SIMULATION ANALYSIS OF ENERGY REQUIREMENTS IN HVAC SYSTEMS USED IN COMMERCIAL AND COMMUNITY BUILDINGS

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Abstract

Energy requirements for HVAC systems operation in buildings must be known on account of the necessity to determine the operation costs of the buildings and to carry out analyses aimed at improvement of design conceptions applied in buildings and installations as well as their operational parameters. It is commonly assumed that the most useful tool for such analyses is a detailed simulation model: building HVAC system. However, the number of details included in the model makes the analyses very labour demanding and may result errors when preparing simulation data.

In many cases simplified models may be equally useful if they reveal main directions of energy demand changes and values when analysing the essential factors. The paper compares the results of energy analyses made with the use of TRNSYS and with the use of a simplified model called "ideal" in some selected existing commercial and community buildings. The effect of the building construction, of indoor climate parameters as well as of the amounts of the supplied and fresh air are tested. Then the results are discussed.

1. Introduction

Air conditioning in buildings implies high costs of energy used for the air conditioning and transport. It is therefore necessary to determine the expenditure of money as well as to introduce rationalizing measures. There are many methods of various complexities and accuracies which may serve the purpose, however, the most useful are computer programmes simulating the system: ”building - HVAC system” installation. It is essential to be able to consider and analyse both the outdoor and indoor climate parameters, performance and control of the HVAC system as well as the conditions of the building use when optimizing measures are implemented.

However, the more detailed a simulation programme is, the more difficult it use is and the more time the input data preparing takes. Moreover, there is relatively much chance of getting wrong results due to e.g. errors in the input data. The inconveniences connected with the use of detailed simulation models limit effectively the number of their users. On the other hand, it is often sufficient to use less precise and simpler models if only they make the analysis of general directions of processes possible and if they take into account the effect of particular factors and parameters on the energy consumption.

The paper includes the results of calculation analyses presented in [1] regarding the energy consumption in the period of a whole year in some selected public buildings. The calculation was based on thermodynamic models of ideal HVAC with constant air flow and its results were then compared with the results obtained from a detailed numerical programme, TRNSYS [2], by simulation of the system: building - HVAC system, which was called a ”real” model. In result of the comparison of the results, it was possible to submit a thesis that in some analyses simple simulating models might be used and the idea of thermodynamic efficiency of HVAC systems could be employed.

2. Evaluation of the energy quality of air conditioning systems

A direct comparison of energy demands for alternative construction - architectural solutions and air conditioning systems applied in buildings yields a so-called ”non - orientated” estimation since there is no reference system i.e. a comparatory system, where optimum energy or external air and water demand occurs for air conditioning processes in given conditions.

The indices of energy or air and water consumption for such a comparatory system will be further called technological parameters (TP). The relevant values acquired in any air conditioning system, existing or being designed, may be compared with these indices. The ratio of the energy consumption in the comparatory and (ideal) real actual system is called here the energy efficiency of air conditioning system.

The energy efficiency values of air conditioning systems, obtained from calculation analyses, may be then used to evaluate the energy consumption of a real system in a given building when employing only the model of ideal air conditioning system.

2.1. Energy efficiency of air conditioning systems

It is suggested [3] ÷ [5] to use a so-called ”comparatory process” as the ideal air conditioning system. It is also advisable to use the term ”ideal system” or ”multi-factor system” [6 ÷ 12]. The latter ought to include even the increments of the air temperature in supply and extraction fans as well as changes in enthalpies of the supply air flux and extracted air flux resulting from energy loss or gain. The energy demand is defined for the period of a year’s use of the ideal and real system.

The air conditioning system efficiency is expressed as:

$$\eta = \frac{q_c}{q_r} \tag{1}$$

where:

- η - energy efficiency of the air conditioning system (air system, air-water system)
- q_c- elementary energy demand in the relevant comparatory system of air conditioning, kWh/m^2a
- q_r - elementary energy demand in the real air conditioning system, adequate to the comparatory system, kWh/m^2a or kWh/m^3a

The efficiency of the real system, defined as above, may be calculated for different forms of energy used in the system i.e. thermal, cooling, electric, primary or final energy. The model of the ideal air conditioning system (or process) is defined in a little different way in publications dealing with the problem [3÷12]. However general assumptions for the model are similar.

