Environmental Engineering and Management Journal November 2014, Vol.13, No. 11, 2765-2770
http://omicron.ch.tuiasi.ro/EEMJ/

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ANALYSIS OF DEGREE DAY AND COOLING ENERGY DEMAND IN EDUCATIONAL BUILDINGS

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Abstract

In European countries, because of low fossil fuel reserves, energy saving is one of the primary research goals in every energy consumer sector. In the last several years, several directives were elaborated by the European Commission to enhance the energy efficiency in buildings and increase the use of renewable energy sources. In European countries with temperate climates, in a residential building with a "traditional" insulation of the envelope, heating represents approximately 65 to 75% of the total energy consumption. Nevertheless, in educational or office buildings, the energy consumption for ventilation and cooling is notably high. The energy consumption for cooling is strongly influenced by the cooling degree day, which varies year by year. This paper presents the analysis of cooling degree day variation in the last five years in Debrecen and the summer overheating in an educational building before and after refurbishment.

Key words: air change rate, blower door, cooling energy, summer overheating

Received: February, 2014; Revised final: October, 2014; Accepted: October, 2014

1. Introduction

Enhancing energy efficiency in the building sector is stipulated by the Energy Performance Directive 2010/31/EU, and measures have been taken in all European countries to reduce the energy consumption of buildings (EC Directive, 2010). Buildings occupied by public authorities and buildings frequently visited by the public should set an example by showing that environmental and energy considerations are considered. Therefore, those buildings should be subject to energy certification on a regular basis.

In European countries with temperate climates in residential buildings with poor insulation of the envelope, heating represents 65 to 75% of the total yearly energy consumption (Kalmár and Kalmár, 2011). These usually buildings have no mechanical ventilation or cooling systems installed. Depending on the glazed area and orientation of facades and the thermal capacity and time constant of spaces, during summer periods, comfort problems may appear because of overheating. In public buildings, the energy use of the ventilation and cooling systems can represent an important share of the total yearly energy consumption. In the case of an educational building built in 2006, ventilation represents 73% of the total energy consumption (Fig. 1).

Naturally, the theoretical energy use differs from the real energy use registered in different years, being influenced by numerous factors, such as the users' needs and meteorological conditions. According to Luterbacher et al., the late 20th and early 21st century European climate is most likely warmer than that of any time during the past 500 years (Luterbacher et al., 2014). In addition to warmer climate, urban heat islands contribute to increased energy consumption for cooling and ventilation (Taha, 1997). To determine the influence of orientation on the indoor temperature in summer periods, a special experimental laboratory was built at the University of Debrecen (Csáky and Kalmár,

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2012). Measurements have demonstrated that the east and west orientations of the glazed area will lead to the highest indoor temperatures during summer periods.

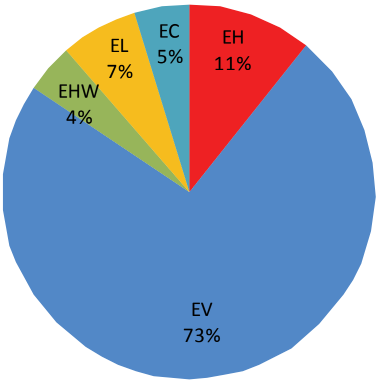


Fig. 1. Energy consumption of an educational building (E_H – energy share of heating; E_V – energy share of ventilation; E_{HW} – energy share of hot water preparation; E_L – energy share of lighting; E_C – energy share of cooling)

The energy consumption of buildings can be calculated with sufficient accuracy using the degree day method. The primary goal of our research was to determine the variation of the degree day for cooling in the last five years in Debrecen and the differences between theoretical cooling degree day used in Hungary and the yearly cooling degree days calculated for Debrecen. Furthermore, the overheating was analyzed for an educational building before and after refurbishment. To determine the air change rate by infiltration, blower door measurements were performed.

