USING ENERGY SIMULATION TO OPERATIVE TEMPERATURE EVALUATION

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ABSTRACT

According to the Czech legislative act the operative temperature is the evaluation criterion for thermal comfort in air-conditioned or heated spaces. The operative temperature respects the air temperature; mean radiant temperature and air velocity. For mean radiant temperature calculation the surface temperature of the surrounding walls must be known. Manual calculation of the mean radiant temperature is very complicated and not suitable for practical usage since the surface temperatures are difficult to determine. On the contrary, the computer-based calculation is prepared to do this automatically and could be particularly useful when seeking multiple solutions for a problem under the optional conditions.

The paper presents the operative temperature analysis in a space, using the dynamic simulation method, respecting the inside and outside climatic changing effect. Three typical rooms were chosen for the analysis: a single façade room, a corner room and a room under the roof. The rooms were analysed in a light of external wall mass, glazing ratio and quality. Three façade types were used in the model. The simulations were examined for extreme and reference summer weather conditions in the Czech Republic.

KEYWORDS

Operative temperature, mean radiant temperature, thermal comfort, energy building simulation

INTRODUCTION

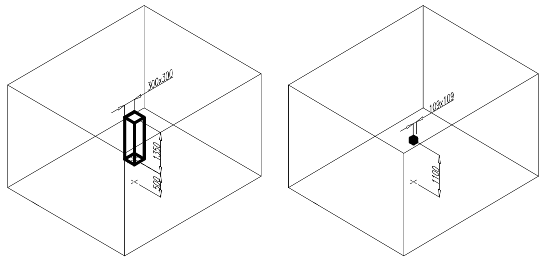
The current computer methods afford opportunity to determine the operative temperature and also the indoor surface temperature (mean radiant temperature) while the stationary or dynamic climatic conditions and indoor heat load. The operative temperature is variable in a room space namely if we suppose a constant air temperature. The operative temperature changes are affected by the mean radiant temperature, which depends on the subject location. In the air-conditioned spaces the effect of cooled surfaces (in winter) and heated surfaces (in summer) is present. The operative temperature is also time variable, because the indoor surface temperature is changing during the day, in dependence on the outside climatic conditions.

The main goal of the studies is to determine thermal environment behaviour for various building dispositions during typical outside and inside climatic conditions.

RESEARCH METHODS

ESP-r program, which is used for dynamic evaluation of building, ventilation and heating thermal behaviour contains *ESPmrt module* (Sars et al. 1988). The module calculates the mean radiant temperature *MRT* in defined position of the room. The *ESPmrt* module is based on the calculation of view factors between particular surfaces (“*View Factors Module*“).

The calculation method uses the *MRT sensor* shaped block or a cube with selectable proportions. The dimensions of the *MRT sensor* block can be set, to replace the body (1.8 m^2) – 300 x 300 x 1350 mm (Figure 1a). A sensor with dimensions 109 x 109 x 109 mm can substitute the globe thermometer with diameter 150 mm (Figure 1b).



a) *b)*

Figure 1 MRT sensor in ESP-r software

MODELLING AND SIMULATION

The studies of the operative temperature were carried out on three types of the rooms (offices):

- Single façade room (F)
- Room under the roof (R)
- Corner room (C)

The external wall represents longer, south façade for all cases (F, R, C). The corner room (C) has also west external wall.

The ground dimension of all types of the room is 5 x 4 m and the high of the room is 3 m. Types of the external wall were chosen according to valid Czech standard (Anon C 1985):

- Light external wall (δ < 18 cm)
- Medium-weight external wall (18 < δ < 45 cm)
- Heavy external wall (δ > 45 cm)

The list of the basic types of the rooms is presented in Table 1. There were 9 basic types of the room analysed. The properties of the external walls are visible in Table 2.

Table 1 List of the examined cases

Combination : room type & external wall	Light external wall	Medium -weight ext. wall	Heavy external wall
Single façade	FL	FM	FH
Room under the roof	RL	RM	RH
Corner room	CL	CM	CH

The light external wall is built of extruded sandwich panel. The medium-weight external wall is compound of Ytong block (25 cm) with thermal insulation EPS (3 cm). The heavy external wall is made of brick (40 cm) with thermal insulation EPS (4.5 cm). On the medium-weight and heavy external there is a plaster (1 cm outside and inside). The ceiling and floor are compound of steel concrete (30 cm). The internal walls are built of firebrick (thickness of 10 cm) with a plaster (1 cm). The roof (only for R case) is made of concrete (22 cm), mineral wool (18 cm) and cowlick (10 cm).