The simulation model of the ideal comparatory conditioning system is based on the following assumptions:

- It is technically possible to carry out each air conditioning process without taking into account energy characteristics of particular conditioning devices. The above means that the instantaneous efficiency of heat and mass change in the devices may vary between 0 and 1.
- The energy demand in the ideal system equipment q_{id} ought to be defined with the use of types of the conditioning devices applied i.e. single air conditioning processes should be similar to the processes occurring in the devices being constructed.
- The energy demand is related neither with the order in which the separate devices are placed nor with the way of control.
- The energy expenditure on the air transport is 0.
- The mass of the supply air is the same as the mass of the air extracted. Directions of processes when the air is cooled and moistened are contained in the area defined by tangents to the line φ = 100% drawn from the given point of the initial state of the air. In this area, the supply point may be reached directly by implementing only one conditioning process (without heating the air).
- The air is moistened only by circulating water at the efficiency η = 100%.
- The enthalpy recovery occurring between the air removed and the outdoor air takes place only by mixing.

2.2. Coefficient of energy expenditure on air conditioning processes.

Except the energy efficiency of air conditioning system, for practical purposes the energy demand index, suggested in [3], may be used. It may be called "energy index of air conditioning efficiency" and defined as:

$$\omega = \frac{q}{q_z} \tag{2}$$

where:

q - elementary energy expenditure (heating, cooling) on air conditioning processes in the ideal or real system, kWh/ m^2 a or kWh/m^{3}a,

q_z - elementary thermal load (heating, cooling) of the air conditioned building, kWh/m^{2}a or kWh/m^{3}a.

The elementary energy demand is defined for comparatory systems or the real system. Thus, ω coefficients may be denoted by indices:

$$\omega_{id} = \frac{q_{id}}{q_z} \tag{3a}$$

$$\omega = \frac{q_r}{q_z} \tag{3b}$$

2.3. Fields of application of the idea of system efficiency and indices of energy expenditure on air conditioning processes.

The use of the idea of energy efficiency of air conditioning system as well as the efficiency values obtained in the analyses, basing on simulation models of ideal systems as well as on ready detailed models of real systems, will facilitate solutions of some problems in the field of air conditioning.

It will be therefore possible to:
1) compare energy demands in different conditioning systems in order to find optimum solutions from the point of view of energy.
2) determine boundary values of energy demand indices for real, i.e. technically possible to implement, conditioning systems in order to improve the energy estimation of the systems being designed (or already existing).
3) fast calculate the estimated yearly demand of energy and media (air, water) used in air conditioning processes in buildings placed in given climatic conditions.

3. Thermodynamic model of the ideal air conditioning system.

Except the above mentioned general assumptions for a simulation model of the ideal air conditioning system, it is worth explaining the principle of the model construction in more detail. The model is called thermodynamic [6],[8] since the factors defining it are thermodynamic parameters of the outdoor climate and the indoor air, and the calculation schemes are based on i-x diagram.

Each model will therefore include dependence of TP on the analysed factors which effect TP i.e. thermal - humidity loads of buildings, air parameters assumed in the room, external air parameters supply air amount inclusive of external air amount. The calculation schemes in the model will comprise selected states of functioning, the most optimum ones for given initial conditions, i.e. positions of points, lines or areas in i-x diagram, which will make calculation of optimum TP values possible.

The calculation schemes will be here a system of lines in i-x diagram which will divide the outdoor climate region, characteristic of the particular region of the country, into separate tones, to which the above mentioned states of functioning will be assigned in a logical way.
Such state of functioning will consist of elementary processes of the air conditioning (heating, mixing, cooling). When creating thermodynamic models, it is therefore necessary to ensure optimum variability of external air flux and mass within a year’s time of building use so that instantaneous air parameters in a room could be maintained in the relevant point of the area (or line) and there wouldn’t occur, when not justified by necessity, contradictory elementary air conditioning processes (e.g. simultaneous air cooling and heating).

The most important assumptions and description of principles of defining optimum states of functioning as well as basic equations for TP calculating (i.e. material consisting thermodynamic model of total air conditioning systems) may be found in [6], [8] and [12].
Extensive description of the method algorithms and simulation programmes listings for selected ideal air systems with constant and variable air amount as well as for an air - water system are presented in [1].

