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Theoretical evaluation of night sky cooling in the Czech Republic

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Abstract

Energy necessary for cooling of building in summer season makes a big part of energy required for building operation. Redundant heat removal in summer can be realized in various ways. One of possible methods, mainly in desert areas, is using thermal radiation against night sky. The paper deals with theoretical efficiency evaluation of night sky cooling in climatic condition of Czech Republic. The numerical simulations of non-steady heat transfer and internal thermal comfort evaluation in an office room has been performed. We have considered a cooling system consists of radiating panels placed on the roof, connected by pipes with the cooling ceiling in an office room. The radiating panel is used to cool down the cooling water by convection and heat radiation against the night sky.

At first we processed the real hourly climatic data for city Brno and by using the extra-terrestrial solar irradiation we calculated night sky temperature during cloudy conditions and other necessary climate parameters for the long-term simulations. From this file of data, we selected seven typical combinations of equivalent sky temperatures, external air temperatures and wind velocities in order to cover the external conditions during the summer nights. Next we assumed a variable mean temperature of water flowing through the radiating panel in order to be able of computing its thermal performance. Then we carried out seven simulations of chosen radiating panel with these boundary conditions by means of computational fluid dynamics method (CFD) in the software Fluent. The data obtained were processed in the own software so we set the appropriate regression functions describing the thermal behaviour of radiating panel, which was then used for long-term thermal performance simulations in software TRNSYS. The multi zone model in TRNSYS links the building and its equipment with thermal the cooling ceiling model as well as with the water loop containing the radiating panels. This computer model is capable of simulating the night sky cooling impact on the building and its internal environment. Since the investigation we carried out at the chosen office building, we used the typical office operation inclusive the schedules of occupancy, natural ventilation, heat gains from lightning, equipment etc. Then have performed two long-term simulations with and without night sky cooling.

The simulations have shown the outlet temperature of the radiant panel below the external air temperature in a few cases. This finding confirms the positive effect of radiation transfer against the night sky in the climate of Czech Republic. The thermal comfort was evaluated according the standard ISO 7730 and has been found the significant improvement of internal thermal comfort by using the night sky cooling in the testing office building.

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Keywords: Night sky cooling; Numerical simulation; CFD simulation; TRNSYS; Thermal comfort;

1. Introduction

Due to the maintaining of thermal comfort in the buildings, various cooling techniques are often used. Nowadays, with the trend of decreasing energy consumption in the buildings and with searching for more ecological friendly building design, the alternative cooling techniques gained interest. One of these techniques is cooling based on radiation against night sky, which is basically heat loss by long wave radiation emission towards the sky [1]. This domain has already been widely studied concerning it usage in hot, dry and also humid climates [2], [3]. In the Czech Republic, this method has not been used yet; therefore we have decided to determine if using of night sky cooling is relevant in the Czech Republic.

In our case, thermal activation of concrete ceiling is the most effective way of distribution and accumulation of cold produced during the night. During the night when the absorber is operating, the heat accumulated in floor slabs is withdrawn and the cold is stored in these slabs. As a result, the ceiling construction is overcooled and the space for heat accumulation from daily heat gains is created. The operative temperature in the room is influenced by lower temperature of the ceiling. We assume that despite of low effectivity of water heating, the absorber is able to preheat water for building operation in summer season.

Nomenclature

q	Density of heat flux [W]	E	Spectral emission coefficient [-]
t	Temperature [°C]	w	Wind speed [m/s]
T	Thermodynamic temperature [K]	T_a	Ambient air temperature [K]
p	Atmospheric pressure [Pa]	p_d	Water vapour pressure [Pa]
x	Specific air humidity [kg/kg]	Θ_z	Normal angle [°]
G	Solar irradiation [W/m^2]	K	Sky clearness index [-]
n	Number of day in the year	σ	Stefan-Boltzmann constant

Subscripts

p	Absorber	e	External
m	Heat transfer medium	i	Internal
con	Convective heat transfer	o	Sky
rad	Radiative heat transfer		

2. Climatic data processing

Nocturnal radiative cooling as a passive cooling method is based on longwave radiation. Therefore when the surface is exposed to the sky, the surface emits longwave radiation towards the sky, due to the temperature difference between the sky and the surface. This process takes place continuously all day and night, but it is useable only during the night in the summer period [4], otherwise the solar radiation during the day may outweigh the cooling effect.