Every room was analysed for different properties of:

- External wall (Table 2)
- Thermal properties of the glazing (Table 3)
- Glazing ratio (Table 4)

Table 2 External walls properties

Type of the room	Light external wall	Medium -weight ext. wall	Heavy external wall
Label	**L**	**M**	**H**
δ (m)	0.075	0.3	0.465
U_w (W/m^{2}K)	0.45	0.45	0.45
f (K)	0.94	0.13	0.05
Φ (h)	2.3	12	15

Three types of glazing were used for study of the operative temperature in the room. Thermal properties of the glazing are visible in Table 3. An optical property of the glazing is the same for every glazing. There was a double-glazing used with an air gap and internal blind to keep the room from direct solar radiation.

Table 3 U-values of the glazing

Label	U1	U2	U3
U_{gl} (W/m^{2}K)	1.12	1.7	2.4

Every room was analysed for different glazing ratio, which is presented in Table 4. The high of the window parapet is the same for all the room types (0.9 under the floor). The window is placed symmetrically in the external wall. The window dimensions for all the room types are presented in Table 5.

Table 4 Glazing ratios

Label	L	M	H
G100	100 %	-	-
G67	67 %	67 %	-
G47	47 %	47 %	47 %
G33	-	33 %	33 %
G27	-	-	27 %

Table 5 Windows dimensions for all the room types

Label	South façade (for F, R, C room)		West façade (only for C room)	
	Dimensions (m)	Count	Dimensions [m]	Count
G100	5 x 3	1	4 x 3	1
G67	5 x 2	1	4 x 2	1
G47	2 x 1.75	2	3.2 x 1.75	1
G36	1.6 x 1.7	2	2.7 x 1.7	1
G27	1.2 x 1.7	2	1.9 x 1.7	1

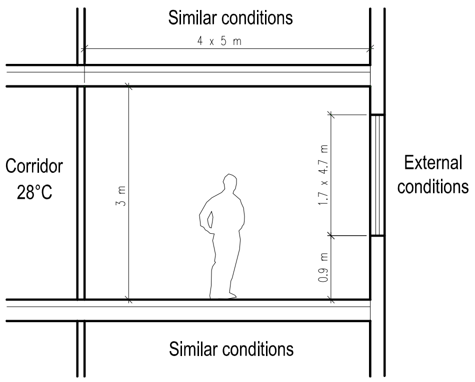


Figure 2 Cross section of the single façade room with middle heavy external wall (case FM)

Schematic drawing of the single façade room with the medium-weight external wall (FM) is visible in Figure 2.

Internal heat gains

The internal heat gains operation was chosen for the thermal environment analysis. It is assumed, that two people (62 W) with PC (40 W) and a screen (58 W) occupied the room. The schedule of internal heat gains during the day is visible in Figure 3. The internal heat gains are transferred by convection (50 %) and by radiation.

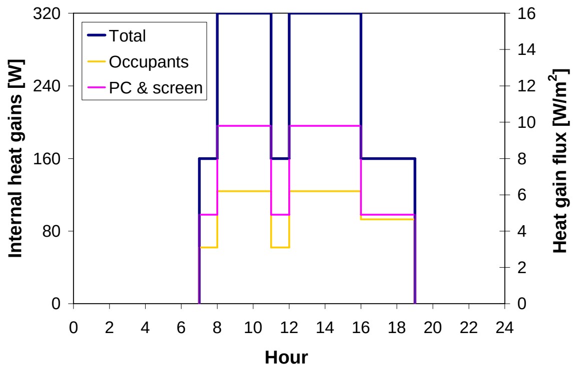


Figure 3 Schedule of internal heat gains

Ventilation

The simulations were carried out for infiltration only. The ventilation rate corresponds to minimal fresh air supplying according to Czech standards, 50 m^3/h per person (Anon A). During simulation, the minimal fresh air flow 100 m^3/h was supplied into the room. The air flow corresponds to the air change 1.67 h^{-1}.

External climatic conditions

The simulations were carried out for two external climatic conditions in Prague (Czech Republic)

- Extreme summer conditions (2003)
- Reference conditions (TRY)

The summer of the year 2003 was a long-term period with extreme climatic data in Prague (Czech Republic). The reference year (TRY) represents characteristic values of climatic conditions and also contains dynamic changes, trends and extreme values. The test reference year for Prague was used for simulation. The summer conditions of TRY represent the characteristic climatic data in the Czech Republic.