The numerical programme simulating the ideal total air conditioning system covers the following operations:

1. Instantaneous thermal loads with sensible heat are calculated for the building analysed (at are hour's time step) by a programme simulating thermal loads at non - stationary heat flow. The authors used TRNSYS 13.6 TYPE 56. The calculation results are input data for IDEALSYS programme as well as for further TRNSYS application in order to simulate the real air conditioning system.
2. The minimum amount of the external air, MI, necessary in respect of hygiene and its maximum amount, MA, are declared. Yearly humidity gains of the building, W, are declared at the same time step as thermal loads. The temperature of cold water supplied to the air coolers is declared.
3. The other co-ordinates of basic points of the polygon defining the area of the assumed air parameters field in room, are calculated, having declared TI, TA, FI, FA values i.e. maximum (A) and minimum (I) values of the air humidity and temperature in the air conditioned room.
4. Instantaneous directional coefficient of the air processing in the air conditioned room, ε, and instantaneous co-ordinates of the basic points or lines of the area supplied in i-x diagram are calculated for the declared air amounts MI and MA. The co-ordinates may be determined with or without taking into account the air enthalpy increase in supply and extracting fans or enthalpy variability in ventilation network ducts.
5. Instantaneous parameters of the external air, Z, are assigned to the relevant parameter zone in the calculation system mentioned above. For the position of Z point, optimum elementary processes of the air conditioning are selected, which form an instantaneous state of the system functioning. The air is supplied to the defined supply parameters and the optimum amount of external air is defined.
6. In every elementary air conditioning process occurring in a given state of the system functioning, instantaneous optimum values of heat, cooling, external air (for air systems) and water (to moisten the air) demands are calculated (they were called TP above). These values are then totalled in a yearly cycle of the system use, having taking into account the whole time of the building use declared in the programme.
7. Optimum supply air amount (inclusive of external air) is calculated for VAV systems.

4. Buildings selected for analysis. Description of the cases analysed and of the simulated air conditioning system

These building types were selected for simulation analyses i.e. a bank where the floor area of the operational rooms was 900 m^2, an office building of the area of rooms and conference halls of 2700 m^2 and a theatre of the area of 2450 m^2. The aim of the selection was to choose buildings which would be substantially different from one another in their construction and, above all, in the way of use and therefore the hours and weekly run of indoor climate parameters.

The above was taken into account both when calculating thermal - humidity loads and when declaring the way of controlling the real system performance in each of the buildings.
The target of the analyses was checking if it was possible to get similar and, above all, reliable simulation results for different building types which could confirm the thesis submitted regarding the usefulness of the ideal system models for some analyses and of

basing on the air conditioning system efficiency idea, in order to calculate yearly energy expenditure on air conditioning.

Each of the buildings was constructed alternatively of three different types of walls whose heat transfer coefficients, were the same but thermal capacities were substantially different (the walls were of so-called light, medium and heavy construction).
In separate simulations, the ambient air temperature values were changed within a year's period of time which yielded different maximum temperature values in the summer (e.g. 24°C, 25°C, 26°C).

The analysed buildings were placed in 7 different towns in Poland. On the basis of many years measurements, so-called averaged year's parameters of the outdoor climate had been worked out for those towns (at one hour's time step) (solar radiation, temperature, humidity, wind velocity). The towns were characteristic of the climate in Poland.

The ideal and real air conditioning system were simulated at a constant VAC air amount. The system diagram is shown in Fig.2. For the separate buildings it differs only in the number of VAC zones. In both programmes the supply air amounts declared were calculated on the basis of thermal energy gain rate obtained from TRNSYS model, TYPE 56 and on the basis of the difference between the inlet and outlet air temperature, assumed for each building. Conventional air distribution systems were assumed. In one case, in order to verify how both models responded to a change in the supply air amount, simulations for two different air amounts were carried out (the bank).

5. Discussion of the simulation results

The simulation results were worked out in a form of charts presenting indices of the yearly consumption of thermal and cooling energy, $mJ/m^2/a$ as a function of the factor tested.
The indices as well as the values of the system energy efficiency index were obtained from simulation by the ideal and real air conditioning system model (TRNSYS 13.6).

The paper presents some charts (see Fig.3 - Fig.8) regarding 3 buildings for one of the temperature values tested in the buildings, i.e. $t_{imax} = 24^oC$, as a function of the geographical location in Poland (the towns numbered from C1 to C7) and of different types of walls.

Fig.9 and Fig.10 shows the results obtained for the bank building in the case when supply and outdoor air amounts were increased by 20%. It should be pointed out that the qualitative changes of the results as a function of the factors tested, acquired when using TRNSYS model (it was assumed that it represented the real air conditioning system) were obtained also when using the ideal system model. The above refers to the tested effect of the partition construction, the way of the building use resulting from its function, the yearly temperature run in the room and the supply air amount.

5.1. The effect of the outdoor climate parameters

Both in the real system model and in the ideal system model, the similar effect of the outdoor climate on the energy consumption index is revealed. This effect results not only from the obtained differences in thermal loads between the buildings in different towns, where the average temperatures of the outdoor air and solar radiation values are different, but also from the different enthalpies of the air conditioned outdoor air.