When evaluating the potential of nocturnal radiative cooling in the Czech Republic, the temperature of night sky is the essential parameter for calculation. Various models for its determination were introduced. The simplest model for calculation of night sky temperatures is the clear sky model – see [5]. However, the clear sky under the climatic condition in the Czech Republic does not occur very often, therefore in our simulations we assumed cloudy night sky.

E_p – emissivity of absorber

E_o – emissivity of sky

$$q_p = E_p \times \sigma \times T_p^4$$

$$q_o = E_o \times \sigma \times T_p^4$$

$$q_t = q_p - E_p \times q_o$$

$$E_o = 0.80 - 0.19 \times \exp(-p_d / 1000)$$

$$q'_o = q_o\,(1 + K \times B^{2.5})$$

Total balance of the absorber

$$q = q_t + q_k$$

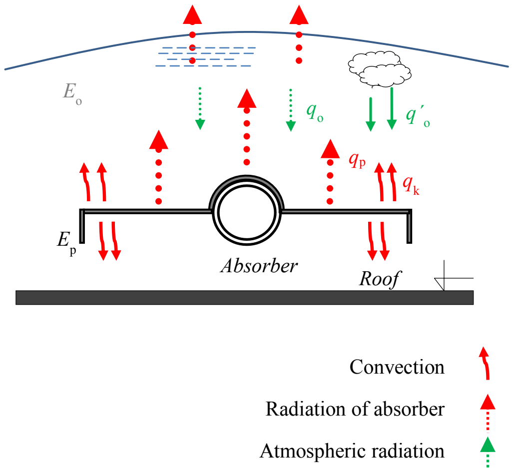


Fig. 1. Heat transfer mechanism of the absorber.

We used real climatic data for the determination of night sky temperature during cloudy conditions for Central Europe, specifically for Brno, Czech Republic. The climatic data we worked with are hourly climatic data for entire year and the most important parameters for our simulation are: month, hour, temperature of ambient, humidity ratio, enthalpy, global radiation and wind speed. However, for simulation of nocturnal cooling only temperatures during the night and during the summer period are relevant. To determine the temperatures which occur during June, July and August, we created histogram showing frequency of temperatures occurring during these months and we chose the temperatures to prove at least 2 °C difference between the absorber and air temperature.

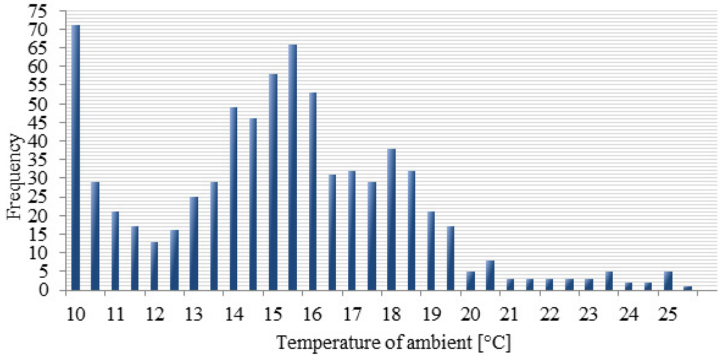


Fig. 2. Histogram of external temperatures during the night in June, July and August in Brno.

