Energy demand for cooling an office building

ANDREEA VARTIRES, ANDREEA BERESCU, ANDREI DAMIAN
Faculty of Building Services Engineering
Technical University of Civil Engineering Bucharest
Address: Bd. Pache Protopopescu nr. 66, sector 2, 021414, Bucharest
ROMANIA
vartires2@gmail.com, andreea_berescu@yahoo.com, adamian7@yahoo.com, http://instalatii.utcb.ro

Abstract: - The analysis presented in this paper is related to three possible evaluation methods for the building cooling load. Therefore, it examines the theoretical bases used for the approximation of this cooling load as close to the real cooling load of a building cooling energy demand for buildings using three methods. The first refers to the method of monthly calculation approach described in the Romanian regulation Mc001/2006-"Calculation methodology for buildings energy performance ". The second method is a simplified hourly calculation method, simulated with CODYBA software. The third method is an advanced hourly calculation method, using the TRNSYS software.

Key-Words: - Tertiary buildings, Buildings energy performance, Monthly calculation, CODYBA, TRNSYS

1 Introduction
In the context of climate plan changes, decreasing energy consumption has become an important objective of EU countries, including Romania. To achieve this goal, there have been developed a series of political measures that point out the reduction of energy consumptions. Buildings sector account for 40% of total energy consumption in the European Union [1]. This sector is expanding, leading to increased energy consumption. Therefore, energy savings and renewable energy use in buildings appear as the most important measures to reduce EU energy dependence.

Due to the development of the buildings sector and to the increase of equipments with high consumption profiles for tertiary buildings, the reduction of buildings yearly energy consumptions has become a major target for the EU countries. In addition, the quality of the indoor environments where people work has a complex influence on their health as well as on their labour productivity. Environmental quality is estimated by the thermal comfort parameters, the chemical composition of indoor air, and by other factors as: lighting level, noise level [2], the ionization degree of the air, etc. By means of natural ventilation, usually intermittent (opening windows by occupants themselves), it isn’t always possible to assure a better quality of indoor air. For instance, in several high-polluted spaces, such as: crowded rooms, production rooms, laboratories, warehouses for industrial growth of animals and so on, The natural ventilation doesn’t provide the necessary air flows for the dilution of the indoor contaminants. To remove odours and even toxic discharges, there is need to control the airflows supplied to such spaces. Thus, it is necessary to implement mechanical ventilation systems (MVS) adapted for buildings indoor processes with pollutant release.

The ventilation and air-conditioning systems implemented within tertiary buildings are high-energy consumers, because of the large cooling loads and of the important ventilation airflows taken from outside. Due to their architectural complexity, there is need for precise tools in order to evaluate their cooling loads.

This paper describes three evaluation methods for a tertiary building cooling load: a monthly calculation method, a method using the CODYBA software and a method using TRNSYS software.

2 Study hypothesis
The monthly and hourly calculations were performed for a cooling area corresponding to an 11 floors office building (Fig.1), situated in Bucharest and built during the period 2009-2010. The indoor comfort temperature set up for this building over the cooling season (summer) was equal to 26°C. The main building entrance is placed on the North-East facade. The building has a parallelepiped shape, with a central staircase space surrounded by open-space offices.
The overall built surface of this building is around 12400 m² and the usable height of each floor is equal to 3,60 m. The overall built surface of this building is around 12400 m² and the usable height of each floor is equal to 3,60 m. The number of occupants evaluated for this building is equal to 1200 persons.