Apparently, in both cases it is possible to separate towns where the summer climate is equally ”mild” for all the buildings and equally ”severe” for all the buildings. These relations occur also for the winter time. In case of the theatre the relations are a little worse but it results from the way and time of its use, much different than in the case of the office building and bank (2 days a week, evening hours).

5.2. The effect of the change in the supply and external air amount

This effect is shown using the bank as an example (Fig.9 and Fig.10) where the amounts of external and supply air were increased by 20% when compared to the case shown in Fig.7 and Fig.8. Both the results obtained from the real system model and from the ideal system model show a reliable direction of changes i.e. the elementary cooling demand in the summer decreases by 40-50% on the average (making better use of ”the outdoor air energy potential - free cooling”) whereas the energy expenditure on the external air heating increases by about 20-30%.

The authors would also like to point out that when repeating the calculation of the building thermal loads by TRNSYS during simulation of the real system with an increased air amount, small discrepancies in thermal loads of the bank were found (heat loss and gain), which theoretically should not have occurred, in spite of the unchanged parameter values. It is a remark directed to the authors of TRNSYS (and not the only one now when much experience in the program implementation has been acquired).

5.3. The effect of the assumed field of the ambient air parameter in the buildings

Simulations were carried out also at $t_{imax} = 25^oC$ and $t_{imax} = 26^oC$. Both in the real system model and in the ideal system model, when t_{imax} increased, the cooling load and cooling energy consumption in the buildings decreased so much that at $t_{imax} = 26^oC$ the cooling energy demand fell to very low values in almost all the towns and was even equal zero while employing the many years’ average parameters of the outdoor climate.

6. Energy efficiency indices for the system with constant air amount

The indices were calculated after the definition given in formula (1) and their values are shown in tables.

For cooling and thermal energy the values were found within the limits 1÷10 while, generally, they were smaller for cooling energy than for thermal energy. It is logical since energy potential of the external air was used for room cooling, both in the real system and particularly in the ideal system.

In the case of functionally similar buildings (bank, office building) the values of the indices for separate towns were also similar both in respect of thermal and cooling energy. The values were, however, different for the building of different type of use (theatre) - generally they were higher.

It is apparent that the value of the energy efficiency index of the air conditioning system, defined as above, strongly depends on the outdoor climate parameters values of the town and the building type, characterized by thermal load variation and the time of its use during a day and a week.

7. Conclusions

It has been proved in the paper that thermodynamic models of so-called ideal systems may be used in comparatory analyses where the effect of basic factors of building construction and use on energy consumption for air conditioning is determined, instead of simulations models of real systems.

- The results obtained from the simulation model of ideal system may be assumed as a ”standard” for real systems being designed or already existing.
- The results obtained in the ideal model show that there are particularly great possibilities of energy demand reduction in the tested buildings hidden in the way in which air conditioning processes are carried out in summer i.e. regarding cooling energy.
- The energy efficiency defined in the air conditioning air system tested, significantly depends on the assumed field of indoor parameters, on the field of outdoor parameters characteristic of the town tested, the type of building and the way of its use.
- In order to evaluate the yearly energy demand for air conditioning processes in real systems in particular buildings and towns, it is possible to use the values of the system energy efficiency index, η, and apply only the model of ideal systems.

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Nomenclature

MI, MA - minimum and maximum amount of the external air,
TI, TA, FI, FA- minimum and maximum values of the air temperature and humidity in the air conditioned room,
TP - technological parameters,
VAV - variable air volume system,
VAC - constant air volume system,
q - elementary energy expenditure,
q_c ,q_r - elementary energy demand in the comparatory and real air conditioning system,
q_{id} - energy demand in the ideal system equippment,
q_z - elementary thermal load,
η - energy efficiency.