According to Aubinet, see [6], water vapour pressure correlate well with the night sky temperature during the cloudy conditions, therefore we calculated water vapour pressure for each of the chosen temperatures according to the:

$$p_{\mathrm{d}} = p \times x / (0.622 + x) \tag{1}$$

Aubinet also introduced another important parameter for calculating the cloudy night sky temperature – the sky clearness index K_0 as an indicator of mean cloud cover [6]. Sky clearness ratio is determined as a ratio between the daily solar irradiation G and the extra-terrestrial solar irradiation G_0:

$$K_0 = G / G_0 \tag{2}$$

The daily extra-terrestrial solar irradiation is given by the (3) according to [7]:

$$G_0 = G_{\mathrm{sc}} \, (1.000 + 0.033 \times \cos(360n / 365) \times \cos \Theta_z) \tag{3}$$

Where G_{sc} is the solar constant [W/m^2], n is the day of the year and Θ_z, is the angle between normal of the surface and direction of sun rays. The cloudy sky temperature is then calculated from the following formula according to the [5]:

$$T_{\mathrm{sky}} = 94 + 12.6 \ln(p_{\mathrm{d}}) - 13\, K_0 + 0.341\, T_{\mathrm{a}} \tag{4}$$

3. CFD Simulations

In order to carry out the simulations, it is necessary to create appropriate geometrical model. The aim of our simulations is to determine the heat output of the absorber per meter squared; therefore the geometry can be simplified and created in 2D. The geometry of the simulated absorber is shown in Fig.3.

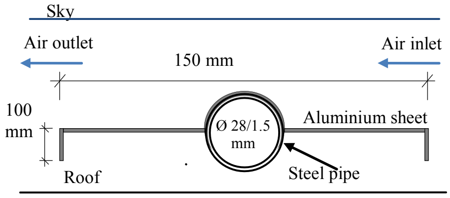


Fig. 3. Geometry of the absorber.

Before initialization of the simulation in CFD we entered boundary conditions types as follows:

- Walls: roof, sky, pipe, aluminium sheet;
- Velocity inlet of air inlet and outflow for air outlet;
- Solid type for the pipe and aluminium sheet, fluid for air inlet and air outlet.

The simulations were carried out in CFD software Fluent in steady state using 2D model with double precision. Viscous and radiation models are necessary to be specified for the simulations. Firstly, we set standard k-ω model, which converged well when the wind speed was low. With increasing wind speed, therefore with increasing influence of convection, solution did not converged even after 10 000 iterations. This problem can be solved by changing the geometry of the absorber or by choosing another viscous model. After analysing the problem, we have decided to choose more general, five equations Reynolds – Stress model, known also as a second-moment closure model. By using this model, the solution converged in all cases with any further changes. For the solution of radiative heat transfer in CFD we have chosen the discrete ordinates model, which solves the general transport equation for finite number of solid angles in Cartesian coordinate system. We carried out seven simulations (A – G) with different boundary conditions, which are shown in Table 1.

Table 1. Boundary conditions for CFD simulations

Simulation	t_m [°C]	t_e [°C]	t_{sky} [°C]	w [m/s]
Simulation A	25.0	24.5	17.4	1.00
Simulation B	25.2	21.4	14.4	1.60
Simulation C	25.4	19.0	11.5	2.70
Simulation D	25.6	17.0	8.71	3.10
Simulation E	25.8	15.3	6.57	5.70
Simulation F	26.0	12.7	3.92	6.90
Simulation G	26.2	9.90	1.16	8.30

4. Approximation of the function for the heat output

For determination of the heat output of the absorber we also approximated function for heat output by radiation and for heat output by convection using least squares method. Equation (5) represents heat output by convection and (6) by radiation.

$$q_{con} = 4.97783899 \times (t_m - t_e)^{1.234143578} \times w^{0.235206619} \quad (5)$$

$$q_{rad} = 0.993199231 \times (t_m - t_{sky})^{0.932828015} \quad (6)$$

$$q = q_{con} + q_{rad} \quad (7)$$

The own function is compared with the results of the simulation of the absorber in the Table 2. The function agrees with the simulation results.

Table 2. Comparing approximation with CFD simulation.