The cooling system is a 4-pipe air-water system with fan coil units and the supply temperature of the ventilation air is equal with the indoor temperature. The ventilation airflow is taken from outside and treated within two Air Handling Units (AHU’s), being heated or cooled until it reaches the supply temperature, equal to the indoor air temperature. These AHU’s are places on the building terrace and contains each the following equipments:
- an Aluminium made plate heat exchanger with the following features: supply airflow: 28050 m³/h, exhaust airflow: 21800 m³/h, heat exchange efficiency 64% outdoor air temperature: -15ºC, indoor air temperature: 20ºC;
- a filtration compartment (F9 class filter with 95% removal efficiency [2] and differential manometer installed for the filter clogging determination);
- heating coil, with a total installed heating power Q_{heat}= 189 kW; the in/out water temperatures are 80/60ºC, while the in/out air temperatures are 2/22ºC; the maximal frontal air velocity is 2,5 m/s; the heating coil is equipped with a removable panel for the mounting of anti-freeze thermostat;
- a cooling coil, with a total installed cooling power Q_{cool}= 187 kW; the in/out water temperatures are 7/12ºC, while the in/out air temperatures are 35/19ºC; the cooling coil is equipped with a removable panel for the acces to the droplet separator and condensing tray;
- an isothermal humidification compartment, including a steam generator and a spraying counterflow system, providing a maximal steam flow of 140 kg/h;
- a centrifugal fan for the supply air with following features: airflow 28050 m³/h, total available pressure 300 Pa, maximum rotor speed 1200 rotations/min, installed electrical power P_{el}=13 kW;
- a noise attenuator with a total length of 1500 mm on the supply and of 900 mm on the exhaust side;
- a centrifugal fan for the exhaust air with following features: airflow 21800 m³/h, total pressure 250 Pa, maximum rotor speed 1000 rotations/min, installed electrical power P_{el}=3.5 kW;
- electrical panel for the control and regulation of the building equipments commissioning.

The building has a structure made of reinforced concrete frames and slabs, while the external masonry is composed of cellular concrete walls insulated with polystirene panels. The building glazing part is composed by curtain walls, while the indoor partitions are made of gypsum board nonstructural walls. At the last floor level, the building is separated form the outside by an insulated slab, having on its external side a circulation terrace. The overall uni-directional thermal resistances of the building elements, R (m²K/W), as well as the corrected resistances, R’, that take account of the thermal bridges effect [3,4], are presented in table 1.

<table>
<thead>
<tr>
<th>Building element</th>
<th>A</th>
<th>R</th>
<th>U</th>
<th>Σ(Ψ·l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[m²]</td>
<td>[m²K/W]</td>
<td>[W/m²K]</td>
<td>[W/K]</td>
<td></td>
</tr>
<tr>
<td>Curtain wall</td>
<td>6215</td>
<td>0,55</td>
<td>1,818</td>
<td>1087,11</td>
</tr>
<tr>
<td>Slab over the basement</td>
<td>1033</td>
<td>2,66</td>
<td>0,376</td>
<td>50,84</td>
</tr>
<tr>
<td>Slab over the last floor</td>
<td>1033</td>
<td>3,77</td>
<td>0,265</td>
<td>59,62</td>
</tr>
<tr>
<td>External wall</td>
<td>68</td>
<td>3,09</td>
<td>0,323</td>
<td>7,27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Building element</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Σ(Ψ·l)]/A</td>
</tr>
<tr>
<td>[W/m²K]</td>
</tr>
<tr>
<td>Curtain wall</td>
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<tr>
<td>Slab over the basement</td>
</tr>
<tr>
<td>Slab over the last floor</td>
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<tr>
<td>External wall</td>
</tr>
</tbody>
</table>

Table 1 (continued). Corrected thermal resistances

where:
A= building element surface (m²);
R= overall uni-directional thermal resistance corresponding to the A surface (m²K/W), [7]
U= thermal transmittance of the building element (W/m²K);
3. Energy balance at the building level using the monthly method

In order to perform the energy balance at the building level, the following terms have been evaluated (for sensible cooling only):
- The thermal flow by transmission through the building envelope (Φ_T, in W), separating the indoor spaces from the outdoor environment;
- The thermal flow necessary to cool the ventilation airflow (Φ_V, in W);
- The thermal flow due to internal heat gains (Φ_int, in W);
- The thermal flow due to the direct or indirect solar gains (Φ_S, in W);
- The energy need for the building cooling, Q_R (in kJ).