2. Cooling degree day

During the summer period, the indoor temperatures in buildings should be kept within a certain range (Standard ANSI/ASHRAE 55, 2004; Standard EN15251, 2007; Technical Report CR 1752, 1998). Because of the heat gains, the indoor temperatures can exceed, by a considerable amount, the highest values accepted by standards (Kalmár and Halász, 2006). In addition to the heat gains, the room geometry and the variation rate of the surface temperatures strongly influence the thermal comfort of the occupants (Kalmár and Kalmár, 2010, 2011, 2012). The variation of the surface temperatures can be kept in a certain interval if the building envelope is provided with additional insulation on the external side. For a long-term energy analysis of buildings, the variation of physical properties of insulation materials should be considered (Lakatos and Kalmár, 2013a, 2013b; Lakatos et al., 2013a; Lakatos, 2014). The time leg of the building envelope can reduce the negative effects of summer solar radiation (Lakatos et al., 2013b). To determine the energy need for cooling, first and foremost, the degree day for cooling has to be determined. Based on the hourly dry bulb temperature records we obtained from Agro-Meteorological Observatory Debrecen (Fig. 2), the degree day curves have been created for the last five years.

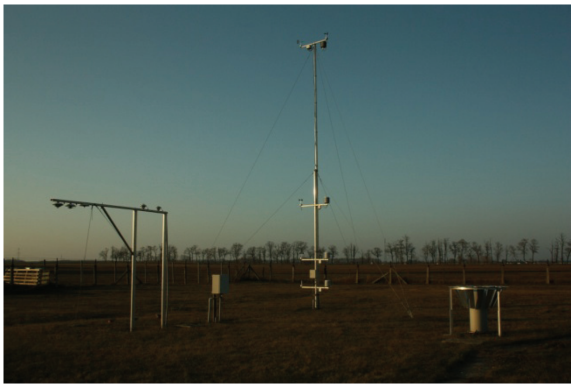


Fig. 2. Agro-Meteorological Observatory Debrecen (photo by Rácz Csaba)

The dry bulb temperature, relative humidity of air, and wind velocity are measured at 1.0 m, 2.0 m, 4.0 m and 10.0 m height. The temperature sensor is Pt100-1/10 with ±0.1 °C accuracy. Using the hourly mean dry bulb temperature values, the degree day curves had been built. The degree day curve shows the frequency of days with a certain mean external temperature. The curves obtained are shown in Fig. 3. Important differences between the mean temperature values in the last several years can be observed. In the analyzed time frame, the hottest year was 2012 and the coldest year was 2010. Figure 4 shows the difference between theoretical degree day curve and the real degree day curve obtained for the mean values of the analyzed years.

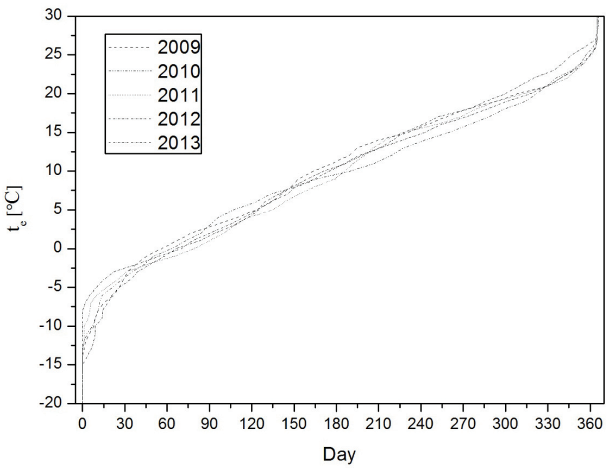


Fig. 3. Degree day curves of the last five years

Using the developed yearly and theoretical degree day curves, the degree day values were calculated assuming a base temperature of 20 °C. The degree day was obtained as the sum of The temperature differences between the daily average temperatures and the base temperature. Table 1 shows the theoretical and real degree day values.

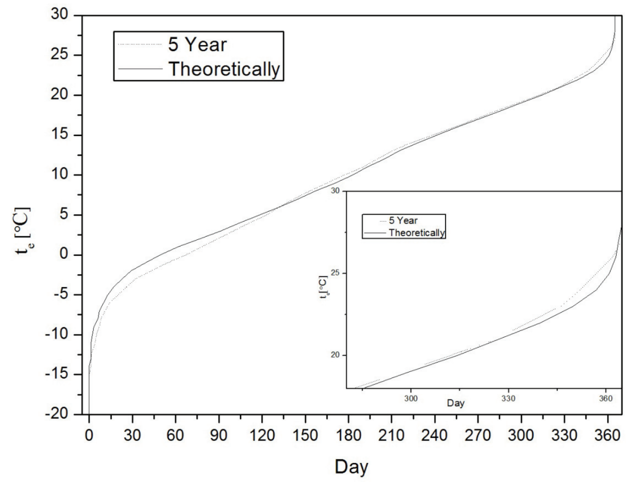


Fig. 4. Theoretical and 5-year mean degree day curve

Table 1. Degree day values

Year	*2009*	*2010*	*2011*	*2012*	*2013*	*5-year mean*	*Theoretical*
Degree day, [hK]	29760	23532	27672	37056	25524	28740	27324