Indoor temperature conditions

During simulation the *MRTsensor* (Figure 1a) was placed in the middle of each room to operative temperature evaluation. The air velocity w in the zone of people is assumed less than 0.2 m/s (Anon A 2002). The operative temperature was calculated as the average of the air temperature and the mean radiant temperature.

$$t_o = \frac{t_a + MRT}{2} \qquad (1)$$

All rooms were air-conditioned in the summer time between 7.00 to 19.00 hours to keep 25 °C. The ideal control of the air temperature was used, which means that a constant required air temperature during the work time was kept.

The adjoining rooms were air-conditioned as the analysed object (the same conditions and dynamic thermal behaviour) except the corridor. The air temperature in the corridor was supposed to reach 27 °C.

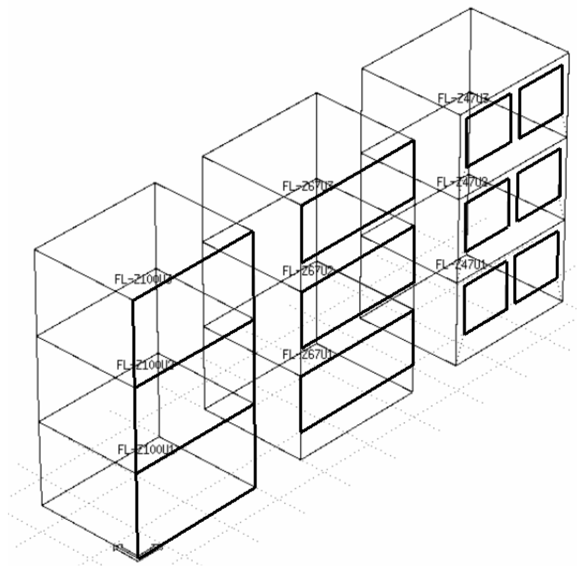


Figure 4a Example of the model in ESP-r software (room type FL)

VALIDATION

The indoor surface temperature knowledge is very important value for the mean radiant temperature calculation. The surface temperature depends on boundary conditions, especially on the convection heat transfer coefficient h_c along the internal walls.

Many authors deal with the problems discussed above with sequence to energy simulation e.g. Fisher (1997), Beausoleil-Morrison (1997, 2001), Khalifa and Marschall (1999) and others. The ESP-r software uses their results for energy calculations.

For validation of the results the thermal environment measurement in real office was executed. The picture of the real office with dimensions of 5 x 4.5 x 3 m and southeast orientation is visible in Figure 4b. During the summer of 2005 (between 1/6 and 9/9), the different air-conditions regimes (ON/OFF) were studied with combination of shading window (no blind/internal blind). The regimes were changed in a week interval.

During the experiments the internal surface temperatures (including transparent surfaces and blind), air temperatures, globe temperature and air temperature in the corridor were monitored.

The experimental results were compared with thermal behaviour of simulation room model in *ESP-r* software. Two result comparisons are showed in Figure 5 and 6.

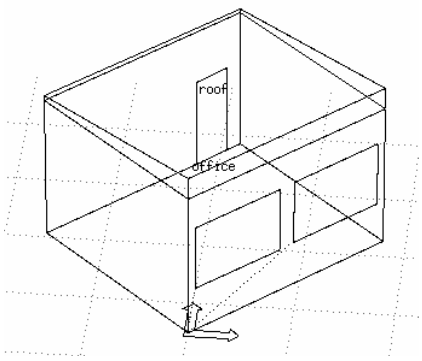


Figure 4b Model of experimental office in ESP-r software

The simulations were carried out throughout the entire year 2005. The real weather file was created for this purpose on the basis of Czech Hydrometeorological Institute data (Prague).

