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THE INFLUENCE OF AIR-CONDITIONING OPERATION SCHEDULE ON ENERGY CONSUMPTION FOR COOLING

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Abstract. *In this paper, presented is the influence of air-conditioning operating schedule on the daily cooling energy consumption. Analysis has been made on the basis of a computer program for dynamic simulation of an air-conditioned room thermal behavior. The program has been developed at the Department for Thermal Engineering at the Faculty of Mechanical Engineering, University of Belgrade. Analysed are three different air-conditioning operating schedule, cooling loads and daily energy consumption, at summer design conditions for Belgrade. The obtained results have been compared, and here upon given a review of the daily energy savings.*

1. INTRODUCTION

In order to investigate the influence of air-conditioning operating schedule on the daily cooling energy consumption, simulated are three different operating schedules for a typical air-conditioned room. Simulation has been aided by a computer program for dynamic simulation of an air-conditioned room thermal behaviour, which has been developed at the Department for Thermal Engineering at the Faculty of Mechanical Engineering in Belgrade. The program, written in C language, which works under Windows operating system, is based on a detail mathematical model of non-steady state heat transfer in an air-conditioned room [7].

2. HEAT TRANSFER IN AN AIR-CONDITIONED ROOM

The analysed air-conditioned room is considered to be typical of residential or commercial buildings. Its shape, dimensions, construction and position are in common with many rooms in a multi-story buildings. The building is in an open position, with no objects near by; therefore its windows are not shaded. Internal dimensions of the room are

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5 by 4 by 2,6 m. Its double-glazed window in the facade wall measures are 2,4 by 1,5 m. Wooden 1 by 2 m door are in a facade-facing wall, leads into the central corridor. All other surfaces are adjacent to the air-conditioned spaces (figure 1.).

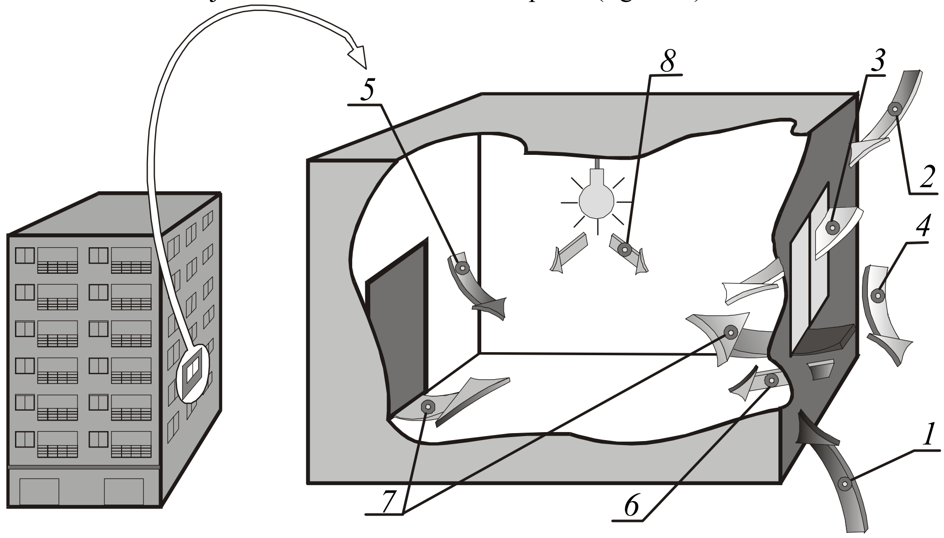

Fig. 1. Air-conditioned room in a multi-story building and mechanisms of heat transfer: 1 - Ground radiation, 2 – Sky radiation, 3 – Solar radiation, 4 – Outdoor convection, 5 – Indoor convection, 6 – Conduction, 7 – Air infiltration, 8 – Light bulb radiation.

