RECENT CZECH BUILDING ENERGY SIMULATION CASE STUDIES

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ABSTRACT

By describing three recent case-studies, this paper aims to elaborate the current state of building energy modelling and simulation in the Czech Republic in general, and at the Czech Technical University (CTU) in Prague in particular. The studies which are described were carried out at the Department of Environmental Engineering, Faculty of Mechanical Engineering, concern practical problems related to heating, ventilating, and air-conditioning (HVAC) systems.

INTRODUCTION

The Czech Republic (CR) belongs to the group of countries with highest energy consumption. The energy consumed for $1000 of gross national product was 19.33 GJ in 1987 (USA 15.11GJ/$1000, Japan 6.98 GJ/$1000). This situation has improved since then but not significantly. In the past, the price of energy used to be heavily subsidised by the government. This is not acceptable in the current introducing of market economy principles in the CR.

The high level of energy production was accompanied with high level of air pollution since most of the energy was produced in power plants burning brown-coal with low heating value and high sulphur content (up to 4%). Because of that the CR was one of the most polluted countries in the world. The last few years have seen an increase in the activities and a number of organisations are trying to improve the energy situation and the associated impact on the environment by introducing more energy efficient technologies and installing emission control devices. There is a drive to switch to other fuels like natural gas. Emissions have already been reduced significantly; for example SO_2 emissions reduced from 2.16×10^6 tons/year in 1987 to 1.09×10^6 tons/year in 1995.

The energy used in buildings for heating, ventilation and air-conditioning represents about 50% of the total national energy consumption. It is therefore essential to reduce the energy consumption and improve the efficiency in buildings and HVAC systems. We feel that computer modelling and simulation of building and HVAC energy performance can play an important role in this respect (Hensen, 1996).

In spite of the rapid improvement of the computational tools in use in the CR, the more sophisticated modelling and simulation techniques are not yet used nor are they commonly known. Specialised design programs are used for specific purposes (e.g. cooling or heating load calculation, duct sizing, etc.), however these are based on many significant simplifications.

In higher education the methods of building energy simulation are just being introduced into the curriculum (ESP-r (ESRU 1996) was first installed in 1993 at CTU, Department of Environmental Engineering) and the results of first case studies have only recently become available.

This paper aims to elaborate the current situation by describing three recent case studies.

The first case study analyses the variation of energy consumption for heating in panel houses depending on different parameters. This study deals with the general problem of high heating energy consumption which affects a significant group of flat owners (Drkal - Dunovska, 1996).

The second study considers the energy efficiency of an existing HVAC system in a newly built archival building. An improved HVAC control strategy is proposed, simulated and finally applied in practice (Skrlant, 1996).

The third case study involves the analysis of the indoor-climate in a large ventilated industrial hall under extreme summer conditions. The influence of skylight size and thermophysical properties of the floor on thermal comfort are presented. The results provide an insight in indoor environment of large ventilated enclosures which can be used for design purposes (Neuzil, 1996).

I. PARAMETRIC STUDY OF HEAT CONSUMPTION IN FLATS

Problem description: The amount of energy used for residential heating is relatively high in the Czech Republic. This problem is evident especially in the case of prefabricated apartment buildings which represent about 70% of the present housing stock. The flat owners were not aware of energy control and reduction since the energy consumption for heating of the flat was calculated only according to the floor area and not the real energy consumption. Even today when energy consumption measuring devices are being introduced to the flats, the most common reaction when it gets too warm is to open a window. As shown in the following, the variation in heat consumption of similar flats can be very high.

Objective: The objective of this study was to estimate the influence of different parameters on the heating energy consumption of the flat.

The parametric analysis of the energy consumption of an average flat was carried out using ESP-r (ESRU 1996).

Model description: The analysis of four different parameters having an influence on the residential building heating energy consumption was carried out. The parameters under consideration were as follows:

- location of the apartment in the building (A)
- set-point increased up to 24°C (B)
- heating pattern of neighbouring flat (C)
- excessive continuous ventilation (D)

The “standard“ prefabricated house, typically built from the 60s to the 80s, was selected as an object of investigation. The average apartment size is 45 m^2 floor area. The buildings were built from the pre-fabricated concrete panels with almost no insulation (external walls U-value = 1.09 W/m^2K, roof U-value = 0.5 W/m^2K, windows U-value = 2.6 W/m^2K, internal walls U-value = 2.9 W/m^2K) and therefore relatively high energy consumption.

