_{Ve}\Theta_v + \Phi_{HC} + \Phi_{G_i}}{H_S + H_{Vi} + H_{Ve}} \tag{19}$$

Lumped capacitance 6R1C building model allows calculating the masonry temperature θ_m, temperature of internal surfaces of building θ_s and internal air temperature θ_i, taking in consideration variable external air temperature θ_e and variable temperature of ventilation air θ_v and transient heat fluxes Φ_{HC}, Φ_{Gi}, Φ_{Gs} and Φ_{Gm} supplying nodes of circuit. Those heat streams can represent heating or cooling systems energy delivered to internal air and heat gains in the radiation and convection form from external e.g. solar and thermal radiation, and internal sources as people, appliances or lighting.

3 Integration with air handling unit behavior

Behavior of ventilation and air-conditioning systems and calculations of energy use for preparation of outside air in AHU is based on EN 15241 "Ventilation for buildings – Calculation methods for energy losses due to ventilation and infiltration in commercial buildings" [2].

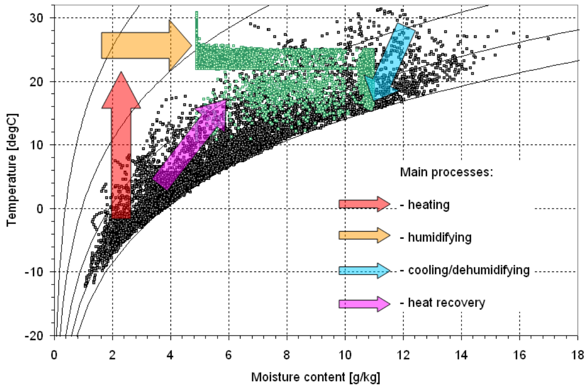


Fig. 3 The main idea of AHU calculation's method

The main idea is to calculate the energy needed for transferring the air parameters from outdoor conditions to required values at supply. The following processes were taken into account (fig. 3): heat recovery (sensible and latent) during winter and summer, heating, humidifying, cooling, dehumidifying, preheating and precooling of air in ground heat exchanger. Sub models 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, the annual behavior of AHU may be quite complex. The advanced logical analysis (the substitution of control system modeling) 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.

4 Verification of the model with BESTEST method

The Bestest method is a procedure that allows scientists to determine the computing capabilities and the applicability of software for energy performance analysis in buildings. The methodology does not allow verifying the correctness of all calculation algorithms of simulation programs, however, it helps to locate the fundamental errors in such types of software, and it allows identifying reasons of the error occurrence. The procedure offers comparison of the results of the buildings energy performance obtained from different computer programs. Set of tests included in the procedure validates software by:

- comparison the results of the calculations with the reference results or the results obtained from other computer programs, which have been generated using this method,
- comparison the results of the calculations with the results of obtained before changing the source code, what can be used to check the impact of the modification,
- comparison the results of the calculations with earlier version before medication of algorithm to determine the differences between the algorithms,

Additionally Bestest helps to identify sources of discrepancies between the results of the program under review, and those references. ANSI/ASHRAE Standard 140 "Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs" [1] was the first method of testing simulation software for buildings in the world. Given in ANSI/ASHRAE Standard 140 2004 consists of the comparative tests that takes into account the structure of the building and analytical verification test for checking the models of mechanical systems.

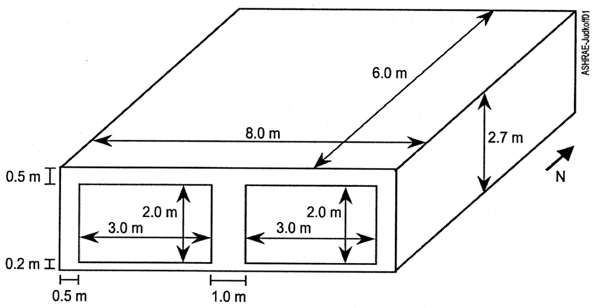


Fig. 4 Isometric view of building model, test 600 and 900 (ANSI Standard 140)

