CFD SIMULATIONS OF THERMAL COMFORT IN NATURALLY VENTILATED PRIMARY SCHOOL CLASSROOMS

by

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The purpose of thermal comfort is to specify the combinations of indoor space environment and personal factors that will produce thermal environment conditions acceptable to 80% or more of the occupants within a space. Naturally ventilated indoors has a very complex air movement, which depends on numerous variables such as: outdoor interaction, intensity of infiltration, the number of openings, the thermal inertia of walls, occupant behaviors, etc. The most important mechanism for naturally ventilated indoors is the intensity of infiltration and thermal buoyancy mechanism. In this study the objective was to determine indicators of thermal comfort for children, by the CFD model based on experimental measurements with modification on turbulent and radiant heat transfer mathematical model. The case study was selected on school children of 8 and 9 years in „France Presern" primary school in Belgrade. The purpose was to evaluate the relationships between the indoor environment and the subjective responses. Also there was analysis of infiltration and stack effect based on meteorological data on site. The main parameters that were investigated are: operative temperature, radiant temperature, concentration of CO_2, and air velocity. The new correction of turbulence and radiative heat transfer models has been validated by comparison with experimental data using additional statistical indicators. It was found that both turbulence model correct and the new radiative model of nontransparent media have a significant influence on CFD data set accuracy.

Key words: *predicted mean vote, predicted percent of dissatisfied, k-ε turbulence model, non-radiative transparent media*

Introduction

Thermal comfort is a subjective human response to the thermal environment. This case study was performed on school children aged 8 and 9 years. The metabolic rate of children aged 8 and 9 is proven in different studies so there was a modification of it (Ma = 1.12 Met) [1, 2]. The thermal indicators that define the level of thermal comfort are on a Fanger's scale [3] of thermal subjective sensations. Fanger's scales for thermal sensation define seven levels of subjective human response to thermal sensation: too cold, cool, slightly cool, neutral, slightly warm, warm, and hot. Indicators according to Fanger's scale have different val-

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Table 1. Fanger's thermal scale of subjective thermal response

PMV value	Thermal scale
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
–1	Slightly cool
–2	Cool
–3	Cold

Figure 1. Local meteorological station on school building roof

ues for different thermal sensation, so there are in the range from –3 (too cold) to +3 (too warm), see tab. 1. Indicators are defined as predicted mean vote (PMV) and predicted percent of dissatisfied (PPD). These types of indicators are integrated in SRPS EN ISO 7730 [4] and they define the whole body temperatures. The thermal sensations of a population of 56 school children were observed in school classrooms in "France Presern", Belgrade. The only heat source was radiators from the district heating system.

Natural ventilation mechanisms

Naturally ventilated indoors has a very complex air movement, which depends on numerous variables such as: outdoor interaction, intensity of infiltration, the number of openings, the thermal inertia of walls, occupant behaviors, *etc*. The most important mechanism for naturally ventilated indoors is the intensity of infiltration and thermal buoyancy mechanism. An investigation was to determine primarily wind influence for objects classroom and define infiltration influence on natural ventilation. There is no mechanical ventilation in selected school, so the only air movements are natural ventilation. Because of the complex nature of air movements of natural ventilation through the building it is necessary to have experimental measurements of outdoor environment, including wind velocity and direction, temperature, relative humidity, and solar irradiation. Local meteorological station was installed on the school building roof for measurements of these outdoor environmental parameters (fig. 1).

Measuring data from the local meteorological station is summarized in tab. 2, measurement period was one month during winter season, with calibration of ±0,01 m/s.