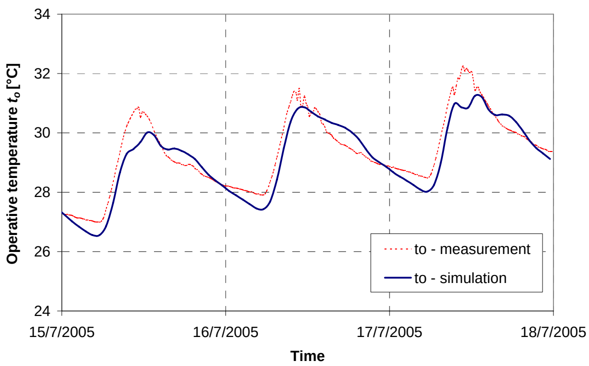


Figure 5a Comparison of operative temperature - measurement vs. simulation (OFF, ib)

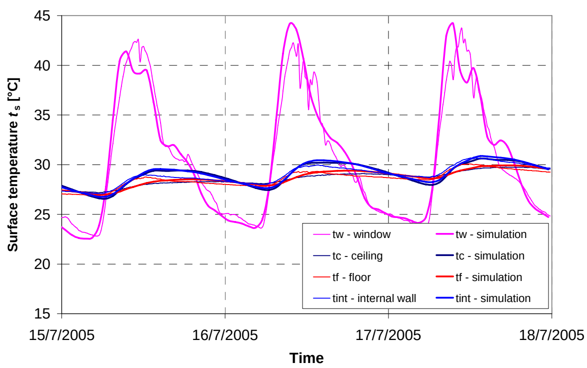


Figure 5b Comparison of surface temperatures - measurement vs. simulation (OFF, ib)

The *Figure 5* presents the result comparison for regime without the air-conditioning (OFF) and with the internal blind (ib). The results of simulation are in a very good agreement with the measurement data. Agreement is valid for the operative temperature (Figure 5a), and also for the internal surface temperatures (Figure 5b).

The Figure 6a and 6b presents the comparison for the air-conditioning regime (ON- 25 °C) and no blind (nb). Also in this case the agreement between the simulation and the experimental study is present. The difference between the operative temperature courses (Figure 6a) is caused mainly by different control process (air temperature control). The air temperature also influences the internal surface temperatures. Secondly the small different between measurement and simulation of operative temperature course can be caused by initial conditions. As mentioned above the measurement regimes were changed in a week interval.

Generally, there is a very good agreement visible between the real experiment and simulation from the results comparison. Especially the agreement of window surface temperatures is present, what is caused by very light inertia. It is very important for the operative temperature, respectively *MRT* calculation. The agreement of opaque walls surface temperature is not predicted very well, because of inertia effect.

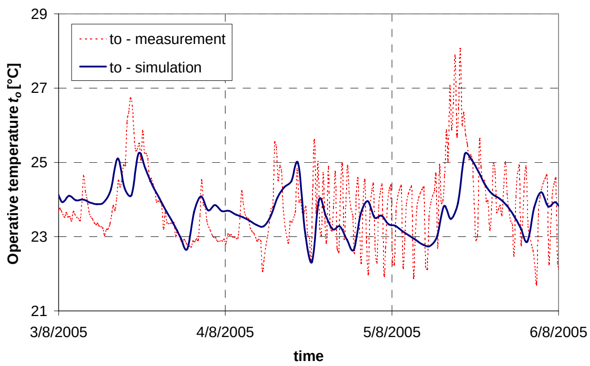


Figure 6a Comparison of operative temperature - measurement vs. simulation (ON, nb)

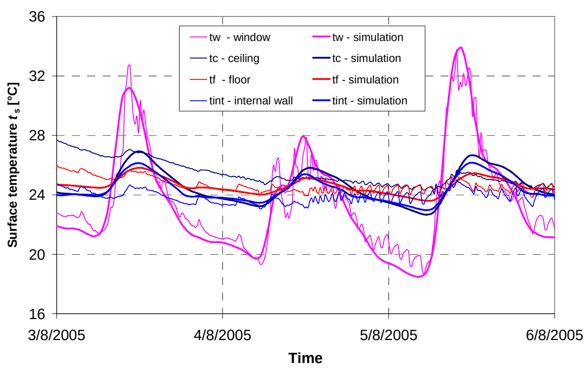


Figure 6b Comparison of surface temperatures - measurement vs. simulation (ON, nb)

RESULTS AND DISCUSSION

According to the Czech legislative act (Anon A 2002) the optimal operative temperature for the office work (1.2 met - sitting) should be 24 °C (0.75 clo), maximum 28 °C (0.5 clo).

According to EN 7730 (Anon B 2005) the optimal operative temperature for the office work (*PPD* < 10 %) is 24.5 ± 1.5 °C (0.5 clo) as visible in Table 6.

Table 6 Optimal operative temperature for office work according to EN 7730

Category	t_o	*PPD*
A	24.5 ± 1.0	< 6 %
B	24.5 ± 1.5	< 10 %
C	24.5 ± 2.5	< 15 %

The effect of glazing on operative temperature

A typical course of simulated operative temperature during extreme summer day is present in Figure 7. The results are valid for the light, single façade case (FL) and for the extreme weather conditions (2003).