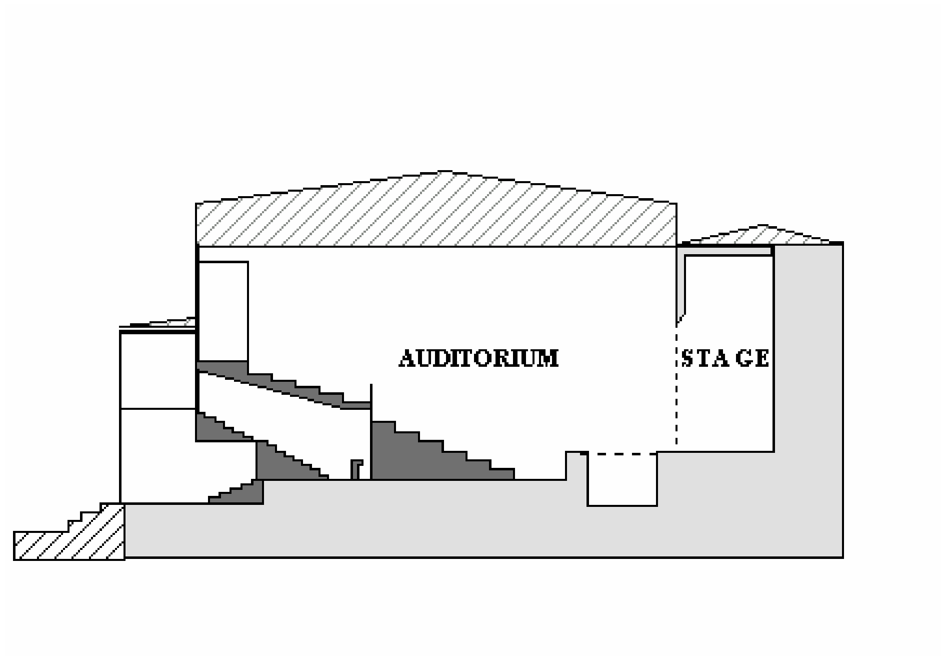

Fig. 1 Cross-section of one of the simulated buildings (theatre)