In order to verify the 6R1C model tests 600, 620, 640, 650, 900, 920, 940 and 950 were performed. Climate data for Denver were used for all diagnostic models. Basic test 600 is used to model the thermal loads in the building. This one zone model is a cube-shaped (fig. 4) without internal partitions and low thermal capacity of building envelope. Heat transfer coefficients of building construction are equal: the external walls 0.51 W/(m^2·K), floor 0.039 W/(m^2·K), roof 0.32 W/(m^2·K), windows 3.0 W/(m^2·K). It was assumed that in the test building the existing system maintains temperature at a preset level in winter and summer period. It was also assumed that the efficiency of this system equals 100% and there are no flow losses and the maximum system power is equal to 1000 kW. Ventilation rate was established constant for whole year at the level of 0.5 air change per hour and the value of internal heat gains is at the level of 200 W during whole year. Heating is switched on when the internal temperature falls below 20°C and cooling is turned on when the internal temperature rises above 27°C. In other cases, heating and cooling is turned off.

Subsequent tests are small modification of basic tests. The tests are used to check the capabilities of computer programs to model the thermal load of the building in case of low and high capacity of building envelope. The following parameters are changed in the models: the orientation of the windows, the configuration of the overhangs, set of the thermostat of the heating and air conditioning systems and control scheme of mechanical ventilation. Tests for building with low thermal capacity of walls (tests from 600 to 650) are characterized by a lightweight construction of walls, floors and roof. Tests of high thermal capacity of walls (tests from 900 to 960) are characterized by a massive slab floors, solid walls and the presence of additional two zone model. Tests indicated FF (tests 600FF, 650FF, 900FF and 950FF) do not have air conditioning and heating systems. These models verify the ability of programs to determine an internal air temperature in the system with low and high capacity of thermal mass and additional mechanical ventilation system. Test 620 is obtained by modifying the test 600. Model 620 has a window with an area of 6 m^2, located on the east wall and the second window with an area of 6 m^2, located on the west wall. The dimensions and physical properties of the windows remain the same as in test 600.

Test 640 is obtained by modifying the test 600. The heating and air conditioning systems are controlled by thermostat responsive to air temperature changes in the room. System always works with full capacity. Work of heating systems is carried out by a certain scheme:

- from 23:00 to 07:00 heating system works only if air temperature is lower than 10°C,

- from 07:00 to 23:00 heating system works only if air temperature is lower than 20°C,
- cooling system works only if air temperature is higher than 27°C.

In other cases, the systems do not work.

Test 650 (for summer conditions) is obtained by modifying the test 600. Air-conditioning system is controlled by a thermostat responsive to air temperature changes in the room. System always works with full capacity. Working scheme of heating system, air conditioning and mechanical ventilation system is carried out according to following schedule:

- mechanical ventilation system is working from 18:00 to 07:00,
- heating system is turned off,
- air conditioning system works from 07:00 to 18:00 if air temperature is higher than 27°C.

In other cases, the systems do not work. Tests from 900 to 960 represent building with high thermal capacity of building envelope. They are obtained by modifications of similar models in a series of 600. Only the model 960 is created on the basis of models from both series - 600 and 900. The results of the annual energy consumption for heating and for cooling are presented in Table 1. Values obtained from the 6R1C model are compared with the values calculated by the simulation software: ESP, BLAST, DOE 2, SRES/SUN, SERIRES, S3PAS, TRNSYS and the TASE.

Tab. 1 The results of the annual energy consumption for heating and for cooling

Case	Annual energy use for **heating**				Annual energy use for **cooling**			
	Minimum	Maximum	Average	**6R1C**	Minimum	Maximum	Average	**6R1C**
	MWh	MWh	MWh	**MWh**	MWh	MWh	MWh	**MWh**
600	4,296	5,709	5,090	**4,599**	6,137	7,964	6,832	**6,526**
620	4,613	5,944	5,407	**5,278**	3,417	5,004	4,218	**5,139**
640	2,751	3,803	3,207	**2,773**	5,952	7,811	6,592	**6,526**
650	0,000	0,000	0,000	**0,000**	4,816	6,545	5,482	**5,569**
900	1,170	2,041	1,745	**1,564**	2,132	3,415	2,678	**2,764**
920	3,313	4,300	3,973	**3,489**	1,840	3,092	2,552	**2,998**
940	0,793	1,411	1,160	**0,854**	2,079	3,241	2,578	**2,764**
950	0,000	0,000	0,000	**0,000**	0,387	0,921	0,605	**1,752**

5 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 cooling 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.