While the 5-year mean cooling degree day value is 5.2% higher than the theoretical cooling degree day, the yearly cooling degree days deviation varies in a much larger interval: -13.8% and +35.6%. Consequently, the yearly energy demand for cooling and the overheating in buildings will be different than the expected values.

3. Energy use for cooling

The specific primary energy use for cooling is calculated using Eq. (1) (Kalmár, 2013):

$$E_c = \frac{\varepsilon\, Q_c\, e_c}{SEER\, A_N} \tag{1}$$

where: Q_c is the net energy demand for cooling, [kWh/a]; e_c is the primary energy transformation factor of cold energy source; ε is the ratio of sensible and total cold energy output of chillers; *SEER* is the seasonal energy efficiency ratio of chillers.

According to Hungarian Regulation 7/2006 TNM on the energy performance of buildings, the net energy demand for cooling is determined using Eq. (2) (Regulation 7-TNM, 2006) (Eq. 2):

$$Q_c = \frac{24}{1000} n_c \left(\sum A_N q_b + Q_{sdsummer} \right) \tag{2}$$

where $Q_{sdsummer}$ is the direct solar gain; q_b is the internal gain; n_c is the number of days for which the following precondition is fulfilled (Eq. 3):

$$t_{em} \geq t_{is} - \Delta t_{bsummer} \tag{3}$$

where t_{em} is the mean outdoor temperature, [°C]; t_{is} is the indoor set point temperature in summer, [°C]; $\Delta t_{bsummer}$ is the temperature difference between the cooling balance point temperature (t_{cb}) and indoor set point temperature, [°C].

The air change rate during the summer period (ACH_{summer}) considerably influences the balance point temperature for cooling (Eq. 4):

$$\Delta t_{bsummer} = \frac{Q_{sdsummer} + A_N q_b}{\sum AU + \sum \Psi l + 0{,}35\, ACH_{summer}\, V} \tag{4}$$

where ΣAU represents the sum of external building elements areas (A, in m^2) multiplied by their overall heat transfer coefficients (U, in W/m^{2}K); $\Sigma\Psi l$ is the sum of thermal bridges lengths (l, in m) and their linear heat transfer coefficient (Ψ, in W/mK); V is the volume of the building [m^3].

The regulation gives certain design values of ACH_{summer} depending on the window's placement on the building facades (Table 2).

Table 2. Design values of ACH_{summer}

Night ventilation	*Mobile windows*	
	on one facade	*on more than one facade*
not possible	3	6
possible	5	9

The determination of the direct transmission gain for a given date is given by Eq. (5).

$$Q_{sd} = \eta_s \sum A_t I_s g \tag{5}$$

where η_s is the utilization factor of solar gains; A_t is the transparent glazed area[m^2]; g is the total solar energy transmittance for glazing; I is the solar radiation intensity, [W/m^2].

For summer overheating risk calculation, the average intensity of solar radiation is 85 [W/m^2] for the facades facing north and 150 [W/m^2] for the facades facing south, east, and west. Table 3 lists the number of cooling days depending on the balance point temperature for cooling.

Table 3. Cooling days

t_{cb}, [°C]	16	17	18	19	20	21	22	23	24	25	26	27
n_c, [days]	110	95	80	66	52	38	25	15	8	5	3	1

4. Air tightness of buildings

The air leakage building envelope in the case of wind or higher temperature differences will lead to important quantities of air infiltration (Fig. 5).