Simulation	Approximation function			Software ANSYS Fluent		
	q [W]	q_{con} [W]	q_{rad} [W]	q [W]	q_{con} [W]	q_{rad} [W]
Simulation A	8.679	2.116	6.563	8.860	2.750	6.110
Simulation B	38.04	28.88	9.160	45.84	36.60	9.240
Simulation C	73.76	62.15	11.61	79.91	68.31	11.60
Simulation D	106.3	92.45	13.87	101.8	87.52	14.23
Simulation E	152.2	136.5	15.66	149.2	133.4	15.75
Simulation F	208.9	191.1	17.81	203.4	185.6	17.74
Simulation G	276.6	256.6	20.03	270.5	205.9	19.55

Fig. 4 shows static and radiation temperatures obtained in ANSYS Fluent. Simulations A, C and G and the distribution of air temperature near to the absorber are shown. In case C we can see how the higher wind speeds and also its direction can influence the temperature around the absorber.

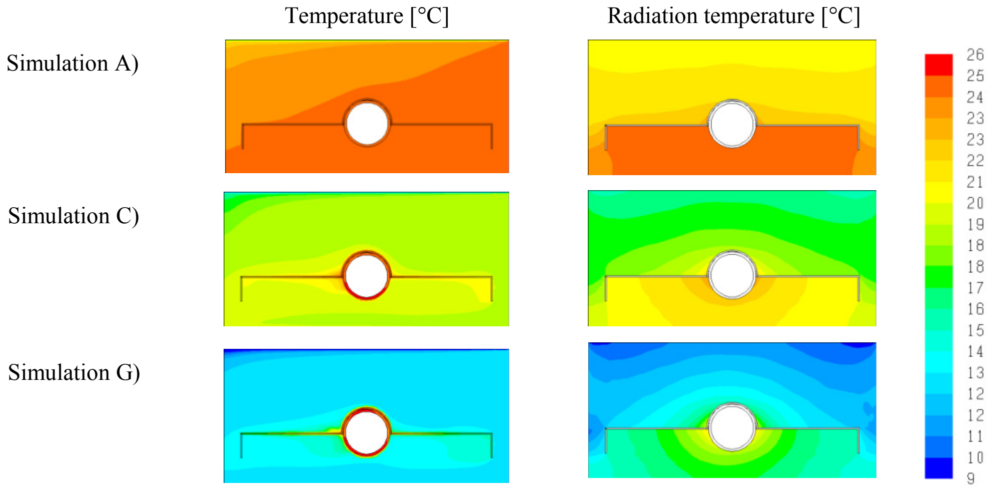


Fig. 4. Static and radiation temperatures of chosen cases obtained by ANSYS Fluent.

5. Simulation in TRNSYS

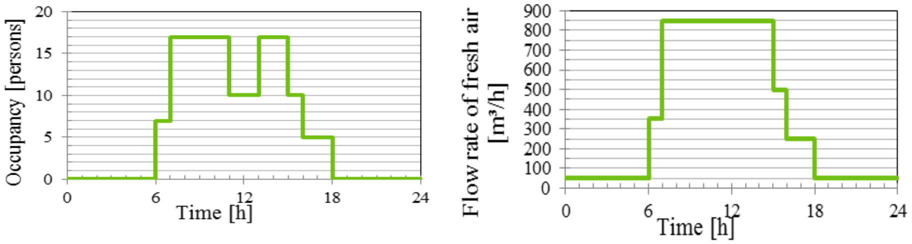
In order to determine the contribution of the absorber during building operation in dynamic conditions we used modular simulation program TRNYS. We used for the simulation one of the buildings in the area of Faculty of Civil Engineering in Brno University of Technology. It is an older, recently reconstructed building with flat roof and concrete skeleton. The building does not have any central ventilation or cooling system, so the ventilation of the building is natural. It is a corner building with facing windows mostly the street.