Simulations and results: The simulation was run through the period of one typical winter week in the Czech Republic (10 to 16 January) when external temperature reaches -5°C during the day and -12°C at night (Dunovska, 1995). The resulting heating energy consumption obtained by simulation for different cases are graphically shown in Figure 1. To make the case study more “realistic”, the cost of one-week of heating expressed in KC (1 US\$ ≈ 29 KC) is presented. When calculating the heating cost, a price of 163 KC per GJ (Czech official price for district heating in 1996) was assumed. The heating consumption of all the cases are stated relative to the 100% base-case heat consumption.

The base-case (A1) denotes the space heating energy consumption of the flat situated in the middle of the building when heated up to 20°C. The heating energy consumption for the base-case during the simulation period was 323 kWhrs and is referred to as 100%. Case A2 shows an increase in energy consumption of up to 217% when the same flat is situated under the roof and in the corner of the building, i.e. about 50% of the walls are external.

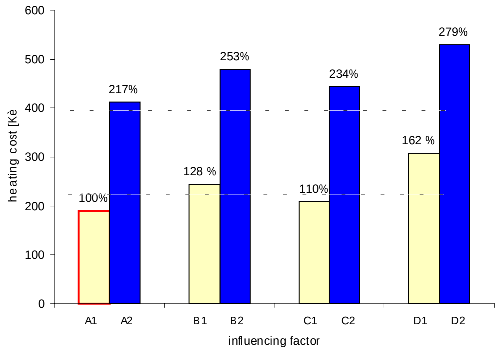

Figure 1: Variation of costs and energy consumption for heating of the flat during one-week depending on flat location, increased set-point, neighbouring apartment and excessive ventilation (price is 163KC per GJ)

Case B1 had a heating energy consumption of 128% which was caused by the set-point increase to 24°C (internal air temperature).

The effect of the heating pattern of the neighbouring apartment was modelled in case C1, which had a resultant energy consumption of 110%. In case C1 it was assumed that the neighbouring apartment on one side (partition wall of 20 m^2) was not heated at all.

In case D1, the natural ventilation rate was assumed to be 1.6 ACH which is double that of the base-case value, and the heating energy consumption was found to be 162%. This represents the situation when, for example, a small ”ventilation window“ is opened during the whole period.

The cases denoted by suffix number 2 illustrate the combination of the flat location (corner) and the other factor’s influence on the heating consumption with the reference case A2 (of 217% energy consumption). For the case B2, the energy consumption was 253% when the flat under roof was heated up to 24°C. The unheated neighbouring apartment increased the energy consumption to 234% (case C2) and in case D2, the energy consumption increased by excessive ventilation to 279%.

The effect of higher desired internal air temperature on the length of the heating period was analysed. The simulation was run through the whole year period with heating set points of 20°C and 24°C respectively for the flat located in the centre and in the corner of the building. The energy consumption for the heating, and the length of the heating period, were compared for different cases and are summarised in Table 1 together with the cost of heating in KC. It can be seen in Table 1 that the length of the heating period differs from the base-case situation by 1,398 hours only because of the location of the flat in the corner position. Setting the internal air temperature to 24°C instead of 20°C increases the heating period by 916 hours for the central flat and by 1,076 hours for the corner flat.

Table 1: The annual energy consumption and hours of heating for the flat located in the central and corner part of the building . The corresponding cost of heating in KC.

Flat location	t_i (°C)	heating energy consumption (GJ,%)	heating period (hours)	cost of heating (KC)
central	20	16 (100%)	3,674	2,609
	24	24.3 (152%)	4,590	3,976
corner	20	45.3 (283%)	5,072	7,384
	24	64.2 (401%)	6,148	10,475

Conclusions: From comparing the above simulation results it can be concluded that the most significant parameter influencing the heating energy consumption (out of the investigated ones) is the location of the flat. The second most important parameter is that of excessive ventilation ("ventilation window" opened), a result of overheating, which is a common problem today. On the other hand the heating pattern of the neighbours had a surprisingly low influence on heat consumption. However, it must be noted that these results were obtained for the specific case and for a one week-period .