Table 2. Weibull wind distribution parameters

	Wind direction											
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
A	3.6	0.5	3.9	6.0	6.7	0.5	3.1	2.8	0.5	5.3	4.3	5.2
k	0.86	10.34	1.08	2.49	5.85	10.34	0.95	1.00	10.34	1.54	1.94	2.39
U	3.90	0.49	3.82	5.34	6.16	0.49	3,15	2.79	0.49	4.76	3.84	4.61
f	43.7	0.5	1.9	28.8	1.9	0.5	2.6	5.4	0.5	4.4	4.4	5.4

The Weibull function is:

$$f(U) = \frac{k}{A}\left(\frac{U}{A}\right)^{k-1} \exp\left[-\left(\frac{U}{A}\right)^{k}\right] \tag{1}$$

The shape of the school building is *L-type*. Wind dataset indicates that prevailing wind direction is from north side: the frequency is 43.7% and wind velocity is 3.9 m/s. The measurement of thermal comfort was in school classrooms in north-west positions of building, which is on the lee-ward side of the wind-slope position. The locations of windows are on the west side of building where wind frequency is 4.4% with wind velocity of 4.76 m/s. Because the frequency of west wind direction is below about 5%, the infiltration of outdoor air can be neglected, so the primary mechanism that prevailing in selected classrooms is thermal buoyancy mechanism (stack effect). An experimental measurement program of thermal comfort has been performed in school classrooms as shown on fig. 2.

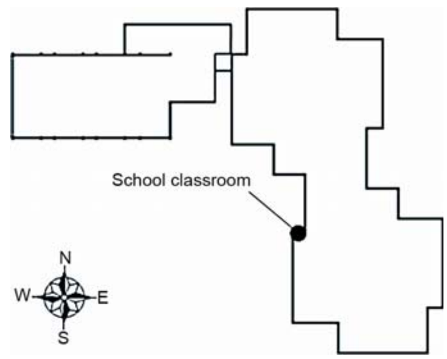

Figure 2. Location of classroom for thermal comfort measurements

Indoor experimental measurements of thermal comfort

To determine local thermal comfort indicators, it is necessary to have different instruments which register any air movements, rise temperature and humidity. In use there were 15 data loggers, black globe and hot-wire anemometer (fig. 3), with accuracy ±0,01 °C for data loggers and ±0,01 m/s for anemometer. Data loggers were located under every school desk, and black glove was installed at a height of 0.8 m height, which is approximately of height of seating children head. Experimental measurements were performed during winter season, so that clotting isolation for children were I_{cl} = 1.01 clo. Thermal comfort measurements were performed for seated children, taking value of metabolism Ma = 1.12 Met.

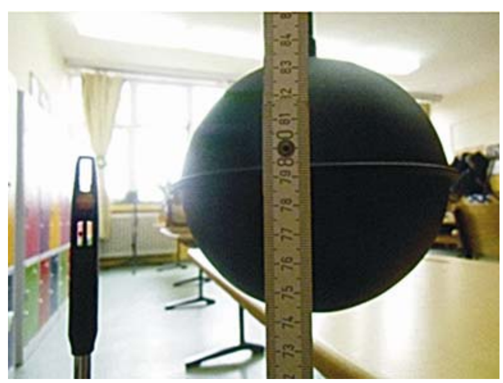

Figure 3. Thermal comfort data loggers, black globe, and hot-wire anemometer

Dispatch of instruments done survey of every child seated is shown in fig. 4. The survey was one month during winter season.

To determine relative air velocity around whole children body, it is necessary to make corrections. Corrections depend on the level of activity and basal metabolic rate of children and corrections are in direct relationship with breathing.

To calculate indicators of thermal comfort it is necessary to have a radiant and operating temperature. Radiant temperature is uniform temperature of globe spheres which repre

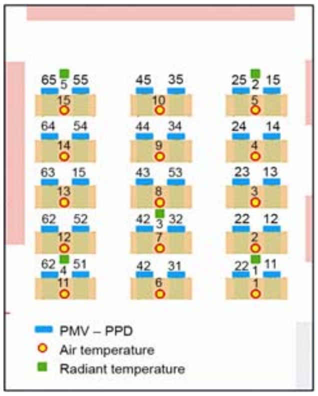

Figure 4. Location of instruments for monitoring survey of indicators of thermal comfort

sent radiant heat transfer from heat sources (Sun, radiators, humans, ... *etc.*) to whole human body in local point in the classroom:

$$t_{\mathrm{r}} = \left[(t_{\mathrm{g}} + 273)^4 + 2.4 \cdot 10^8 U_{\mathrm{a}}^{0.6} (t_{\mathrm{g}} - t_{\mathrm{a}}) \right]^{0.4} - 273 \tag{2}$$

where U_a [ms^{-1}] is the relative air velocity.