Table 1. Building construction materials properties [5]

Construction material	Thickness δ[cm]	Thermal conductivity λ [W/m^{2}K]	Heat capacity c_p [kJ/kgK]	Density ρ [kg/m^3]
Facade wall: m=390kg/m^2, U=0,80 W/m^{2}K				
Face brick	12	0,56	0,92	1300
Insulation, mineral wool	3	0,043	0,84	80
Common brick	12	0,76	0,92	1800
Cemented mortar	1	0,81	1,05	1600
Floor construction: m=205 kg/m^2, U=1,2 W/m^{2}K				
Cemented mortar	1	0,81	1,05	1600
Concrete layer	20	1,50	1,10	900
Parquet	1,5	0,14	2,10	700
Carpet (woolen)	1	0,05	1,68	380
Inner wall: m=250 kg/m^2, U=2,63 W/m^{2}K				
Cemented mortar	1	0,81	1,05	1600
Common brick	12	0,76	0,92	1800
Cemented mortar	1	0,81	1,05	1600

Mathematical model of non-steady state heat transfer consists of a system of equations that describe convection, conduction and radiation, and include appropriate boundary and initial conditions. The equation system describing one-dimensional non-steady state conduction is solved using finite volumes explicit numerical method [6]. In such a way, partial differential equation for conduction:

$$\rho \cdot c \frac{\partial t}{\partial \tau} = \left(\frac{\partial^2 t}{\partial x^2} \right), \tag{1}$$

is transformed into the form:

$$\frac{\rho \cdot c_p \cdot \Delta x}{\Delta \tau} t_i^1 = \frac{\lambda_i}{(\delta x)_i} t_{i+1}^0 + \frac{\lambda_{i-1}}{(\delta x)_{i-1}} t_{i-1}^0 + \left(\frac{\rho \cdot c_p \cdot \Delta x}{\Delta \tau} - \frac{\lambda_i}{(\delta x)_i} - \frac{\lambda_{i-1}}{(\delta x)_{i-1}} \right) t_i^0 , \tag{2}$$

which enables temperature at the point *i* in the next period of time τ+Δτ to be calculated, using temperature values for the period τ. Appropriate boundary condition for the point *i* at the surface in contact with the air is:

$$\frac{\rho_i \cdot c_{pi} \cdot \Delta x_i}{\Delta \tau} t_i^1 = \frac{\lambda_i}{(\delta x)_i} t_{i+1}^0 - q + \left(\frac{\rho_i \cdot c_{pi} \cdot \Delta x_i}{\Delta \tau} - \frac{\lambda_i}{(\delta x)_i} \right) t_i^0 , \tag{3}$$

where q heat source or risk for boundary conditions and for the point *i* at the surface between two wall layers:

$$\left[\rho_{i-1} \cdot c_{p,i-1} \frac{(\delta x)_{i-1}}{2\tau} + \rho_i c_{p,i} \frac{(\delta x)_i}{2\tau} \right] (t_i^1 - t_i^0) = \frac{\lambda_i (t_{i+1}^0 - t_i^0)}{(\delta x)_i} - \frac{\lambda_{i-1} (t_i^0 - t_{i-1}^0)}{(\delta x)_{i-1}} . \tag{4}$$

Convection is defined by appropriate criteria equations, for vertical and horizontal, as well as for indoor and outdoor surfaces, separately. Convection (film) coefficients for the horizontal, vertical and outside surfaces are given in equations (5-7) respectively:

$$\alpha_h = 0.74 \cdot |t_a - t_w|^{0.229} \uparrow \text{q} , \qquad \text{and} \qquad \alpha_h = 1.41 \cdot |t_a - t_w|^{0.326} \downarrow \text{q}, \tag{5}$$

$$\alpha_v = \{[1.5(\Delta t / h)^{1/4}]^6 + [1.23(\Delta t)^{1/3}]^6\}^{1/6} , \tag{6}$$

$$\alpha_e = 3.5 + 5.6 \cdot w . \tag{7}$$

Heat flux transferred by convection from the surface "j" to the air, equals to:

$$q_{Cj} = \alpha_j (t_a - t_j) . \tag{8}$$

Radiation heat transfer is very complex due to many radiation sources.