The effect of the glazing ratio (G100 - G47) and thermal conditions (U1, U2 and U3) on the operative temperature, or more precisely on the mean radiant temperature, is visible in Figure 7.

During the day the change of the operative temperature is visible, which is caused by solar radiation (higher window surface temperature). The highest operative temperature is achieved in the room with large glazing (apparent increasing is visible).

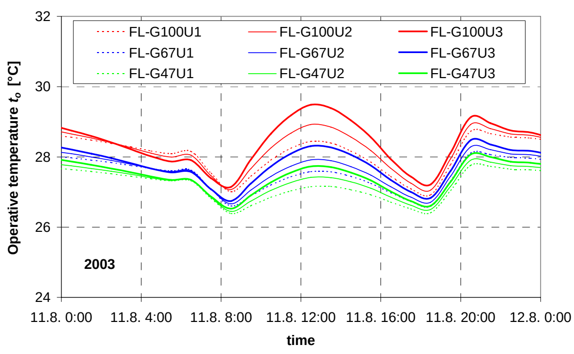


Figure 7 Typical course of operative temperature (room FL) for typical summer day in 2003

Maximal operative temperatures

The maximal operative temperatures $t_{o,max}$ obtained for all the simulation cases are presented in Figure 8. There were 81 different configurations of external façade constructions analysed. The results show the maximal operative temperature for both studied weather conditions, 2003 and TRY.

The effect of the glazing ratio and construction on the maximal operative temperature $t_{o,max}$ is definitely apparent (Figure 8).

In the room with the light external wall (L) with large glazing (100 and 67 %) the operative temperature is considerably higher than it is recommended (Anon A, B). Mostly it is visible for the corner room (C), where the maximal operative temperatures culminate up to 28 – 31 °C in dependence of window construction. A similar situation is visible for the single façade room under the roof (R), with the maximal operative temperature between 27.5 and 30 °C.

The similar trend is visible in the room with the medium-weight external wall (M). The operative temperatures are not so high, but maximum, in some cases, can still reach over 28 °C.

The effect of glazing is present also for the room with the heavy external wall (H). The differences between the maximums are not very expressive in those cases.

As it is shown in Figure 8 the operative temperature is influenced by glazing ratio and also by glazing quality. The building construction of the external wall (L, M, H) has a minimal effect. Generally it can be said the larger and thermally worse glazing will be used the higher operative temperature will be achieved.

Number of operative temperature during summer working time

The percentage of working hours (weekdays from 7.00 to 19.00) during four summer months (from 1/5 till 31/9) with the operative temperature in a specific interval for all analysed cases is presented in Figure 9 and 10.

In the room with the light external wall (L) with large glazing (100 and 67 %) the operative temperature is higher than 28 °C during the studied time interval. Especially it is visible (Figure 9) for the corner room with light façade and 100% glazing (CL-G100U3) where the operative temperature is over 40 % of the total work time (extreme weather conditions 2003)! The test reference year simulation (Figure 10) shows better results and the operative temperature is over only 15 % of working hours.

In the room with the single façade, medium-weight external wall (FM) and glazing ratio 67, 47, 36 % the operative temperature rarely goes over 28 °C (for extreme weather conditions 2003). Unfavourable situation is visible in the corner room (CM) with 67% glazing ratio (G67), where the operative temperature goes over 28 °C for a longer working time.

On the other hand in the room with the heavy external wall (FH a RH) and small glazing ratio (47, 36 and 27 %) the operative temperature is not very changed, and not exceed 28 °C (FH), or rarely (CH in 2003).