Operating temperature is uniform temperature given by convection and radiation in local point in the classroom (SRPS EN ISO 7730):

$$t_{op} = \frac{t_r + t_a \sqrt{10\, U_{\mathrm{a}}}}{1 + \sqrt{10\, U_{\mathrm{a}}}} \tag{3}$$

From experimental analysis based on SRPS EN ISO 7730 average value of PMV is –0.57 which is *slightly cold* based on a Fanger's scale, and average value of PPD is 12.24% (tab. 3).

Mathematical modeling

Governing equations

The mathematical model has been developed for the steady-state air flow, including turbulent dispersion model of pollutant, buoyancy effects, and radiant heat transfer model. Using diffusion approximation for radiation, known as Rosseland model [5], the conservation equations of mass, heat, and momentum can be written in the form of partial differential equation:

$$\partial_i (\rho U_i) = 0 \tag{4}$$

$$U_i \partial_i (\rho U_j) = \partial_i [\mu (\partial_i U_j + \partial_j U_i - \rho \overline{u_i u_j})] - \partial_j P + \mathrm{g}_i (\rho - \rho_{\mathrm{ref}}) \tag{5}$$

$$U_i \partial_i (\rho C) = \partial_i [D \partial_i (\rho C) - \overline{\rho c u_i}] \tag{6}$$

$$U_i \partial_i (\rho T) = \partial_i [a \partial_i (\rho T) - \overline{\rho \theta u_i}] + \varepsilon_{\mathrm{a}} \sigma (T_{\mathrm{rad}}^4 - T^4) \tag{7}$$

$$\partial_i [\lambda_{\mathrm{rad}} \partial_i (\rho T_{\mathrm{rad}})] = \varepsilon_{\mathrm{a}} \sigma (T^4 - T_{\mathrm{rad}}^4) \tag{8}$$

where D is the laminar diffusivity and σ – the Stefan-Boltzmann constant.

Turbulence model

Turbulence model is extended two-equation dissipative k-ε model by taking into account buoyancy effects of production term:

$$U_i \frac{\partial k}{\partial x_i} - \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] = P_k + G_k - \varepsilon \tag{9}$$

$$U_i \frac{\partial \varepsilon}{\partial x} - \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] = \frac{\varepsilon}{k} (C_{\varepsilon 1} P_k + C_{\varepsilon 3} G_k - C_{\varepsilon 2} \varepsilon) \tag{10}$$

Table 3. Operative and radiant temperature, PMV and PPD for 30 local points in classroom