The methods presented here are designed to calculate the cooling loads needed to reach a prescribed indoor temperature. One of them (the third method which use TRNSYS software) can also evaluate the energy consumption of the air conditioning system for achieving this purpose. The following quantities were evaluated to determine the energy performance of the building:
- the thermal flow by transmission, Φ_T when the building is cooled at constant indoor temperature;
- the heat flow related to the building ventilation airflow (Φ_V) when it is cooled form the outdoor temperature to a supply temperature equal to the indoor air temperature, in this case, the temperature difference is zero so the energy dissipated by ventilation is nil:
  \[ Φ_V = 0 \]  \( (1) \)
- the contribution of internal heat gains and of overall solar gains (Φ_int+ Φ_S);
- the yearly energy demand for cooling to maintain the prescribed temperature inside the building, Q_R.

The methods used to calculate the energy required for space cooling are applied without taking into account the air humidity control inside the building. According to the monthly method, the cooling demand is calculated for the whole cooling period determined by summing monthly values for each month of the cooling period.

According to the other two methods, which use CODYBA and TRNSYS software, the cooling load is determined by summing the hourly values obtained, indicating at the end the energy load for the whole cooling period.

4. Evaluation of the cooling period

If the supply temperature of the fresh airflow is fixed at a constant value (equal to the indoor temperature), the heat losses by ventilation are zero (Φ_V=0) and the internal heat gains are amplified, resulting a high cooling period which leads to high energy consumption.

The easiest method to determine the cooling period is the graphical method, when representing and comparing the variations of two temperatures over a 1-year time lag: the average monthly temperature, θ_e (°C), for the geographical location considered, and the "equilibrium temperature" θ_eq(°C).

Based on the building’s energy balance, the "equilibrium temperature" (θ_eq) is calculated by the following relation [5]:

\[ θ_{eq} = θ_i - \frac{η(Φ_{int} + Φ_S)}{(H_T + H_V)} \]  \( (2) \)

where:
- θ_i is the indoor air temperature (°C);
- H_T is the overall heat transfer coefficient by transmission (W/K);
- H_V is the overall heat transfer coefficient by ventilation (W/K);
- η is the losses utilization factor for cooling (-).

According to the graphical representation of the two temperatures previously mentioned, the outside temperature curve crosses the equilibrium temperature curve in two points: the first point, \( τ_s \) (day begin) indicates the beginning of the cooling period, while the second point, \( τ_e \) (day end) indicates the end of the cooling period. Therefore, the cooling period will correspond to the period when the condition: θ_e>θ_eq is satisfied and could be graphically read on the abscissa between \( τ_s \) and \( τ_e \).

For the building analysed, the application of this method has lead to a cooling period extended between 15 May and 20 September (128 days)-Fig.2.

5. Description of CODYBA method

CODYBA (COMportement DYnamique des BAtiments) is an informatical tool, developed at INSA Lyon [6], created to calculate the buildings heating and cooling loads under variable outdoor and indoor conditions. It allows to evaluate the
hourly cooling or heating loads needed to maintain a given set-point temperature, or to calculate the indoor temperatures when the cooling or heating useful powers are known. CODYBA can be used to investigate the energy performance of buildings and it is specially oriented toward the optimization of buildings energy performance.

![Fig. 2: The cooling period of the building studied](image)

The CODYBA software is based upon a thermal transfer model applied to a building placed within an outdoor environment. This tool contains elementary models such as: walls, windows, thermal zones, internal gains, which are connected to the indoor or outdoor air nodes, composing the overall building thermal model.

The outside climate is taken into account by loading pre-defined weather data files within the CODYBA model. The envelope composition and the internal gains are input data and can be introduced by the users.