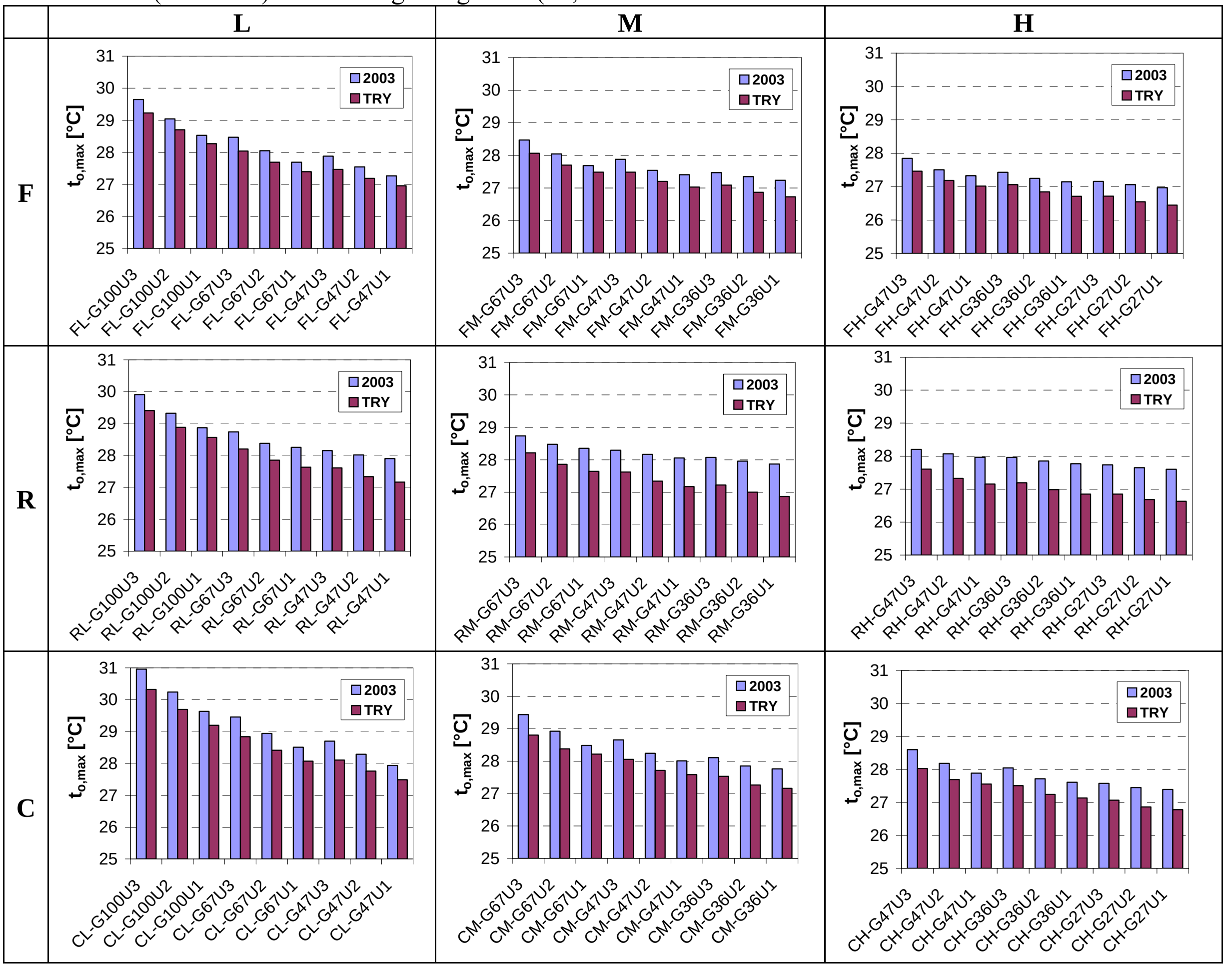


Figure 8 Maximum of operative temperature for all simulation cases (results for extreme summer condition 2003 and reference conditions TRY - Prague)
Note: Example of label RM-G67U1: R=Room under the roof, M=medium-weight façade, G67=67% glazing ratio, U1= U-value of the window is 1.12 W/m^{2}K

CONCLUSION

The comparison of the experimental study with the simulation results confirms, that the energy simulation is suitable for the operative temperature evaluation in summer.

The results of simulations show the effect of the building construction on the operative temperature. Especially the effect of transparent external surfaces is visible. On the opposite, the construction of the external wall has a minimal effect.

The presented study shows, that if the transparent surfaces are shaded (internal blind), the operative temperature will be higher than the air temperature, which is kept by the air-conditioning.

FUTURE WORK

The used method combines the effect of the external wall mass and glazing area for different glazing ratio. The energy simulation method allows carrying out other analyses. The presented solution was focused on summer weather conditions. A similar way can be used for the indoor thermal environment in winter. It will be necessary to validate a model again for boundary conditions setting (convection heat transfer coefficient).

ACKNOWLEDGMENT

This paper is integrated in the framework of CTU Research Aim MSM 6840770011.