No	Air temperature t_a [°C]	Black globe temperature t_g [°C]	Relative air velocity U_a [ms^{-1}]	Radiant temperature t_r [°C]	Operating temperature t_{op} [°C]	PMV	PPD
11	19.698	21.170	0.294	22.899	20.978	–0.53	10.91
12	20.406	20.830	0.343	21.379	20.795	–0.60	12.49
13	20.122	20.925	0.270	21.816	20.800	–0.53	10.91
14	20.945	20.925	0.260	20.903	20.928	–0.47	9.70
15	21.027	21.020	0.265	21.012	21.021	–0.46	9.37
21	19.698	21.170	0.271	22.794	20.936	–0.51	10.48
22	20.406	20.830	0.349	21.387	20.798	–0.60	12.61
23	20.122	20.925	0.317	21.918	20.840	–0.57	11.90
24	20.945	20.925	0.328	20.900	20.927	–0.54	11.04
25	21.027	21.020	0.180	21.014	21.021	–0.36	7.63
31	19.830	20.413	0.341	21.171	20.366	–0.71	15.51
32	20.246	20.490	0.364	20.816	20.474	–0.69	14.95
33	20.471	20.755	0.315	21.103	20.724	–0.58	12.17
34	20.576	20.755	0.251	20.948	20.725	–0.52	10.58
35	20.629	21.020	0.170	21.348	20.989	–0.36	7.75
41	19.830	20.413	0.247	21.032	20.311	–0.62	12.97
42	20.246	20.490	0.315	20.790	20.464	–0.65	13.79
43	20.471	20.755	0.351	21.129	20.734	–0.61	12.92
44	20.576	20.755	0.318	20.978	20.737	–0.58	12.08
45	20.629	21.020	0.193	21.376	21.003	–0.40	8.27
51	20.009	19.580	0.365	18.998	19.605	–0.87	21.12
52	20.293	20.035	0.361	19.687	20.051	–0.77	17.45
53	20.591	20.528	0.309	20.451	20.535	–0.61	12.93
54	20.662	20.528	0.306	20.366	20.544	–0.61	12.76
55	20.573	21.020	0.232	21.476	20.934	–0.45	9.18
61	20.009	19.580	0.253	19.110	19.649	–0.76	17.29
62	20.293	20.035	0.260	19.749	20.075	–0.67	14.53
63	20.591	20.528	0.315	20.451	20.535	–0.62	13.07
64	20.662	20.528	0.296	20.368	20.544	–0.60	12.52
65	20.573	21.020	0.206	21.444	20.921	–0.42	8.61
					Average	–0.57	12.24

$$P_k = \nu_t \left(\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i} \right) \frac{\partial U_i}{\partial x_k} \tag{11}$$

$$G_k = \nu_t \beta \mathrm{g}_i \frac{\partial T_\mathrm{a}}{\partial x_i} \tag{12}$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \tag{13}$$

$$(\sigma_k, \sigma_\varepsilon, C_{\varepsilon 1}, C_{\varepsilon 2}, C_\mu) = (1.0, 1.314, 1.44, 1.92, \text{and } 0.09) \tag{14}$$

where β is the air thermal expansion coefficient, ν – the laminar viscosity, ν_t – the turbulent viscosity, u – the turbulent velocity, θ – the temperature fluctuations, C – the concentration, and c – the concentration fluctuation.

The empirical coefficient has been found $C_{\varepsilon 3}$ to depend on the flow situation [6]. It should be close to zero for stably-stratified flow, and to 1.0 for unstably-stratified flows. We introduced the possibility to compute $C_{\varepsilon 3}$ from the function proposed by [6]:

$$C_{\varepsilon 3} = \tanh \left(\frac{U_\mathrm{P}}{U_\mathrm{N}} \right) \tag{15}$$

where U_P and U_N are the velocity components parallel and perpendicular to the gravity vector, respectively.

Radiation model

The basic idea of radiative heat transfer model is solution of variable T_rad, from a gradient-type equation with local diffusivity depended on: nature of the medium (air), on its temperature, and on the distance between nearby solid walls. Therefore, the model distinguishes two temperatures: temperature of the air (T_a) and the radiant temperature (T_rad) [7]. For solid materials which may be immersed in the medium, T_rad is defined as being equal to the local solid temperature. Based on the Rosseland radiation model [8] and formulation of λ_rad for both optically thick and thin media that is embedded in the PHOENICS code [9], the expression for λ_rad is:

$$\lambda_\mathrm{rad} = \frac{16}{3} \sigma T_\mathrm{rad}^3 \frac{1}{\varepsilon_a + s_a + \dfrac{1}{X_\mathrm{gap}}} \tag{16}$$

where X_gap stands for the distance between the solid surfaces, it's reciprocal value represents additional medium resistivity; ε_a and s_a are effective atmospheric emissivity and scattering coefficients, respectively. There is a convenient technique to calculate X_gap. It can be obtained using additional scalar variable L, which obeys the differential equation [9]:

$$\partial_{ii} L + 1 = 0 \tag{17}$$

This equation is similar to that for temperature within a uniformly conducting medium, having a uniform heat source, and in contact with solids and other surfaces at which the temperature is held at zero. Its dimension is indeed those of length squared within the fluid, and equals zero within the solid. However, it is a plausible estimate of the effective distance between walls X_gap.