It follows from the whole year simulation that in the same building the heat consumption of the same flat can vary from 100% up to 400% depending on the flat location and the desired internal air temperature (4°C variation in this case) and the heating period can be 1.6 times longer as a result of that.

II. ENERGY CONSERVATION AND EFFICIENCY OF HVAC SYSTEM IN AN ARCHIVAL BUILDING

Problem description: The new building of the State Archives was constructed in Prague in 1995. Separate HVAC systems for each floor were installed which use recirculation air only. To ensure the special internal conditions for archival purposes (i.e. internal air 15 ± 1°C, rel. humidity 55 ± 5%) the HVAC system was designed to work continuously during the whole year. During the first year of operation it was observed that the cooling was on continuously, even during the winter time. The reason for that was that the heat losses of the building are in reality much lower than was assumed when designing the HVAC system. It was found that the heat gains from the fan of the designed HVAC system would be sufficient to cover all the heat losses of the building in winter.

Objective: The objective of this study was to propose a new control strategy for the existing HVAC system in the archival building to achieve energy conservation while maintaining the required special internal conditions.

A dynamic simulation model of the building and HVAC system was constructed using ESP-r. 12-hours cycled "On/Off" control strategy was proposed, applied and analysed in order to achieve efficient use of energy.

Model description: The investigated building of the State Archives can be referred to as a medium-heavy building with no windows, consisting of 13 floors, with minimized heat gains and losses. The external walls have a U-value = 0.2 W/m^2K and the internal surfaces (floors) have a U-value = 2.49 W/m^2K. The middle five floors were modelled as being representative for the building.

The indoor-air quality requirements for archival purposes were in this case defined as an air temperature of 15 ± 1°C and a relative humidity of 55 ± 5%.

The casual heat gains from electrical equipment, occupants and lighting were neglected. Based on how the building is constructed, infiltration could also be neglected.

Artificial hourly climate data derived from long-term average monthly weather data for Prague was used (Dunovska, 1993).

Simulations and results: The energy consumption for the current situation was obtained by whole-year simulation with the HVAC system operating continuously in each floor. This case is referred to as “continuous operation” further on. As outlined above, the cooling was working even during the winter period. The simulation results for the middle floor (3rd) are discussed in detail in the following.

The cooling load for *continuous operation* of the HVAC system shows a maximum value of 2.6 kW in the summer period and a minimum of 1.1 kW in the winter period.

The “On/Off” operation was modelled with 12 hour operating cycles alternating between floors, as indicated in the following table:

floor	0 - 12 h	12 - 24 h
1.	ON	OFF
2.	OFF	ON
3.	ON	OFF
4.	OFF	ON
5.	ON	OFF

Figure 2 shows the cooling loads of the middle floor (3rd) for the case of 12-hour cycles *On/Off operation* with a minimum of 0 W and a maximum of 3.1kW in summer and 0.3 kW in winter. The instantaneous value of cooling required is higher in this case than in case of continuous operation, as a result of warming up during the 12-hour Off period.

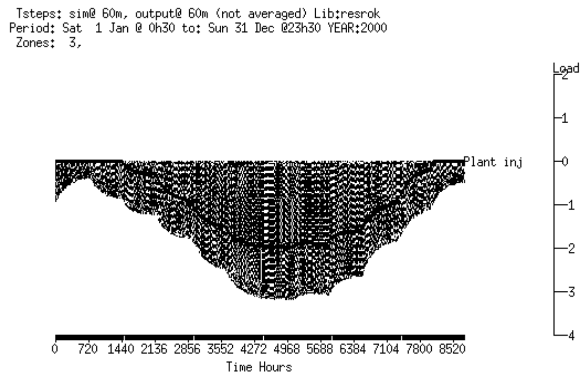

Figure 2 : Cooling loads in case of 12-hour cycles *On/Off operation* (i.e. proposed situation)