The fresh air flow entering the buildings through filtration has an important influence on the energy balance of buildings and makes the control system operation difficult. Using a blower door instrument, the expected air change rate can be determined as a function of the indoor-outdoor pressure differences. Using a blowing fan, the pressure is increased to 50 Pa overpressure in the analyzed closed space. After extracting the air from the analyzed room, a vacuum is created until a -50 Pa pressure difference is reached. Keeping this pressure difference constant, the air flow ($\dot{V}$), which has to be introduced or exhausted from the analyzed room, is measured. The air change rate at 50 Pa will be given by Eq. (6).

$$ACH_{50} = \frac{\dot{V}}{V} \qquad (6)$$

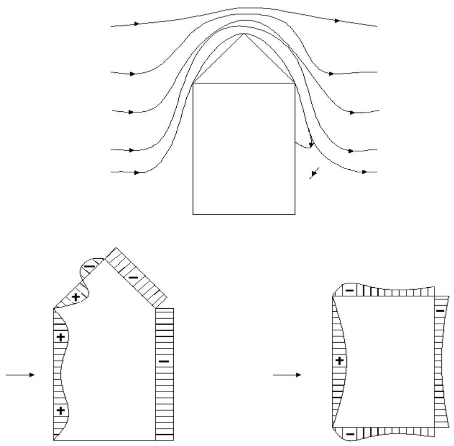


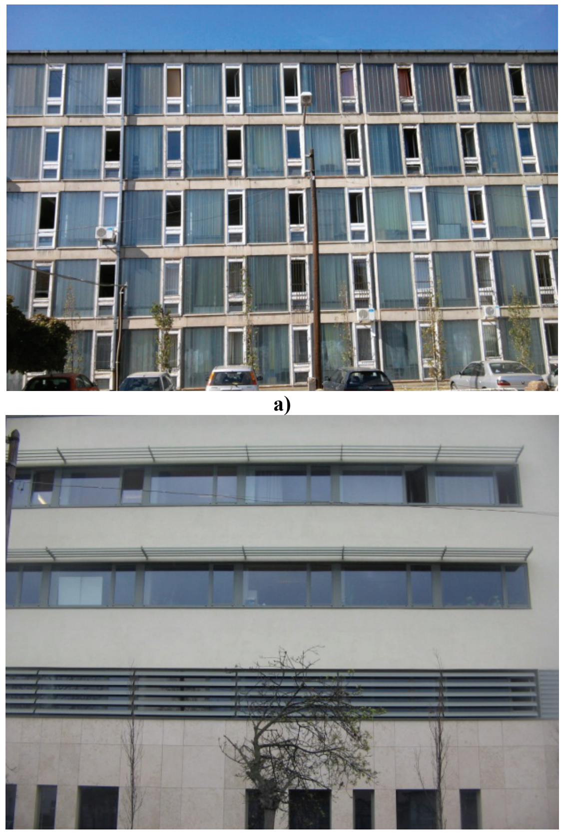
Fig. 5. Pressure differences created by wind on the building envelope

5. Case study

The air tightness, the summer overheating and the energy need for cooling of an educational building before and after refurbishment is analyzed below. The building has five levels and a flat roof; the ground floor is placed directly on the ground. Geometrical parameters are shown in Tables 4 and 5.

In Fig. 6, the east facade can be observed before and after thermal refurbishment of the building envelope. As shown in the figure, the transparent area was reduced considerably after refurbishment. The overall heat transfer coefficient of the windows was reduced from 2.8 W/m^{2}K to 1.34 W/m^{2}K.

The overall heat transfer coefficient of the opaque elements after refurbishment is 0.36 W/m^{2}K. Furthermore, shading elements were installed to reduce overheating in the summer.



a)

b)

Fig. 6. East facade before and after refurbishment

Theoretically, using Eq. (4), the risk of overheating would be reduced by increasing the air change rate through natural ventilation. In Fig. 7, the variation of Δt_b can be observed for the analyzed building before and after refurbishment. As observed, after refurbishment, the balance point temperature for cooling will decrease by 1-2 °C at low ACH values, but, at high ACH values, the refurbishment has a lower influence on the balance point temperature for cooling (approximately 0.5 ^{o}C).

The blower door measurements conducted before and after refurbishment (Fig. 8) show that the ACH_{50} due to infiltration decreased from 8.25 [h^{-1}] (a) to 2.2 [h^{-1}] (b). Fig. 9 shows the variation of ACH with pressure difference in a room. As shown in the Figure, the differences between air change rates before and after refurbishment of the building increase with the indoor-outdoor pressure difference.