Determination of effective emissivity and scattering coefficients are more complex since they are influenced by the indoor environmental condition. In this study, it is accepted, the following expression for effective indoor environment emissivity:

$$\varepsilon_{\mathrm{a}} = \varepsilon_{\mathrm{a}}(\mathrm{H_2O}) + \varepsilon_{\mathrm{a}}(\mathrm{O_3}) + \varepsilon_{\mathrm{a}}(\mathrm{overlap}) + \varepsilon_{\mathrm{a}}(\mathrm{CO_2}) \tag{18}$$

Based on the indoor environment condition during the measurement periods and numerical simulation, as well, it is assumed constant relative humidity, whereas the concentration of CO_2 is related to the occupant behavior. Therefore, we assumed that the first three terms in eq. (18) are constant and found relation for the effective indoor air emissivity and scattering coefficients related to CO_2 only:

$$\varepsilon_0 = A + BC_{\mathrm{CO_2}} \tag{19}$$

$$s_0 = 0.2\varepsilon_0 \tag{20}$$

The constants A and B: $A = 0.31$ and $B = 1.852\text{E-4}$ were determined by experiment.

Numerical simulation

Simulation was performed in PHOENICS software code [9]. For models simulations it was in use experimental data for boundary conditions (walls, windows). Some simulation results of indicators of thermal comfort indices PMV are presented in fig. 5 for thermal figures of school children. As an example, it is taken to school children as a whole body temperature according to SRPS EN ISO 7730. On a left child, thermal figure is distinguishing two cooler areas blue and green. This is normal for the temperature of the whole body because there is core temperature (heart, lungs, stomach) and there is a temperature of peripherals (arms and legs). For left child, PMV according to Fanger's scale is *slightly cold*. For the right child, we can see that core area of the head and lungs is yellow and red so it is according to PMV *slightly worm*.

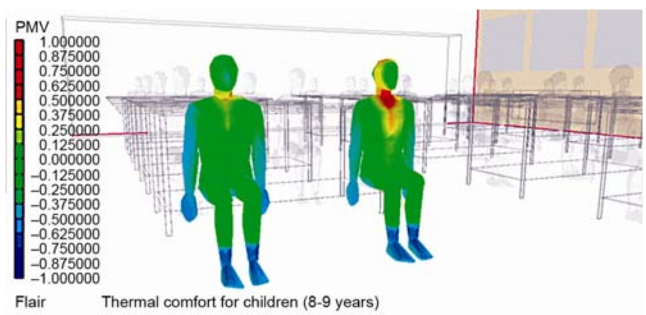

Figure 5. The PMV of two thermal figures of school children

Indicators of PMV and PPD of whole school classrooms are shown in fig. 6. It is non-uniform field of PMV values and PPD values. This non-uniformities are the result of the radiant asymmetry of cold and warm walls. The average value of PMV is –0.288 and PPD is 7.5%, which is on a Fanger's scale *slightly cold* value.