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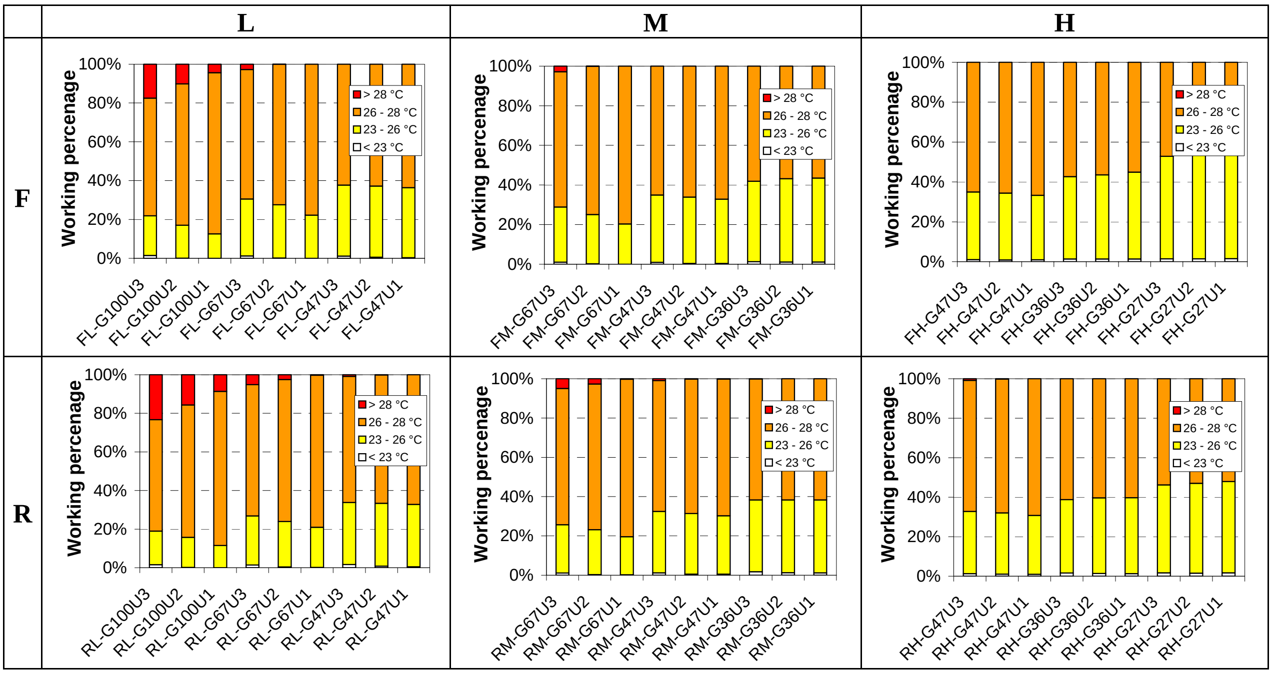

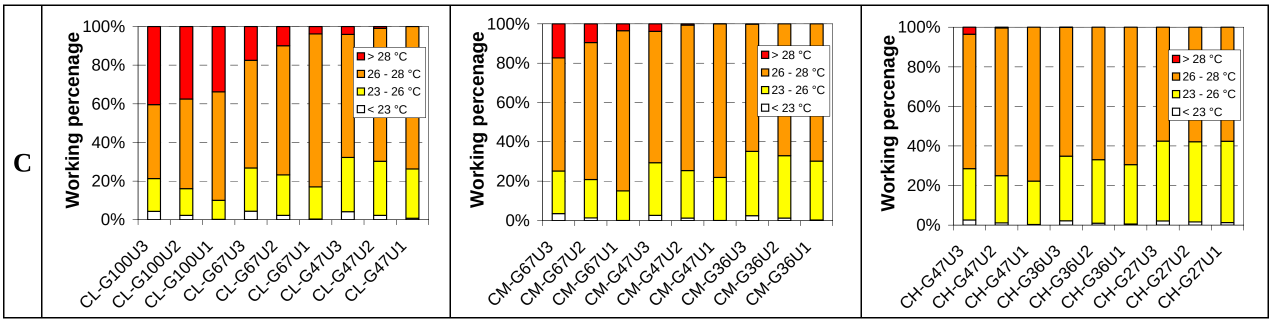

Figure 9 Percentage of working hours during four summer months with operative temperature in a specific interval (simulation results for extreme summer condition in Prague - 2003)