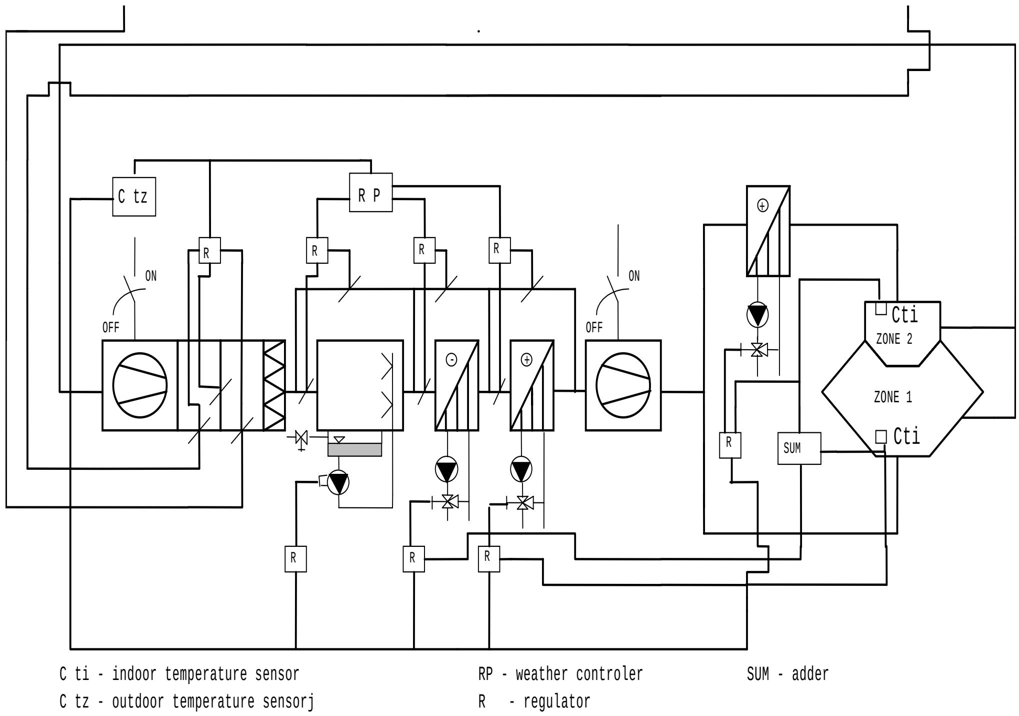

Fig. 2. Air conditioning system

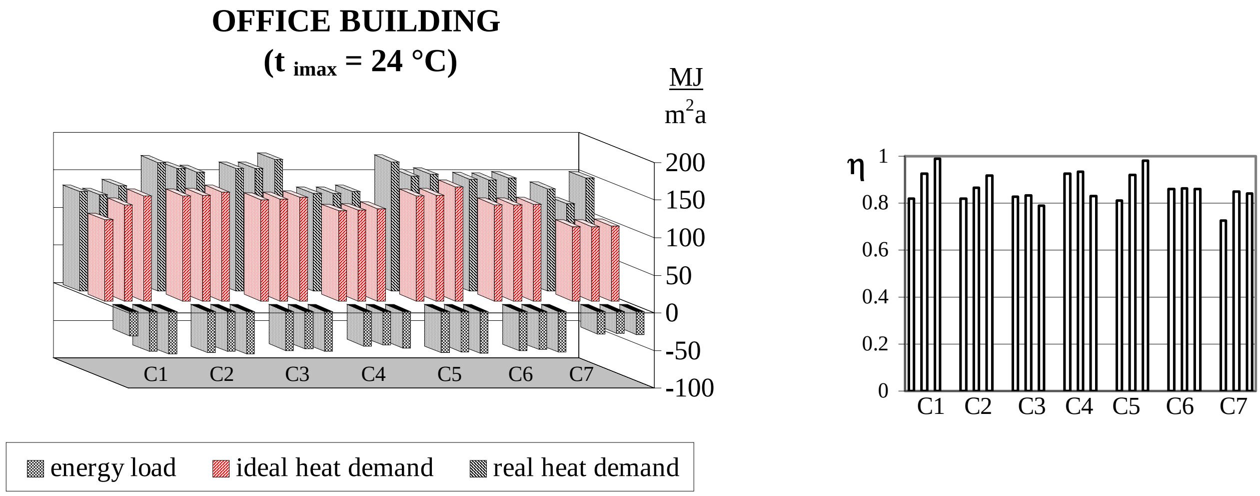

Fig. 3. Thermal loads and heat demand in ideal and real system. Energy efficiency of the real system

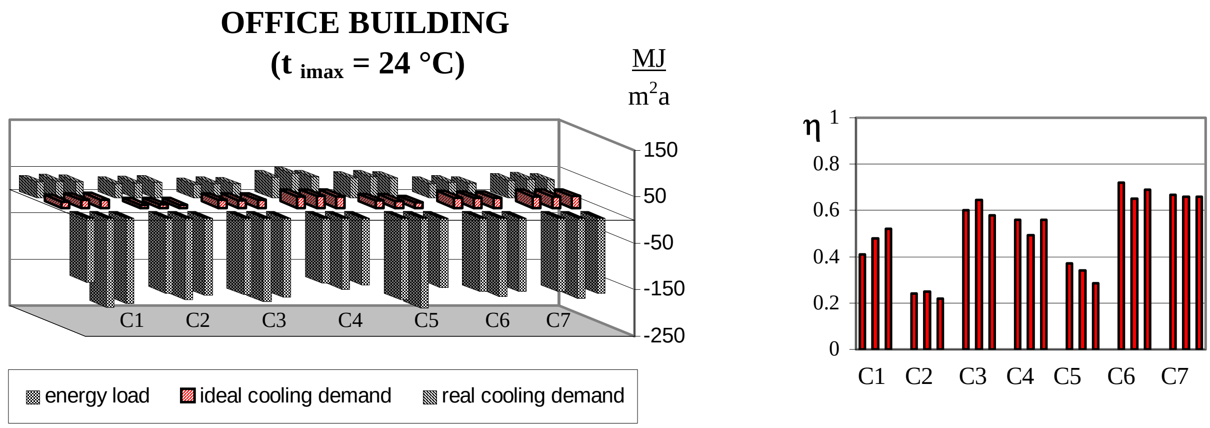

Fig. 4. Thermal loads and cooling demand in ideal and real system. Energy efficiency of the real system