Outside the room, there appear:

- Solar radiation,
- Sky radiation and
- Ground radiation.

Total heat flux transferred by radiation from the outside surface "j" is:

$$q_{Rtot,ex,j} = q_{ground,j} + q_{Sky,j} + q_{Ddj} . \tag{9}$$

Solar radiation is treated differently depending on whether it is about direct or diffuse one, thus enabling more precise calculation of Solar radiation heat transfer for each surface. All outside surfaces are considered to be exchanging heat by temperature radiation with the sky and ground. Model of non-steady state heat transfer for window is based on ASHRAE method [2].

Inside the room, there appear:

- radiation heat transfer among the indoor surfaces,
- solar radiation transmitted through the window,
- short and long wave light radiation.

Heat is exchanged by low temperature radiation among all the room surfaces and is defined by appropriate radiation configuration factors F_{ij} [3]:

$$q_{TR,j} = \sum_{i=1}^{n} \frac{1}{A_j} \cdot \frac{C_C \cdot F_{ij} A_i}{1 + (1/\varepsilon_i - 1)F_{ij} + (1/\varepsilon_j - 1)F_{ji}} \left[\left(\frac{T_i}{100} \right)^4 - \left(\frac{T_j}{100} \right)^4 \right]. \tag{10}$$

The heat flux tranfered from the internal surface "j" by Solar short-wave and both, short and long-wave lighting radiation is:

$$q_{SL,j} = \sum_{i=1}^{n} (q_{SD,i} + q_{Sd,i} + q_{L,sw,i}) \cdot \frac{F_{ij}(1 - \varepsilon_{sw,j})}{1 + (1/\varepsilon_{sw,j})F_{ij}} + \sum_{i=1}^{n} q_{L,lw,i} \cdot \frac{F_{ij}(1 - \varepsilon_{lw,j})}{1 + (1/\varepsilon_{lw,j})F_{ij}}, \tag{11}$$

and the total heat flux exchanged by the internal surface "j" is:

$$q_{Rtot,in,j} = q_{TR,j} + q_{SL,j}. \tag{12}$$

Thermal balance has been made for each surface. For the case of the air-conditioning system being "off", infiltration of the outside air has been taken into account:

$$Q_{INF} = V \cdot \rho \cdot c_P (t_{out} - t_{in})_{air}. \tag{13}$$

3. SIMULATION OF THE ROOM THERMAL BEHAVIOR FOR DIFFERENT AIR-CONDITIONING SYSTEM OPERATING SCHEDULES

In order to investigate the influence of an air-conditioning operating schedule on the daily cooling energy consumption, simulated are three different operating schedules:

- continuous operation,
- 16 hours per day operation and
- 10 hours per day operation.

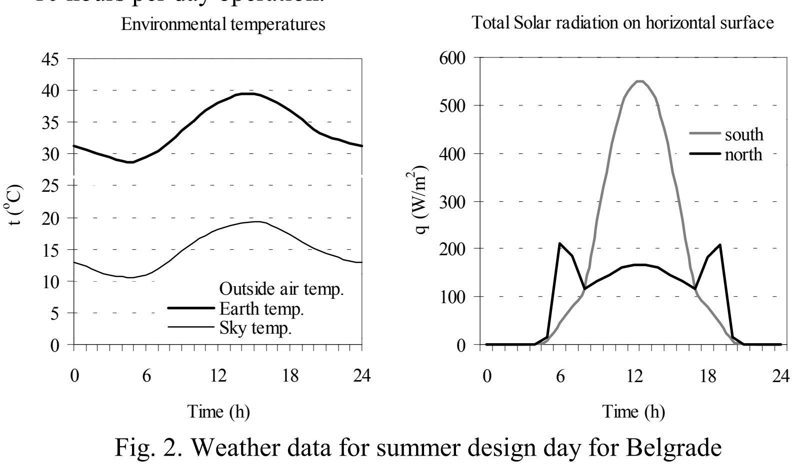

Fig. 2. Weather data for summer design day for Belgrade

Calculation of the room envelope temperature fields is done with periodical outside influencing values, for the one-day period. Simulation has been done for the summer design conditions for Belgrade [1] (figure 2.). The initial calculation temperature is 28°C, and the program runs until the daily temperatures and cooling load become steady state.