Model validation

To make the final assessment of the validity of the model, there is comparison with experiment, the obvious conclusion is that the ideal model is one that meets the requirements that the values of the statistical parameters, geometric mean bias (*MG*), geometric variance (*VG*), hit rate, *q*, and factor of two (*FAC*2) unity, values and statistical parameters fractional bias (*FB*), normalized mean square error (*NMSE*) zero. However, these ideal conditions are

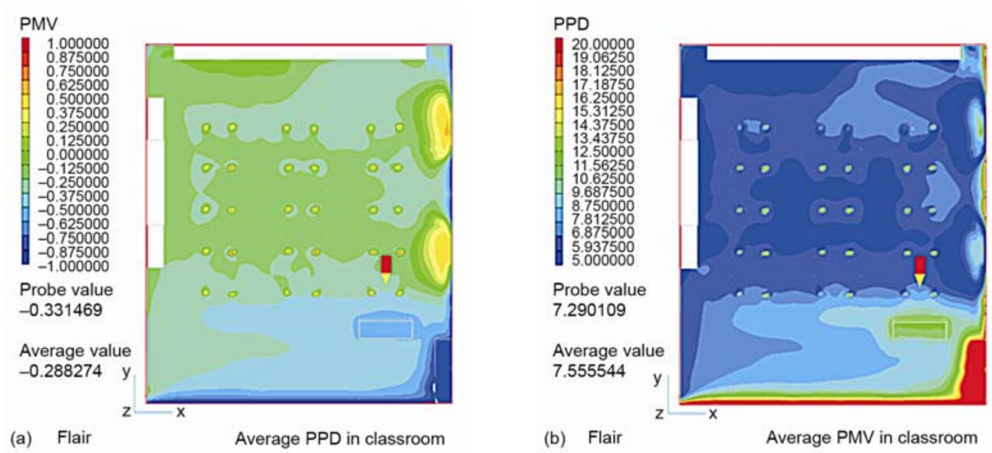

Figure 6. Average indicators of PMV (a) and PPD (b) in modified model

very difficult to achieve, it is necessary to adopt specific criteria for these parameters that give the assessment of the successful validation of the model. The adopted criteria are given in [7, 8] and summarized values are specified as statistical validation indicators for air temperature, radiant temperature, and PPD (tab. 4, fig. 7).

Table 4. Validation of statistical parameters CFD model with experimental values

Parameter	Value							
	T_{exp}	T_{cfd}	*FB*	*MG*	*NMSE*	*VG*	*FAC2*	*q*
Air temperature	20.405	19.821	0.0290	1.029	0.0011	1.001	0.971	0.800
Radiant temperature	20.767	20.256	0.0249	1.025	0.0018	1.002	0.976	0.800
PPD	12.250	12.401	0.0123	1.014	0.0706	1.064	1.016	0.800

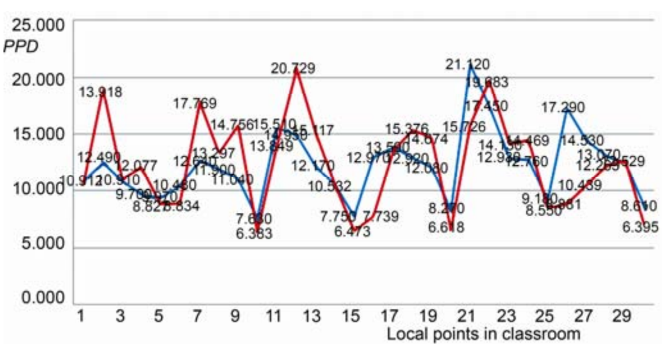

Figure 7. Validation of statistical parameters PPD_{CFD} model with PPD_{exp} experimental values

Parameters are calculated:

$$FB = \frac{\overline{\Phi_{exp}} - \overline{\Phi_{cfd}}}{0.5(\overline{\Phi_{exp}} + \overline{\Phi_{cfd}})}, \qquad |FB| < 0.3 \tag{21}$$

$$MG = \exp[\ln(\Phi_{\text{exp}}) - \ln(\Phi_{\text{cfd}})], \qquad 0.7 < MG < 1.3 \tag{22}$$

$$NMSE = \frac{\overline{(\Phi_{\text{exp}} - \Phi_{\text{cfd}})^2}}{\overline{\Phi_{\text{exp}}}\,\overline{\Phi_{\text{cfd}}}}, \qquad NMSE < 1.5 \tag{23}$$