The simulation results presented in Figure 3 prove that the internal air temperature variation is within the temperature limits of 15 ± 1°C when 12-hour cycles *On/Off operation* would be used during the whole year. The extreme values of internal air temperature occurring in a typical winter month (January) and a typical summer month (July) for both HVAC continuous and *On/Off operation* strategies are summarised in Table 2. In the assumed climate, the diurnal external temperature fluctuates between 5°C and 2°C in January and between 18°C and 25°C in July. The energy consumption for January and July for the different cases is also included in Table 2. It can be seen that by applying the *On/Off operation* strategy the energy consumption can be reduced to 17% during January and to 56% during July.

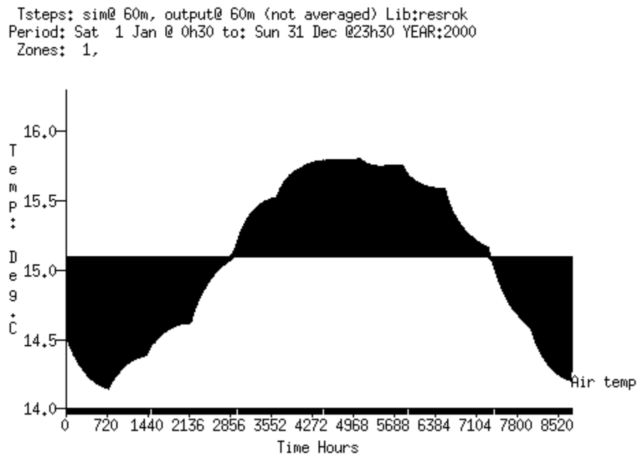

Figure 3 : Internal air temperature fluctuation for 12-hour cycles *On/Off operation* during the whole year.

Table 2 : Minimum and maximum internal air temperature, and energy consumption for continuous and 12-hour cycles *On/Off operation* in selected months.

	operation	$t_{i\,min}$ (°C)	$t_{i\,max}$ (°C)	energy (kWh)
January	continuous	15.1	15.1	4,259
	On/Off	14.1	15.1	745
July	continuous	15.1	15.1	9,740
	On/Off	15.1	15.9	5,445

The predicted annual energy consumption is 83,040 kWh for continuous HVAC operation and 38,630 kWh for 12-hour cycles *On/Off operation*. This suggests that the current annual HVAC energy consumption can be reduced to 47%.

Conclusions: By employing a dynamic model of the State Archives building, it was possible to propose the 12-hour cycles *On/Off operation* of HVAC system instead of *continuous operation*, while satisfying indoor air requirements. It follows from the results that the energy consumption can be reduced dramatically to 47% when this On/Off control strategy is used. The most significant energy conservation can be achieved during the winter period; the energy consumption can be reduced down to 17%.

The On/Off control strategy proposed in this paper was applied in the investigated building and proved its relevance in practice.

III. THERMAL COMFORT ANALYSIS IN AN INDUSTRIAL HALL

Problem description: The internal environment of industrial halls may have an impact on the thermal comfort of workers, on the productivity of workers, on the quality of the products and on the number of workplace accidents. The internal environment of industrial halls is influenced by external and internal factors. During the summer period external factors are: outdoor air temperature, solar radiation and ground temperature. Internal factors are: ventilation operation, thermal insulation and thermal capacity of the hall and casual heat gains. From the energy consumption point of view we want to use the minimal outdoor air flow rate for ventilation, on the other hand we don't want to disrupt thermal comfort of the internal environment. By simulation it is possible to optimise the operation of the ventilating system in relation to the construction of the building (integral approach).

Objective: The objective of this study was to estimate the influence of the area of skylights and the floor construction on the thermal comfort in an industrial hall ventilated during the summer period by displacement system.

The building and ventilating system were modelled and simulated with ESP-r (ESRU 1996).