Table 4. Geometrical parameters

Geometrical parameters	*Before refurbishment*	*After refurbishment*
net floor area, [m^2]	11645.94	12646.41
ground floor area, [m^2]	4289.09	4289.09
flat roof area, [m^2]	4562.08	4123.23

Table 5. Facades parameters

Orientation	***Facades area,[m²]***	***Transparent area,[m²]***	***Facades area,[m²]***	***Transparent area,[m²]***
	before refurbishment		***after refurbishment***	
N	1945	634.1	1769.5	571.4
S	2024	1063.4	1808.9	728.2
E	2546	1419.7	2172.5	992.5
W	2598	634.1	2071.9	661

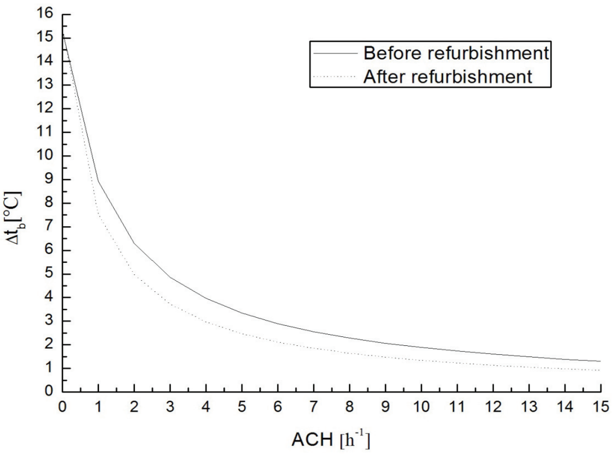


Fig. 7. ACH influence on the balance point temperature for cooling

a b

Fig. 8. Measurement of air tightness with a blower door instrument

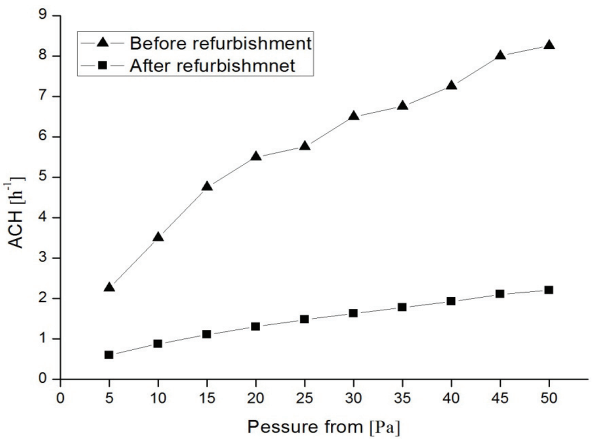


Fig. 9. Air change rate as a function of pressure difference

Using Eq. (6), the direct solar gains were determined. The internal gains were determined assuming the heat load of the occupants, lighting, PC-s and other appliances. The obtained heat gain values are presented in Table 6.

Table 6. Heat gains of analyzed building

	Internal gains, [W]	***Direct solar gains, [W]***
Before refurbishment	104813.5	176477.8
After refurbishment	113817.7	126485.9

The yearly cooling energy demand of analyzed building is determined using Eq. (1) for different air change values before and after refurbishment (Table 7).

Table 7. Yearly cooling energy demand

ACH_{summer} [h⁻¹]	***Before refurbishment kWh/year***	***After refurbishment kWh/year***
3	85512.54	48060.72
6	33754.95	15379.43
9	18002.64	9612.14

6. Conclusions

In the educational building, the "workplace" is fixed; consequently, the comfort problems should be analyzed properly. Because heating represents an important share of the building's energy consumption in countries with temperate climates, the energy consumption for cooling and the summer comfort problems are treated superficially.

Although educational buildings are usually not occupied in the hottest summer months (July-August), in the case of large transparent surfaces, poor shadowing and disadvantageous orientation of the facades, comfort problems may appear or the energy consumption for cooling may increase in May, June and September.

The energy consumption for cooling may be reduced, even with a 75% increase in the air change rate from 3 to 9 h^{-1}. Thermal refurbishment of the envelope will lead to a reduction of the air change rate generated by infiltration to 25%. The energy use for cooling can be reduced to 50% at a certain values of air change rate.

Acknowledgments
The work is supported by the TÁMOP-4.2.2.A-11/1/KONV-2012-0041 project. The project is co-

financed by the European Union and the European Social Fund. The authors would like to express their gratitude to the Agro-Meteorological Observatory Debrecen for providing indispensable meteorological data.

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