The results shown in figures 3. and 4. indicate heat gain and cooling load for the period of one week, and three different operating schedules of an air-conditioning system. Analysed are south and north oriented rooms, chosen as characteristic ones.

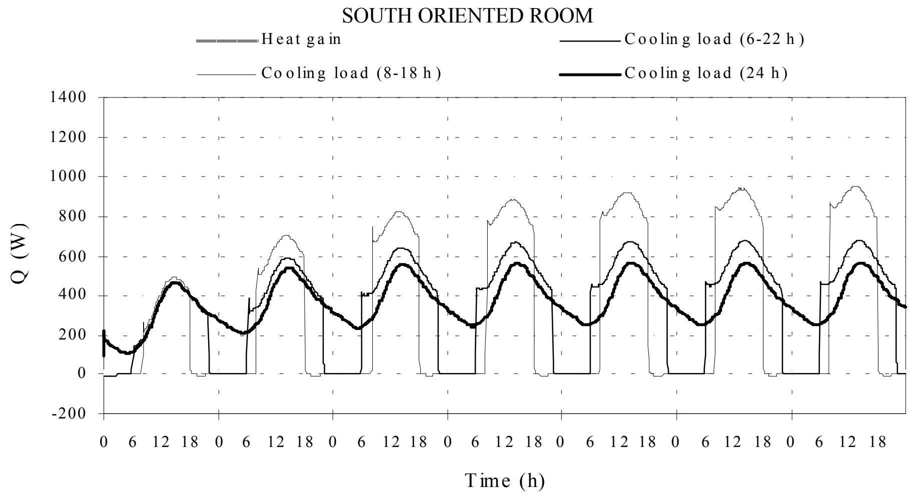

Fig. 3. Heat gain and cooling load for south oriented air-conditioned room under three different operating schedules.

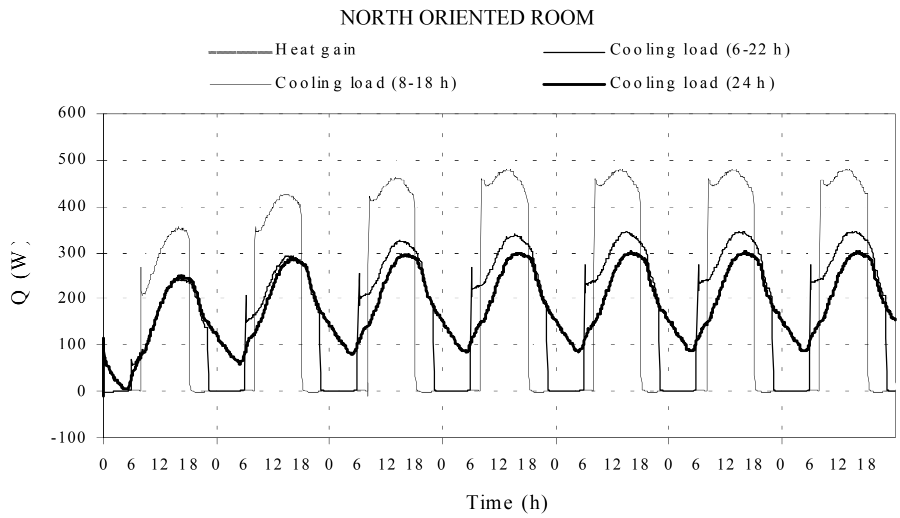

Fig. 4. Heat gain and cooling load for north oriented air-conditioned room under three different operating schedules.