The building thermal behavior is due to the hourly method used by CODYBA, which solves thermal transfer equations for indoor air node with one-hour time step. These equations are written according to an analogy made between a thermal and an electrical problem which are formally similar. The first problem describes the heat conduction across a wall and the second one calculates the electrical current crossing an electrical resistance between two battery poles.

As depicted in fig.3 [6], the thermo-electric analogical sketch of the CODYBA method is based on the following elementary models: external walls, internal partitions, windows, slabs, internal gains, big wavelength radiation transfer and ventilation.

The thermal balance equations are written for several temperature nodes, resulting final values for: walls indoor surface temperature, walls outdoor surface temperature and indoor air temperature (only when its evolution is free).

![Fig. 3: The sketch of building flows used in the CODYBA model](image)

6. Description of TRNSYS method

TRNSYS (TRaNsient SYstem Simulation) is an extremely flexible software tool used to simulate the performance of buildings equipped with different HVAC systems, under non steady-state conditions (for weather and internal gains). Although most often the investigations are focused on energy problems, TRNSYS can equally be used to model other dynamic systems such as traffic flow, or biological processes.

The TRNSYS software uses, as CODYBA does itself, an hourly method to determine building heating cooling loads. The time step should be chosen by the user lesser than one hour, but in this case the computational time would be more prohibitive. According to the internal method of calculation of the walls heat conduction (by transfer functions coefficients) and to other improved subroutines, the results supplied by this software are much more accurate than those obtained with the previous two methods described herein.

A TRNSYS model is described by a set of modules (also known as subroutines or TYPES) interconnected in a logical manner to solve a particular task. It is a modular program, which allows the simulation of system performance by simulating overall performance of a building and its installations [7].

To run the program, the modules must be connected each other, by making an information flow diagram. This is a schematic representation of the transfer of information that is made between system components. All information that is received or transmitted by a component is represented graphically by an arrow.
7. Energy need for cooling

For each area of the building and for each month the energy need for the space cooling is calculated as follows [8]:

\[ Q_R = Q_{\text{sources},R} - \eta Q_{\text{Tr},R} \] (3)

where:
- \( Q_{\text{Tr},R} \) = the total energy transferred by the building in the cooling mode (kWh), determined by the equation (4);
- \( Q_{\text{sources},R} \) = the total building energy gain (external and internal) in the cooling mode (kWh), determined by the equation (5);
- \( \eta \) = the dimensionless utilization factor for heat losses, in the cooling case (-);
- \( Q_R \) = the building energy need for continuous cooling, (kWh).

The total energy transferred by the building in the cooling mode, \( Q_{\text{Tr},R} \) could be written [8]:

\[ Q_{\text{Tr},R} = Q_T + Q_V \] (4)

where, for each zone and calculation period, the terms appearing in the right side of the equation (4) have the following interpretation:
- \( Q_T \) = energy transferred by transmission through the building envelope (kWh);
- \( Q_V \) = energy transferred by ventilation by means of ventilation airflow (kWh);

The total building energy gain, \( Q_{\text{sources},R} \) is written:

\[ Q_{\text{sources},R} = Q_{\text{int}} + Q_S \] (5)

where:
- \( Q_{\text{int}} \) = energy gain from internal sources (kWh);
- \( Q_S \) = energy gain from solar radiation (kWh).

Because of the diurnal variation of climatic parameters during summer and of the building thermal inertia, a thermostat operating day/night or on/off has a smaller effect on the cooling demand than it has during winter, where there is a continuous need for heating. This leads to differences in the calculation procedures used for the cooling mode. So we will take in consideration the energy need for cooling corresponding to an intermittent operation mode, \( Q_{R,\text{interm}} \).

\[ Q_{R,\text{interm}} = a_{R,\text{interm}} Q_R \] (6)

where:
- \( Q_{R,\text{interm}} \) = the energy need for cooling taking into account the effect of intermittence (kWh);
- \( Q_R \) = the energy need for cooling calculated using equation (2) (kWh);
- \( a_{R,\text{interm}} \) = dimensionless reduction factor for intermittent cooling [8].