Tab. 2 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^2year)]			
Heating and cooling	188,2	78,6	156,4

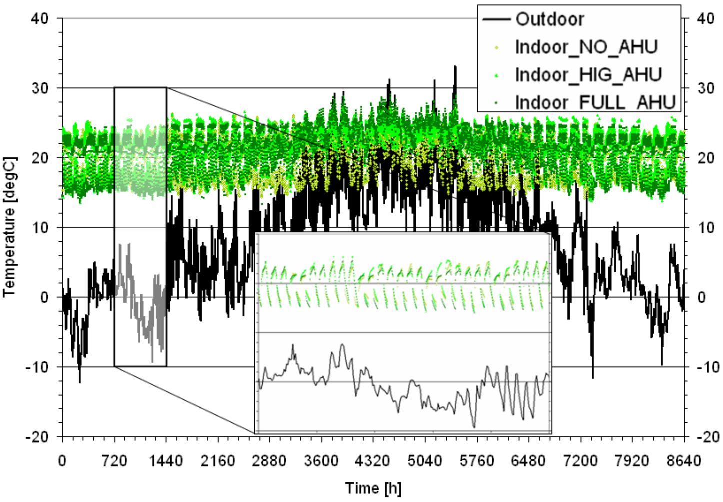
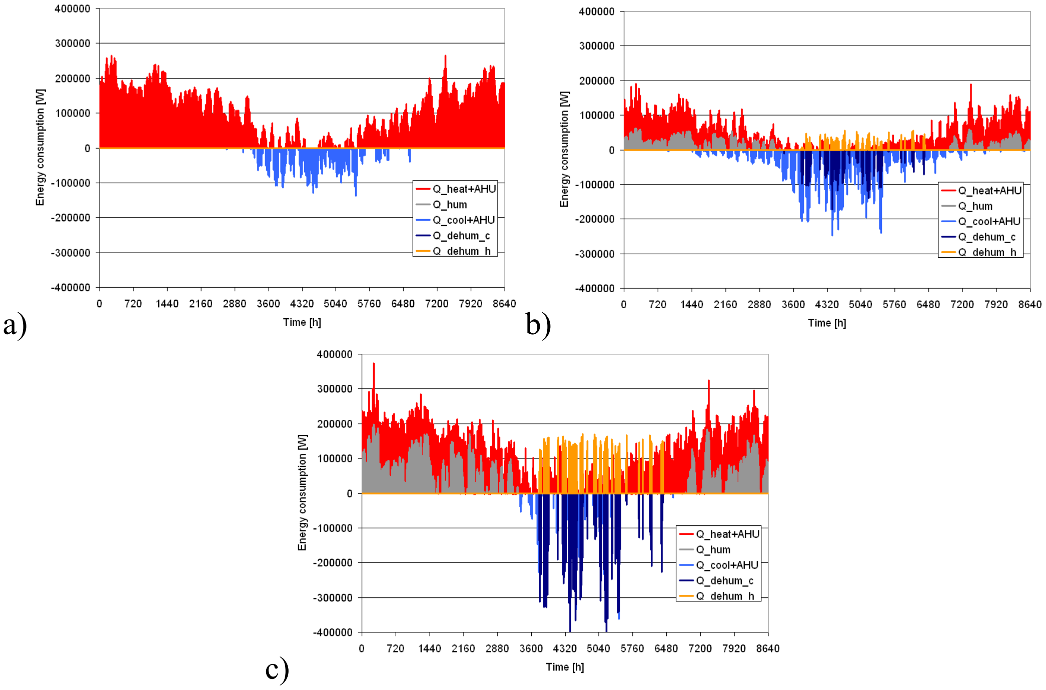


Fig. 5 Indoor and outdoor air temperature



a)

b)

c)

Fig. 6 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.

6 Simulation results

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^2year) to 188,2 kWh/(m^2year). 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 3. 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.

Tab. 3 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.