$$VG = \exp[\ln(\Phi_{\text{exp}} - \ln\Phi_{\text{cfd}})^2], \qquad VG < 4 \tag{24}$$

$$FAC2 = \frac{\Phi_{\text{cfd}}}{\Phi_{\text{exp}}}, \qquad 0.5 \le FAC2 \le 2.0 \tag{25}$$

$$q = \frac{1}{N}\sum_{n=1}^{N} i_n, \qquad q \ge 0.6 \tag{26}$$

Based on analysis of errors and statistical parameters of the CFD model validation, it could be concluded that the model for validation criteria is 0.8 which is satisfactory because value is above limit criteria of 0.66.

Conclusions

From experimental analysis based on SRPS EN ISO 7730 average value of PMV is –0.57 which is *slightly cold* based on a Fanger's scale, and average value of PPD is 12.24%. The mathematical model has been developed for the steady-state air flow, including turbulent dispersion model of pollutant, buoyancy effects and radiant heat transfer model. The turbulence empirical coefficient $C_{\varepsilon 3}$ has been found to depend on the flow direction. The remaining part of the task of defining models of heat transfer by radiation is the determination of the coefficients of emissivity and scattering per unit length. The coefficient of emissivity is known for solids and can be taken from a wide literature. However, coefficient emissivity and scattering of non-transparent medium, in this case, is that the air in the classroom is contaminated with carbon dioxide and water vapor and it has to be determined. Carbon dioxide and water vapor are three atomic gases that make the contaminated air in the classroom still not transparent environment, especially in the last third of the time staying in school when the average concentration of carbon dioxide raises over 2000 ppm. Based on analysis of errors and statistical indicators of the CFD model validation, it could be concluded that the model for validation criteria is 0.8 which is satisfactory because value is above limit criteria of 0.66. It is non-uniform field of PMV values and PPD values. This non-uniformities are the result of the radiant asymmetry of cold and warm walls. The average value of PMV for the modified CFD model is –0.288 and PPD is 7.5%, which is on a Fanger's scale *slightly cold* value.

Nomenclature

A – Weibull parameter, [–]
a – thermal diffusivity, [m^2s^{-1}]
f – frequency, [%]
$f(U)$ – Weibull function
g_i – gravitational acceleration, [ms^{-2}]
I_{cl} – insolation for clothing, [clo]
k – Weibull parameter, [–]
q – hit rate
s_a – scattering coefficient, [cm^2]
T_{cfd} – CFD temperature value, [°C]
T_{exp} – experimental temperature value,[°C]
T_{rad} – radiant air temperature,[°C]
t_a – air temperature, [°C]
t_g – black globe temperature, [°C]
t_r – local radiant temperature, [°C]
U – wind velocity, [ms^{-1}]
U_a – air velocity around the globe, [ms^{-1}]
U_j – wind velocity components (j = 1, 2, 3), [ms^{-1}]
U_N – velocity components perpendicular to the gravity vector, [ms^{-1}]

U_P – velocity components parallel to the gravity vector, [ms^{-1}]
X_{gap} – distance between the solid surface, [m]

Acronyms

FAC2 – factor of two
FB – fractional bias
MG – geometric mean bias
NMSE – normalized mean square error
PMV – predicted mean vote
PPD – predicted percent of dissatisfied
VG – geometric variance

Greek symbols

ε_a – effective atmospheric emissivity, [m^{-1}]
ε_a (CO_2) – effective atmospheric emissivity for carbon dioxide, [m^{-1}]
ε_a (H_2O) – effective atmospheric emissivity for water wiper, [m^{-1}]
ε_a (O_3) – effective atmospheric emissivity for ozone, [m^{-1}]
ε_a (overlap) – effective atmospheric emissivity for overlap, [m^{-1}]
λ_{rad} – effective radiant diffusivity, [m^{2}s^{-1}]
ρ – density, [kgm^{-3}]

Subscripts

a – air
cl – clothing
exp – experimental
g – globe
rad – radiant

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