The simulation results have proved that intermittent air-conditioning operation leads to an increase of the daily cooling load profile values. Once the air-conditioning system is shut down, the indoor air temperature starts rising, on account of walls cooling, until thermal equilibrium is achieved. Since there are no conditions for heat to be transferred, certain amount of heat is being stored in the building envelope. The next day, when the air-conditioning system is started, the indoor air temperature starts dropping, thus enabling heat transfer. But, in that moment, the cooling load value is higher than the previous day, because of the superposed heat gain and the heat stored inside the walls. This process is repeated continuously until the steady state of cooling load is achieved.

The daily operating time reduce from 24 to 16 hours leads to an 16,5% increase in the maximum cooling load value for the south oriented room, and 13,5% for the north oriented one. Further reduction of the air-conditioning daily operation down to 10 hours results in an 40,5% increase of the maximum cooling load value for the south oriented room, and 37,4% for the north oriented one. The less the daily working hours are, the higher increase of the daily cooling loads profile are. Thus, intermittent air-conditioning operation requires higher cooling capacity. The increase of maximum cooling load values in correlation with the daily operating hours is given in figure 5.

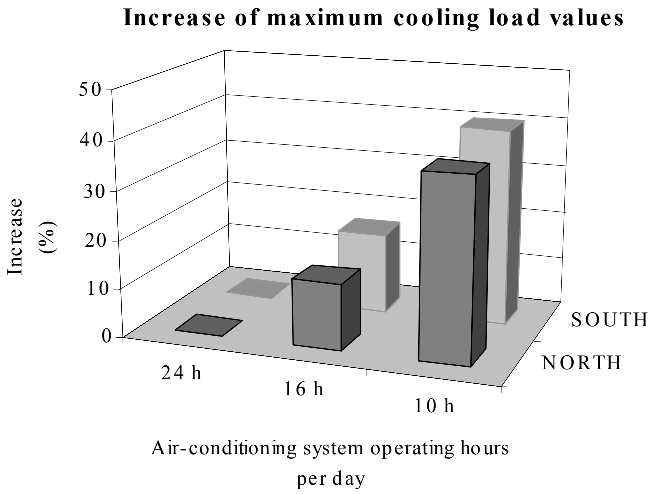

Fig. 5. Increase of maximum cooling load values for air-conditioned room under three different operating schedules.

4. DAILY CONSUMPTION OF COOLING ENERGY

Daily consumption of cooling energy is determined as:

$$P(\tau) = \int_0^\tau Q(\tau) \cdot d\tau \,. \tag{14}$$

The simulation program works with the fixed 5 seconds time step, but the obtained results of temperatures, heat gain and cooling loads are written in output files for every 60 seconds. Such a storing data is chosen in order to avoid too large number of output values, not affecting accuracy. The output file can be imported into a spreadsheet application for further calculation process. In that way, the daily consumption of cooling energy may be calculated as:

$$P(n) = \sum_{i=1}^{60 \cdot n} \frac{Q_i}{60} \cdot n \,. \tag{15}$$

The cooling energy daily consumption in correlation with air-conditioning operating hours per day is given in figure 6, for both south and north oriented room.

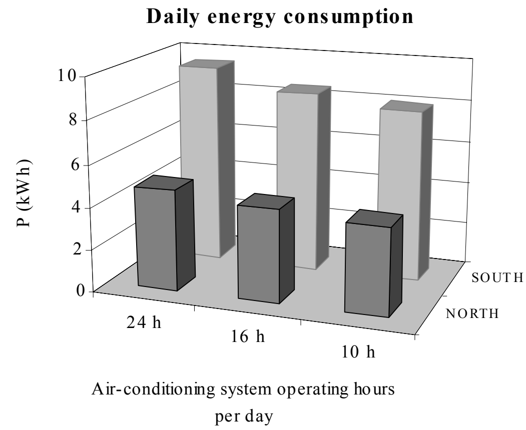

Fig. 6. The cooling energy daily consumption for an air-conditioned room under three different operating schedules.

Daily energy savings accomplished by intermittent air-conditioning operation are shown in figure 7, concerning only savings of energy required for air cooling.