5.1. Computational model

One zone in typical floor with the offices was chosen for the simulation. Multi-zone model was created using module TRNBuild, which allows creating mathematical model of the building. Here we defined parameters of particular constructions and windows which enclose the simulated zone. Heat gains and their distribution during the day were entered – see Fig. 5. We calculated with typical office operation with working hours from 6 am to 6 pm – see Fig 5 a), we assumed 8m2/person, i.e. 17 people in the office. Heat gains were entered according to the standard ISO 7730 – degree of activity of people - seated, light work, typical application – office, hotels, total heat 150 W / sensible heat 75 W / latent heat 75 W. Due to previous experience, we assumed one computer per employee and the artificial lighting set to 100 % on from the arrival of first employee to the departure of the last one. For the simplification we assumed minimal hygienic dose of fresh air 50 m3 per hour according to the Czech standard. Intensity of ventilation is shown in Fig 5 c).

a) Occupancy

c) Natural ventilation



b) Lighting

d) Equipment

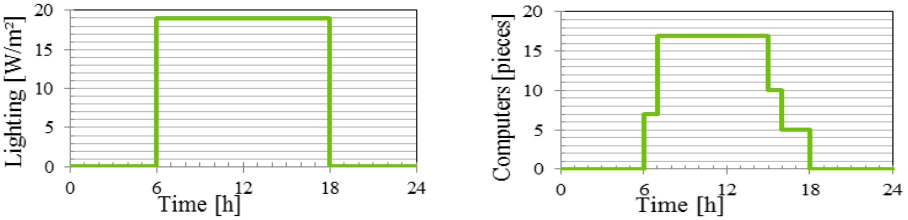


Fig. 5. Schedule in the office a) occupancy, b) lightning, c) natural ventilation, d) equipment

5.2. Thermal activation of concrete ceiling system

Thermal activation of concrete ceiling system (TACC) deals with the cold storage into a reinforced concrete slabs. Unfortunately TRNSYS does not allow simulating the chilled ceiling with variable input values. It was therefore necessary to find out a new model which is capable to simulate this system in software TRNBuild. There is a scheme of the office – vertical cut – on the Fig. 7 and here we show the main input variables of our TACC model. The concrete layer with piping in the middle of the ceiling was substituted by a fictive thermal zone which represents all their thermal properties. The thermal capacity of the fictive zone corresponds to the reality. The ceiling layers above and below this zone were connected to the fictive thermal zone and were further discretized and solved as standard wall. The flow rate, thermal capacity and heat transfer coefficients of the air flow were set to be corresponding to the reality – the flow of the cooling water.

5.3. Boundary conditions and the thermal model of the absorber

We used climatic data for typical metrological day in Brno as boundary conditions for external walls, temperature behaviour in internal constructions was assumed to be the same as in the observed room. Equations obtained from the simulations of absorber in 2D were the base for the simulation of absorber in TRNSYS. Above mentioned simulations do not consider cooling of medium in the length of absorber; therefore this was solved by model of solar absorber field. We created this model in Excel and consequently, we joined it with model in TRNSYS. Model of absorber field calculates with constant temperature in one lamella. The output temperature from the lamella is then calculated based on flow and removed heat and this temperature is then used as an input temperature to another lamella. Flow of water in one absorber field is based on velocity of flow in duct and pressure losses on 0.125 kg/s. One field of absorber contains fifty lamellas. The scheme of connection of the absorber is shown in Fig. 6.