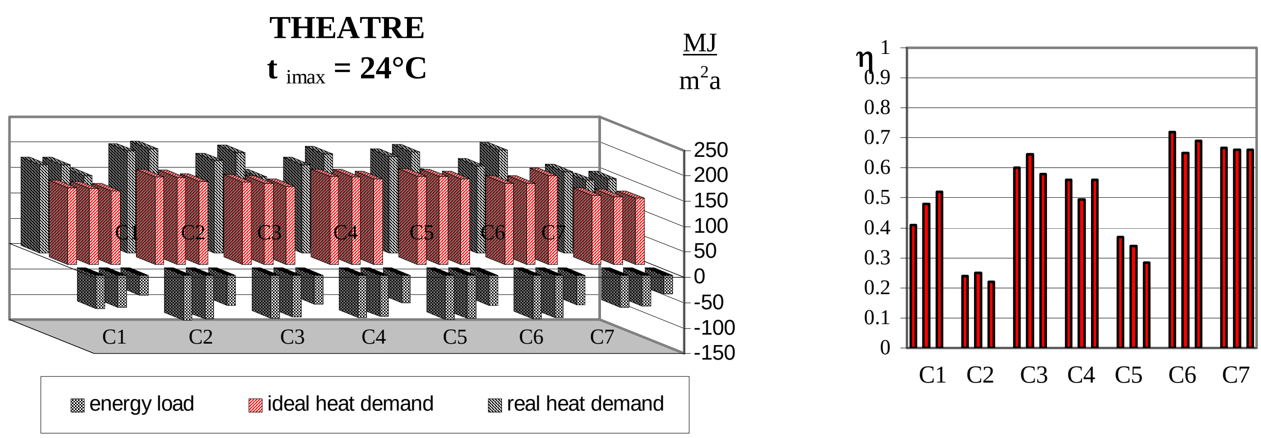

Fig. 5. Thermal loads and heat demand in ideal and real system. Energy efficiency of the real system

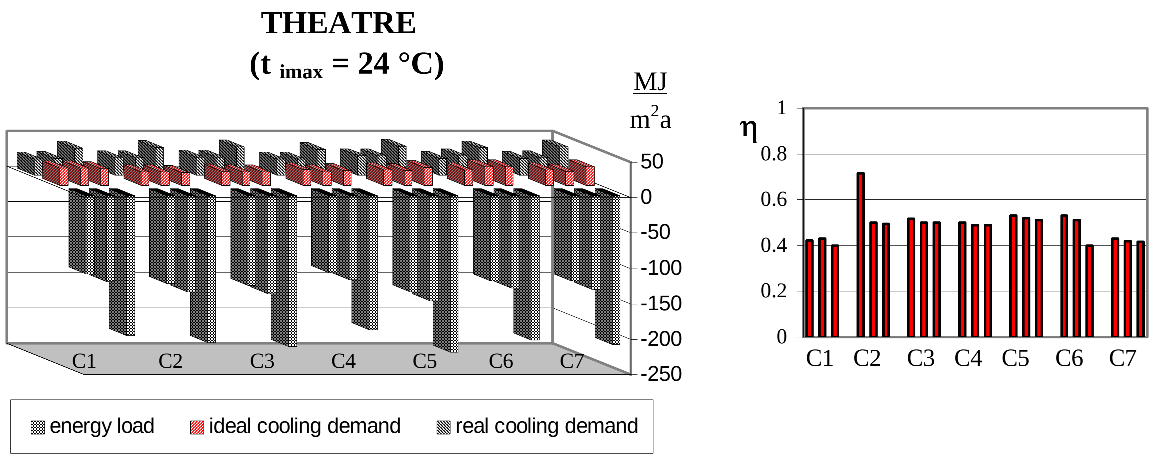

Fig. 6. Thermal loads and cooling demand in ideal and real system. Energy efficiency of the real system

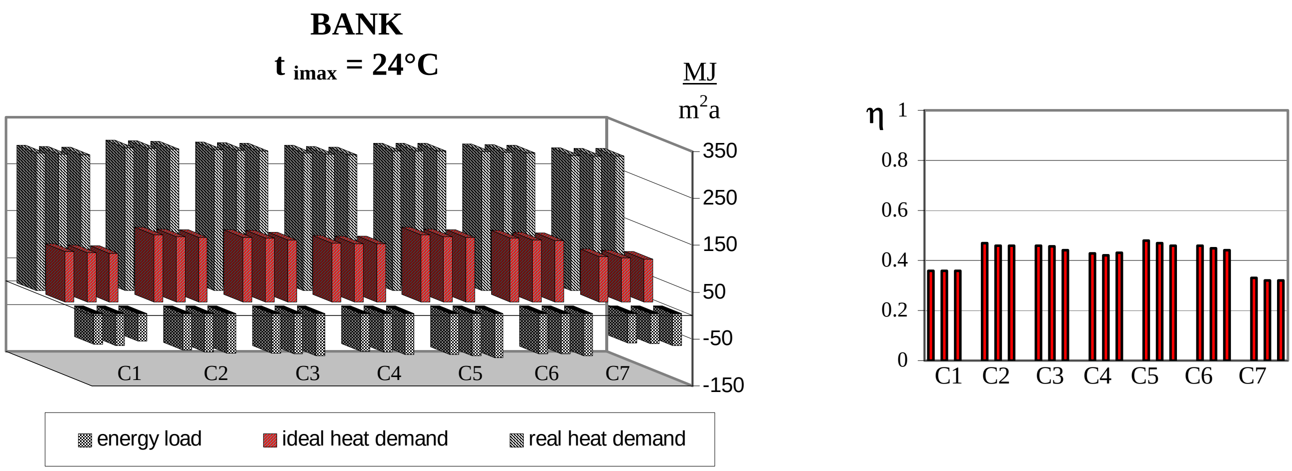

Fig. 7. Thermal loads and heat demand in ideal and real system. Energy efficiency of the real system