Model description: The mounted hall type HARD Jeseník was used as an example of an industrial hall. The hall consists of modules with dimensions 18 x 6 x 7.2 m (length x width x height), slope of the roof is 11 ° (Figure 4). The external walls and roof consist of thermally insulated sandwich panels. The floor is made of concrete and has thermal insulation. The U-values are presented in Table 3. The ground temperature was assumed constant at 10 °C. The flat polycarbonate skylights allow for natural lighting. The hall is used for welding of large support constructions. The casual heat gains of each module are 3360 W. The displacement ventilation system provides ventilation of the hall. The working period starts at 6.00 and finishes at 22.00. The air flow rate is constant during this period (10.8 air changes per hour) and suffices to eliminate external heat gains. The polluted air (welding) is exhausted and filtered. The infiltration rate during the night period is 0.5 changes per hour.

The basic central module of the hall was used as a single zone model for simulation purposes. The central line of the roof is in an East-West direction. The above indicated climate for Prague was used (Dunovska, 1993). The maximal external air temperature was expected to be 30 °C and minimal external air temperature was expected to be 16 °C.

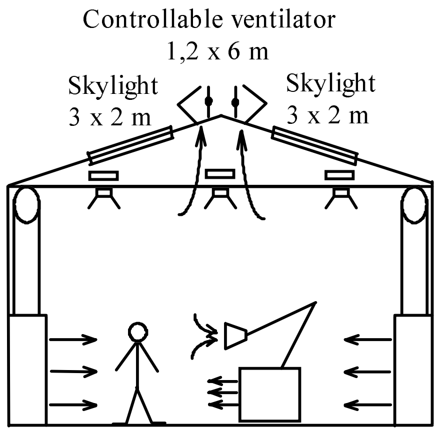

Figure 4: The displacement ventilation system and its operation during the summer period in an industrial hall

Table 3: U-values of the industrial hall.

Structure	U-value coefficient ($W/m^2.K$)	
Floor - light, thermal insulated	0,38	0,36
Floor - heavy, thermal insulated	0,61	0,44
Floor - heavy, non-insulated	0,44	0,85
External wall - sandwich panel	2,9	
Roof sandwich panel		
Door		
Skylight		

Simulation and results: The indoor climate conditions were predicted for the summer period. In the central part of the hall they are represented by the internal air temperature, surface temperature of the floor and thermal comfort sensation (PMV, PPD). The external heat gains (solar radiation) through the skylights seriously affected the thermal comfort in the working zone . The skylights have to provide the visual comfort which is essential for the type of work. The oversized skylights cause glare problems during the summer period and increased energy consumption during the winter period. The optimised skylights (Neuzil, 1996) have an area of 6 x 2 m (two skylights each 3 x 2 m). The oversized skylights 6 x 3 m and 6 x 5 m which are very often used in practice were used as an example. The impact of various constructions of the floor was tested too. Three types of floor (upper concrete layer, thermal insulation) were used: light floor (120 mm concrete layer) with thermal insulation, heavy floor (270 mm concrete layer) with thermal insulation and heavy floor without thermal insulation (see Table 3).

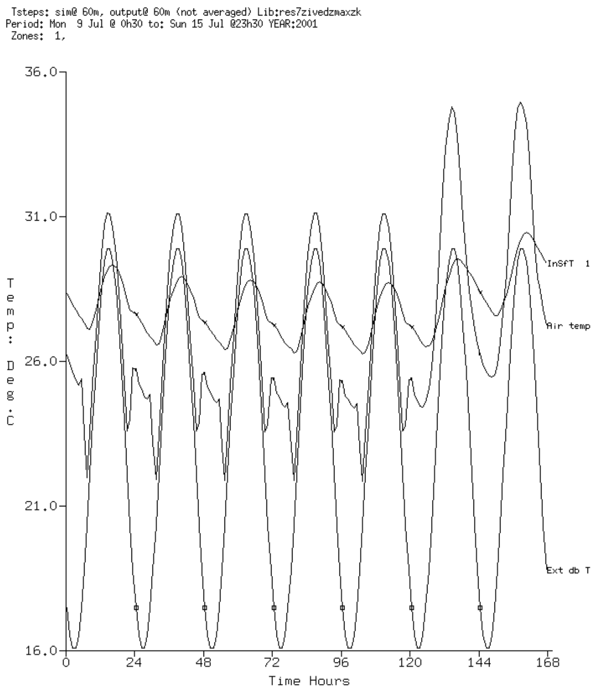

Figure 5 : Internal air temperature t_i and floor surface temperature t_s as a function of external and internal conditions during the working week and weekend (external air temperature t_e)