NOMENCLATURE

- h_c convection heat transfer coefficient [W/m^{2}K]
- f decrements factor [K]
- MRT mean radiant temperature [°C]
- PPD predicted percentage of dissatisfied [-]
- Q sensible heat load [W]
- q sensible heat load flux [W/m^2]
- t_a air temperature [°C]
- t_o operative temperature [°C]
- t_g globe temperature [°C]
- U_{gl} U-value of glazing [W/m^{2}K]
- U_w U-value of external wall [W/m^{2}K]
- w air velocity [m/s]
- δ thickness of the external wall [m]
- Φ time delivery [h]

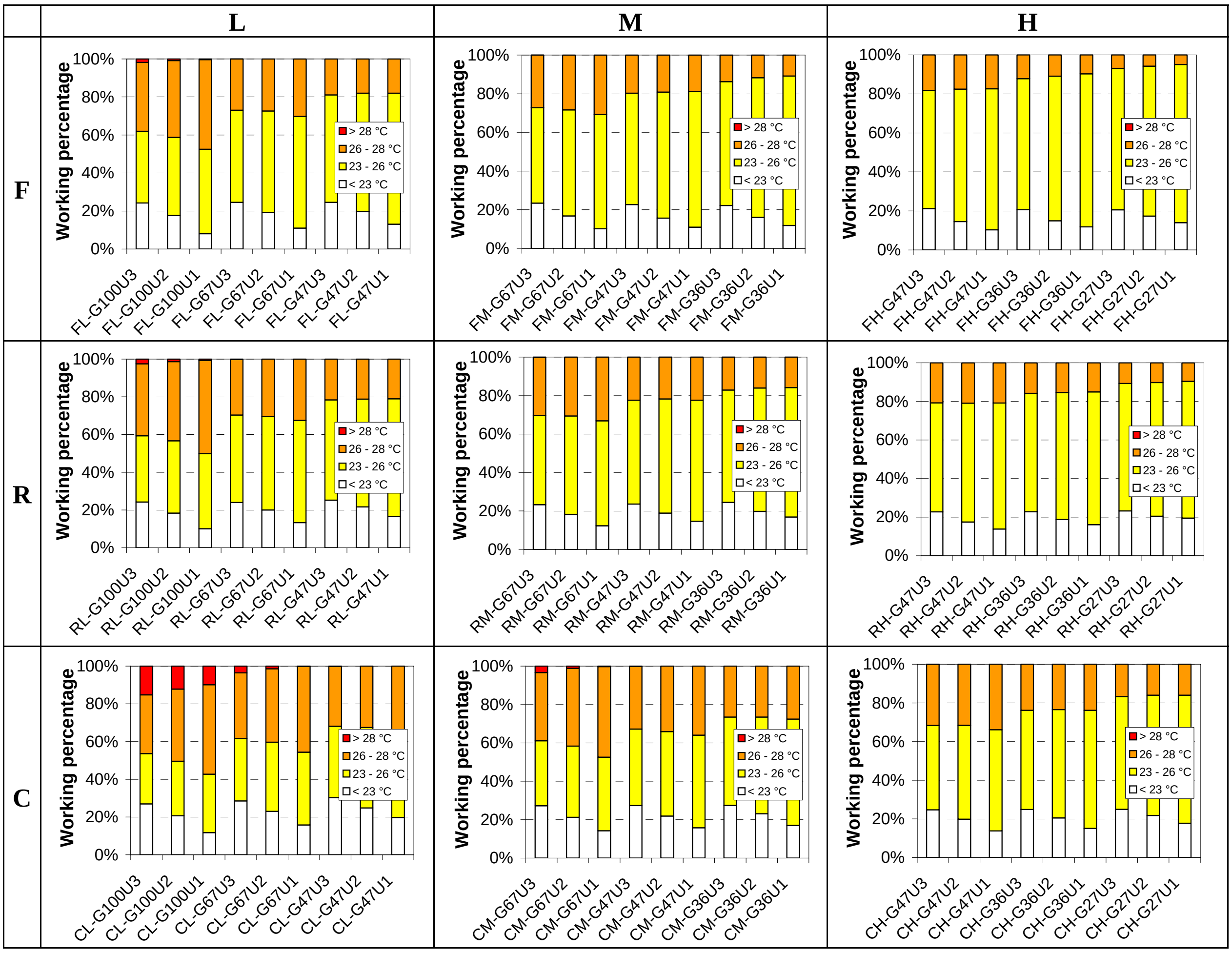

Figure 10 Percentage of working hours during four summer months with operative temperature in a specific interval (simulation results for test reference year - TRY)