The energy need for cooling which has resulted using the three methods described previously is presented in table 2 and in Fig. 4:

| Energy need for cooling, \( Q_{R,\text{interm}} \) (kWh) |
|----------------|----------------|----------------|
| Monthly method | CODEYBA        | TRNSYS         |
| 971363         | 630066         | 330578         |

Table 2. Energy need for cooling an office building

Some observations should be made relatively to the HVAC system modeling used for the studied building. This solution with fresh air introduced with a constant indoor temperature is not profitable in terms of energy consumption, because the building would require cooling also during transition months (spring and autumn), when the cooling load could be partially covered by introducing outdoor airflow with outside temperature, thus obtaining a passive cooling [9].

Relatively to the density of human occupation, its variation influences in a great extent the magnitude of internal heat gains due to electronic office equipments (computers, printers or plotters).

At the same time, it also influences the ventilation airflow value, directly dependent of the number of persons present within the building. Accordingly, the energy consumption for cooling this ventilation airflow will vary with the occupant schedule [10].

When the ventilation airflow is supplied at the outside temperature, in the monthly method, the fact that the monthly average outside temperature, \( \theta_e \) is smaller than the indoor temperature, \( \theta_i \), leads to the apparition of heat losses by ventilation even during summer period! These losses are as important as the ventilation airflow is important too.

This observation shows that the monthly calculation method offered by the Mc001 methodology has here one week point and should be improved.

If the supply air temperature is fixed to a constant value (equal to the indoor temperature), the term \( Q_V \) representing the building heat losses by ventilation is nil, while the internal heat gains are very important. It results from this a high value of the cooling period, extended over almost one year, and a very high energy need for cooling (see the blue value in Fig.4)

This behavior is outlined by all the methods presented in this study, but, for the hourly methods, it is much more attenuated, because the model itself is much more accurate. This explains why the energy demands calculated with CODEYBA and TRNSYS (see red and green values from Fig.4) are much smaller than those obtained applying the monthly method.
Generally speaking, it has been shown that the monthly method doesn’t take into account with good accuracy the particularities of the ventilation and air-conditioning systems from tertiary buildings.

8. Solution
In order to eliminate the drawbacks of the monthly method and to make an accurate evaluation of energy needs, the supply air temperature should be variable, depending on the outside temperature [11]. Therefore, the monthly calculation method for the month endings should not be done for the whole month but by dividing the month duration into two intervals, namely:
- The period of time while the ventilation airflow is supplied with the outside temperature (untreated), when it is lower than the indoor temperature, and
- The period of time while the ventilation airflow is cooled and supplied with the indoor temperature, when the outside temperature is higher than the indoor temperature.
These intervals may be determined by several attempts, but then monthly method would become more complicated and harder to use.

9. Conclusion
In a thermodynamically closed system, any power dissipated by a system that is being maintained at a set point temperature requires that the rate of energy removal by the air conditioner increases. This increase has the effect that, for each unit of energy input into the system, the air conditioner removes that energy. In order to do so, the air conditioner should increase its power electrical consumption according to its performance coefficient (COP).
In conclusion, the cooling need of the overall system increase if we adopt the solution to supply fresh air with the indoor temperature.

Therefore simulation tools as TRNSYS prove to be more effective due to their complexity by allowing the use of various computing scenarios. This leads to results closer to reality compared with those obtained by the monthly method.
Due to the large number of components and connections that need to be defined, the software requires detailed information about the building and its systems.
This study also has presented the energy analysis of a building by using a more simplified simulation software, as CODYBA. Although the CODYBA is a software with a user-friendly interface, it is limited in use, as it can not calculate energy consumptions, but only building cooling loads.

References:
[6] CODYBA software, INSA Lyon, version 6.50 g