Figure 5 shows the behaviour of the following temperatures: external air temperature (t_e), internal air temperature (t_i) and surface floor temperature (t_s) during the working week (0 - 120 h, during working time ventilation equals 10,8 air changes, and during the night the infiltration equals 0,5 air changes) and weekend (120 - 168 h, infiltration equals 0,5 air changes). The optimised skylights (6 x 2 m) and the thermally light and insulated floor were used. The internal air temperature rises when the ventilation is stopped because the infiltration rate is very small and the heat (solar radiation) accumulated in the floor cannot escape from the hall. After that the internal air temperature decreases very similarly to the external air temperature which is caused by transmission heat losses of the hall. The internal air temperature drops when the displacement ventilation starts because the external air temperature (supplied air) is lower than the internal air temperature and causes ventilation heat losses. The accumulated heat in the floor construction has an impact on the amplitude of the floor surface temperature which is smaller than the air temperature amplitude. The ventilation system is out of operation during the weekend and external heat gains increase the maximal value of internal air temperature because the infiltration is too small to remove the heat gains.

The temperatures in the case of 6 x 3 m and 6 x 5 m skylights are similar but the maximum values of the internal air temperature and floor surface temperature are higher (see Table 4).

Table 4 : Maximum values of internal air temperature t_i and floor surface temperature t_s (in °C) as a function of the skylight area and the floor construction

	1	2	3	4	5
t_i (Mon - Fri)	31,3	31,4	31,4	32,1	32,0
t_i (Sat - Sun)	35,0	39,0	38,7	44,7	42,8
t_s (Mon)	29,3	32,1	31,4	36,0	35,3
t_s (Fri)	28,6	30,7	31,0	34,0	34,0
t_s (Sun)	30,6	33,8	33,0	39,5	36,9

1 - Skylights 6x2 m, floor light, thermal insulated
2 - Skylights 6x3 m, floor light, thermal insulated
3 - Skylights 6x3 m, floor heavy, thermal insulated
4 - Skylights 6x5 m, floor light, thermal insulated
5 - Skylights 6x5 m, floor heavy, thermal non-insul.

The skylights of 6 x 3 m increase the maximum internal air temperature by 0.1 K during the working week and by 4 K during the weekend (light floor, thermal insulated). The skylights of 6 x 5 m increase the maximum internal air temperature by 0.8 K during the working week and by 7.8 K during the weekend (light floor, thermal insulated). The skylights of 6 x 3 m increase the maximum value of floor surface temperature by 2.8 K on Monday, by 2.1 K on Friday and by 3.2 K on Sunday (light floor, thermal insulated). The skylights of 6 x 5 m increase the maximum floor surface temperature by 6.7 K on Monday, by 5.4 K on Friday and by 8.9 K on Sunday (light floor, thermal insulated).

The impact of the various types of floor (light, heavy) on the maximum inside air temperatures during a hot summer working week is negligible (see Table 4). Also the impact of the various types of floor on the maximum floor surface temperature is very small (see Table 4).
The simulation results confirm the practical experience, i.e. that temperature changes resulting from a 24 hour cycle of outdoor climate do not penetrate in the concrete floor deeper than approximately 100 mm, and concrete thicker than 100 mm is not necessary from the point of view of summer thermal accumulation.