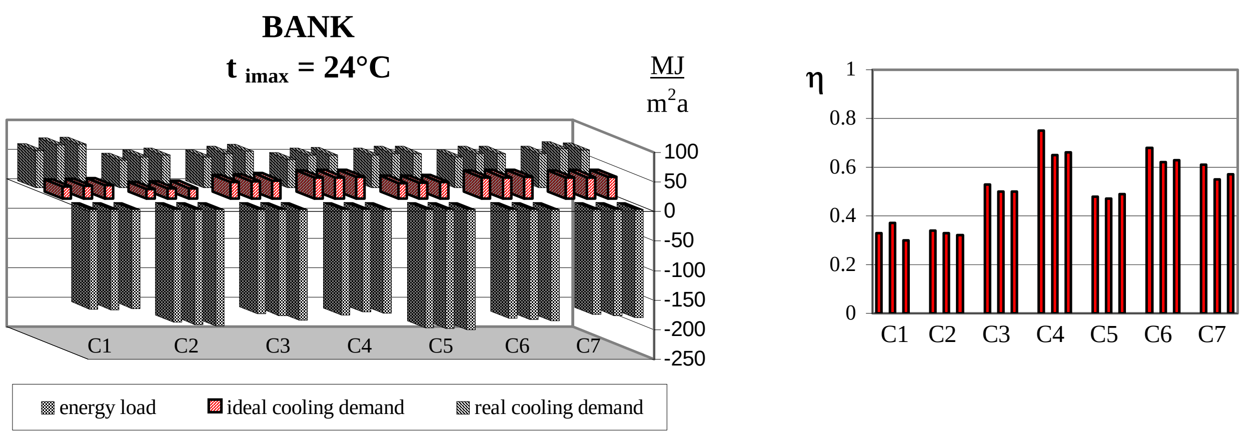

Fig. 8. Thermal loads and cooling demand in ideal and real system. Energy efficiency of the real system

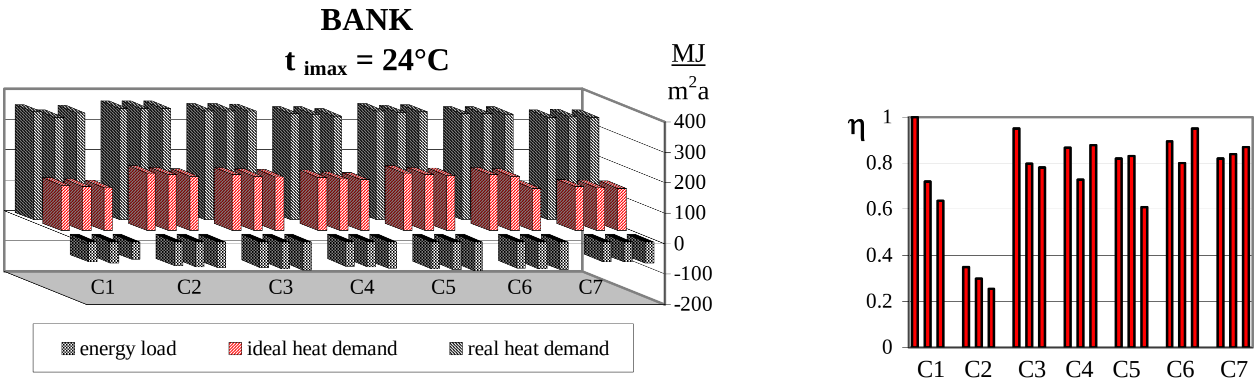

Fig. 9. Thermal loads and heating demand in ideal and real system. Energy efficiency of the real system. (Supply and external air volume rate increased by 20%)

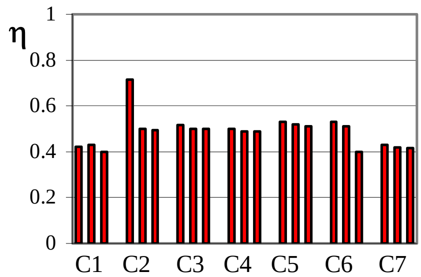

Fig. 10. Thermal loads and cooling demand in ideal and real system. Energy efficiency of the real system. (Supply and external air increased by 20%)volume rate