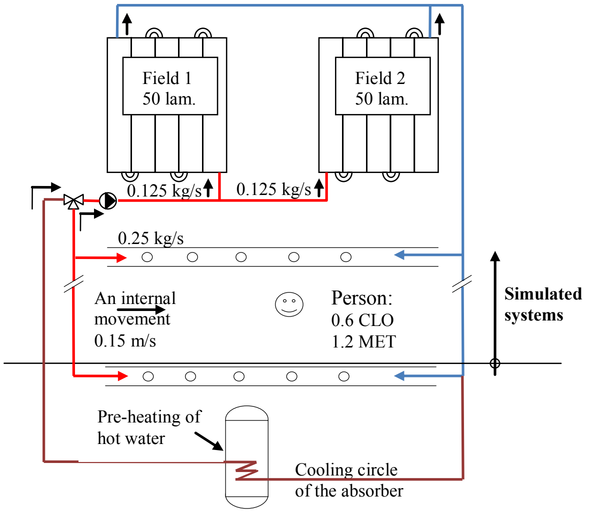
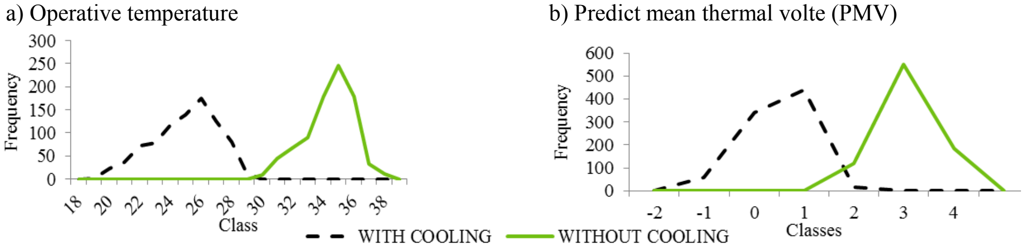


Fig. 6. Scheme of connection of absorbers

6. Results of the simulation

We performed the energy simulation for three consequent summer months. State of internal climate of area with no cooling was compared with area where thermally activated concrete core is used.


a) Operative temperature

b) Predict mean thermal volte (PMV)

Fig. 7. Histogram of a) Operative temperature, b) Predicted mean thermal vote (PMV).

For better imagination about impact on this cooling system on working space, we set the parameters of thermal comfort – PMV and PPD. First of the parameters, PMV shows Predicted Mean thermal Vote. Values of PMV < predict cold slightly, but values PMV > 0 predict warm slightly. Fig. 7 shows histogram with PMV index during the working hours. In a case of area without cooling we can see that during the working hours the warm slightly is predicted, but in the area with cooling system we can see that thermal comfort is in the domain of cold slightly due to night overcooling.

Fig. 8 a) shows histogram with PPD (Predicted Percentage of Dissatisfied) parameter. We can see the effect of night radiative cooling on working space. More than 90 % of unsatisfied people are in the area without cooling during the most of the working time; on the other hand in the area with cooling, there is less than 15 % unsatisfied during 70 % working time.

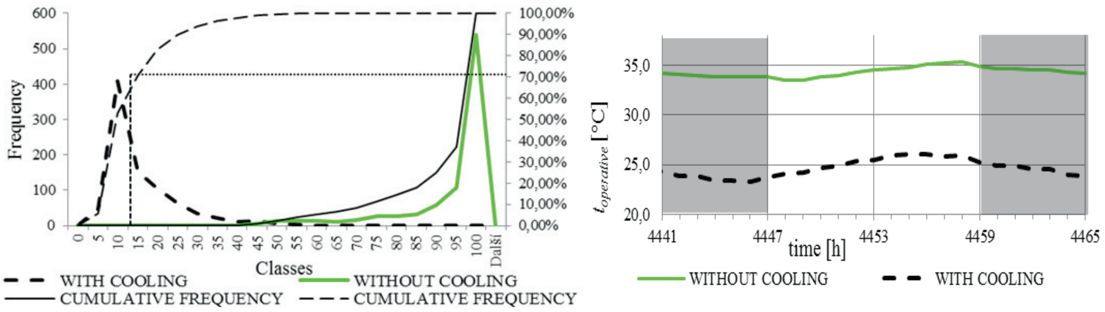


Fig. 8. (a) Histogram predicted percentage of dissatisfied (PPD); (b) Operative temperatures during a typical day

7. Conclusion

The contribution deals with evaluation of night sky cooling by coupled simulation by using software ANSYS Fluent, TRNSYS and also by using own improvements of this thermal model, in the Czech Republic. The results show possibility of improvement of internal climate by heat removal from solar absorbers without using conventional ways of cooling. However it is not possible to guarantee the highest thermal comfort in the interior - as for alternative cooling systems [8]. On the other hand it is possible to maintain sufficient level of microclimate during the working hours.

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