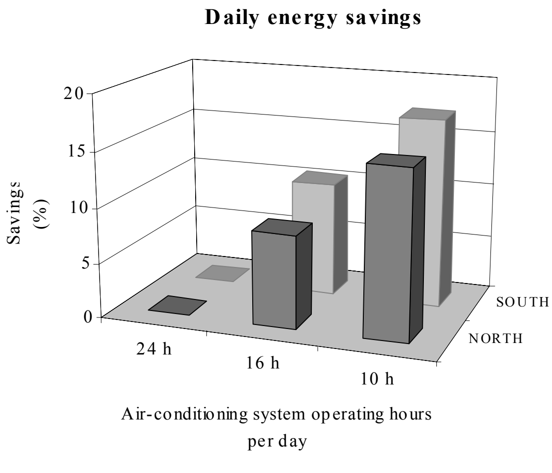

Fig. 7. The cooling energy daily savings for an air-conditioned room under three different operating schedules.

In this analysis electrical energy consumption needed for fans and pumps operation is not taken into account, neither is the energy needed for the outdoor air treatment. The obtained results have shown that the cooling energy consumption for intermittent air-conditioning operation schedule is less than in the case of 24 hours operating schedule. However, savings in cooling energy consumption are not proportional to the number of operating hours per day. For instance, when air-conditioning works with a time break of 33,3% during the day (16 hours) the saved cooling energy consumption is not 33,3%, but 10,4%, for south oriented room, and 8,5% for the north oriented one. This disproportion results from the cooling load values increase for intermittent air-conditioning operating schedule.

5. CONCLUSION

Analysis of the obtained simulation results has shown daily energy savings in cooling energy needed for the model room air-conditioning. Analysed are three air-conditioning operating schedules and cooling energy consumption. Both electrical energy consumption needed for fans and pumps operation and the energy needed for the outdoor air treatment, are not taken into account. Intermittent operating schedule leads to an increase of cooling load values, thus cooling energy savings are not proportional to number of operating hours per day.

Notation

- A - surface (m^2)
- c - heat capacity (J/kgK)
- Cc - Radiation constant, Cc=5,67 W/m^2K^4
- Fij - Radiation configuration factor (-)
- h - characteristic height (m)
- q - specific thermal flux (W/m^2)
- Q - thermal flux (W)
- t - temperature (^oC)
- T - absolute temperature (K)
- U - U-value (W/m^2K)
- V - volume (m^3)
- w - wind velocity (m/s)
- α - film coefficient (W/m^2K)
- δ - layer thickness (m)
- ε - emissivity (-)
- λ - thermal conductivity (W/mK)
- ρ - density (kg/m^3)
- τ - time (s)
- δx - length between points of numerical network (m)
- Δx - finite volume thickness (m)
- Δt - temperature difference (^oC)
- $\Delta\tau$ - period of time (s)

Indexes

- a - air
- C - convection
- D,d - Direct and diffuse Solar radiation
- e - outside
- ex - external
- h - horizontal
- i - reference surface "i"
- in - inside
- INF - infiltration
- j - reference surface "j"
- lw - long wave
- R - radiation
- S,L - Solar and light
- sw - short wave
- tot - total
- TR - temperature radiation
- v - vertical
- w - wall

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UTICAJ REŽIMA RADA KLIMATIZACIONOG POSTROJENJA NA POTROŠNJU ENERGIJE ZA HLAĐENJE

Maja Todorović, Branislav Živković

U radu je data analiza uticaja ražima rada klimatizacionog postrojenja na potrošnju energije za hlađenje. Sprovedena analiza je izvršena uz pomoć kompjuterskog programa za dinamičku simulaciju termičkog ponašanja klimatizovane prostorije. Program je razvijen na Katedri za termotehniku Mašinskog fakulteta u Beogradu. Ispitivana su tri različita režima rada sistema za klimatizaciju, dnevni tok toplotnog opterećenja i dnevna potrošnja energije za hlađenje, pri letnjim projektnim uslovima za Beograd. Dobijeni razultati simulacije su upoređeni i dati su podaci o dnevnoj uštedi energije za hlađenje.