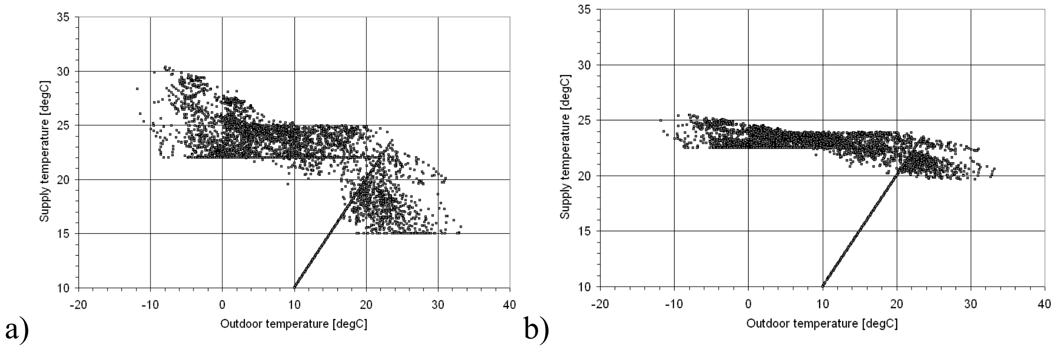


Fig. 7 Supply temperature as a function of outdoor temperature for variants: HIG AHU (a); FULL AHU (b)

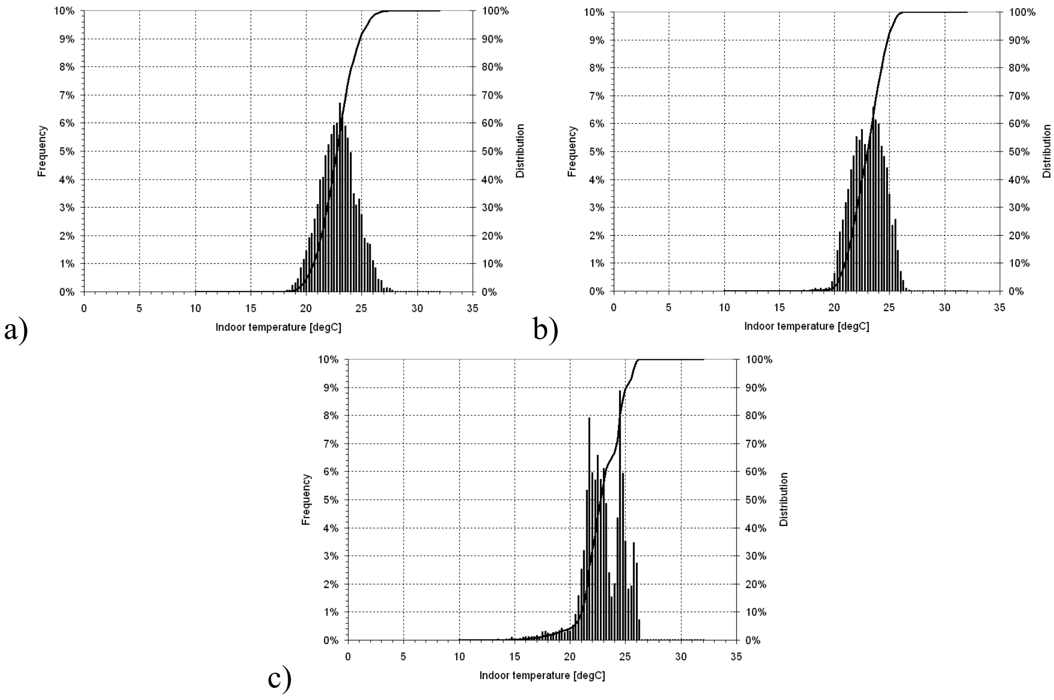


Fig. 8 Histograms of indoor temperature variation during operating hours for variants: NO AHU (a); HIG AHU (b); FULL AHU (c)

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 [kWh/(m^{2}year)] for (NO_AHU). Of course these values are much higher than presented in table 2. 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. 7). On this figure one may identify:

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

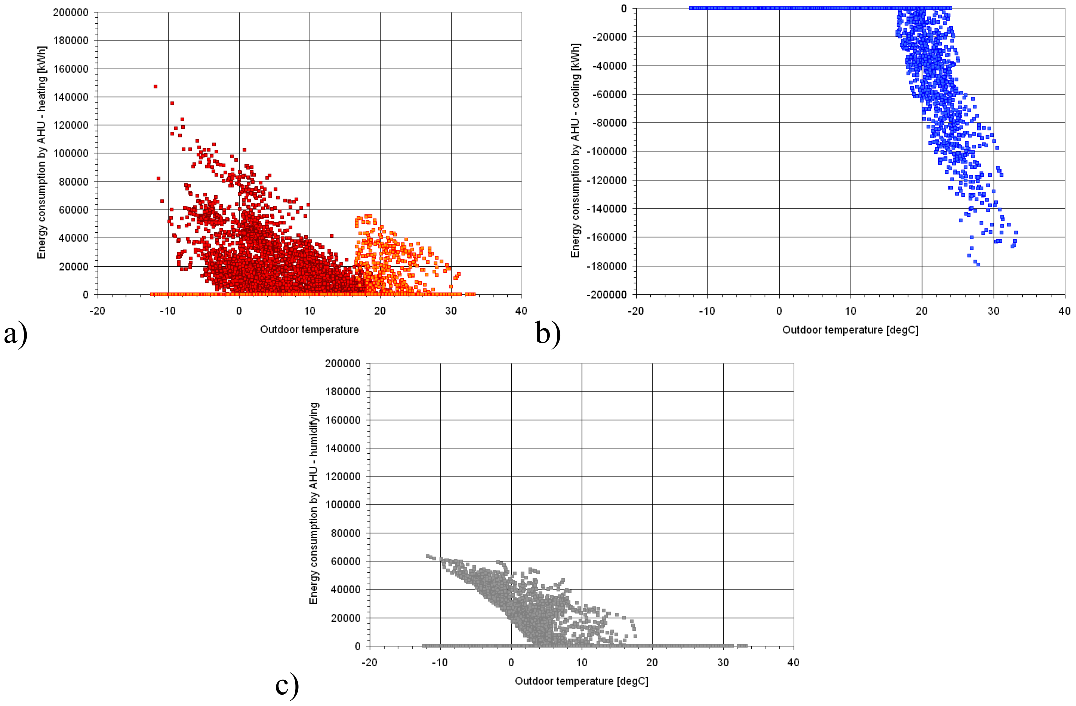


Fig. 9 Energy used for different processes in AHU (HIG_AHU) as a function of outdoor temperature: heating energy (a); cooling energy (b); energy used for humidification (c)

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. 8 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.

7 Results

Presented 6R1C method integrated with AHU model adopted for polish conditions is a simple but successfully accurate tool for annual analysis of energy consumption in buildings. Validation by Bestest method seems to be satisfactory. In the case of the annual energy consumption for heating the results of all tests are between the minimum and maximum values obtained from other simulation programs. The amount of energy for cooling obtained by 6R1C model in the test of 620 and 950 exceeded the maximum value from other programs. In the test 620 the reason of this difference may be connected with energy loses by radiation. The radiation energy entering the test zone by one of the window may leave the space by the opposite located window.

Comparison of the results of both integrated peak heating loads and integrated peak cooling loads obtained from the 6R1C model are not as good as annual energy demand. In some of the cases the results do not fit between the minimum and maximum values obtained from the Bestest. This discrepancy of calculation results of peak heating and cooling loads between 6R1C and Bestest is caused by the proportional control algorithm of heating and cooling used by the 6R1C model. It is possible to add PID control algorithm to the 6R1C model what should improve the results of peak heating and cooling loads and make them compatible with Bestest.

Calculation methods are very sensitive on the assumptions and input parameters. Thus it is important to verify the correctness of obtained results by e.g. use of Bestest. The method was used for calculations of energy performance of several non residential buildings. Results obtained for standardized meteorological year are similar to real energy use of sample building population. The results published in other papers (presented on CLIMA 2010) confirmed that both type of HVAC system and range of indoor parameters have essential influence on energy consumption and in some cases may be more important than energy loads themselves [4, 5].

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