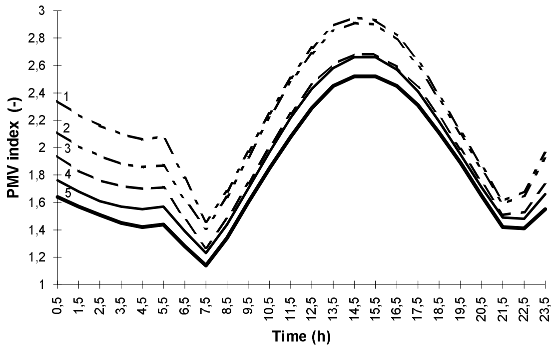

Figure 6 : Thermal comfort sensation - PMV index - as a function of skylight area and floor construction during the working day, 1-Skylights 6 x 5 m, floor light, ther. insulated, 2-Skylights 6 x 5 m, floor heavy, ther. non-insulated, 3-Skylights 6 x 3 m, floor light, ther. insulated, 4-Skylights 6 x 3 m, floor heavy, ther. insulated, 5-Skylights 6 x 2 m, floor light, ther. insulated

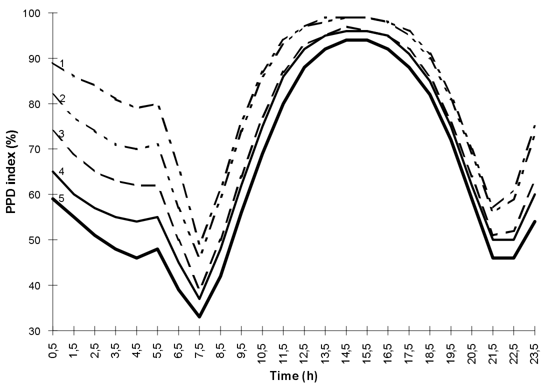

Figure 7 : Thermal discomfort - PPD index - as a function of skylight area and floor construction during the working day: 1-Skylights 6 x 5 m, floor light, ther. insulated, 2-Skylights 6 x 5 m, floor heavy, ther. non-insulated, 3-Skylights 6 x 3 m, floor light, ther. insulated, 4-Skylights 6 x 3 m, floor heavy, ther. insulated, 5-Skylights 6 x 2 m, floor light, ther. Insulated

The impact of various skylights and floor constructions on the thermal comfort and discomfort during the Monday is presented in Figure 6 (Predicted Mean Vote - PMV) and in Figure 7 (Predicted Percentage of Dissatisfied - PPD). The assumed average air speed was 0.3 m/s, the activity level 120 W/m^2 A_{Dubois} and the clothing level 1.0 clo. The critical situation occurs at 14.30.

Conclusion: From the simulation results it was possible to predict the summertime indoor environment in an industrial hall equipped with a displacement ventilation system. Two constructional variables were studied. The *area of skylights* has a significant impact on the indoor environment of the industrial hall. The *floor construction* has a small impact on the indoor environment.

It is obvious that during the summer period the predicted sensation of the hall indoor air quality has mostly discomfort character (see Figures 6 and 7).

The halls with smaller skylights (6 x 2 or 6 x 3 m) have of course more favourable microclimate than those with oversized skylights (e.g. 6x 5 m) at the same ventilation and internal heat gains conditions - see Table 4.

For a given skylight nearly the same thermal comfort can be reached regardless of the floor mass (see Figures 6 and 7).

Only during the night when the ventilation rate is lower, the PMV and PPD values show some merit of a heavy floor.

CONCLUSIONS

This paper describes three studies by graduate and postgraduate students at the Department of Environmental Engineering, CTU in Prague. Computer modelling and simulation was only recently incorporated in the curriculum.

From our initial experiences some general conclusions can be drawn:

- The interest of students in computer modelling and simulation increases as their theoretical knowledge of environmental engineering grows.

- ESP-r is very useful for education, particularly for many hands-on exercises and assignments, using also e-mail. The courses for postgraduate students lectured at CTU in Prague by Dr. Jan Hensen , visiting professor at CTU, are the foundation for wider uptake of modelling and simulation methods in the higher education of mechanical and civil engineers .

- Problems with the practical usage of modelling and simulation at the Department of Environmental Engineering of the CTU in Prague concern

    - lack of hardware (teaching laboratory, workstations)

    - lack of data (incl. climate)
    - relatively low English language skills by a number of students

- Future work at CTU in Prague will concentrate on:
    - further integration of modelling and simulation in the curriculum
    - dissemination of information about computer modelling and simulation possibilities for HVAC systems and buildings and promoting this technology in practice (in journals, at seminars)
    - continuing education courses for introduction of modelling and simulation in practice

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