INFLUENCE OF THE BUILDING ENERGY EFFICIENCY ON INDOOR AIR TEMPERATURE
The Case of a Typical School Classroom in Serbia

by

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Greenhouse gases emission as well as total energy consumption in buildings of public importance, such as schools, municipal buildings, health care centers, can be significantly reduced by increasing buildings' energy efficiency. Buildings' energy consumption adds up to 37% of total energy consumption in the EU countries. In the Republic of Serbia this amount is significantly higher, about 50%. School buildings are considered as one of the most diverse structures from the point of energy-efficient design and construction. The main aim of this paper is to determine the most appropriate settings for possible improvements in energy efficiency and temperature comfort inside a typical primary school classroom in Serbia. The energy efficiency analysis was performed during the heating season for the naturally ventilated primary school classroom located in the eastern Serbia region. The analysis was performed using novel CFD model, suggested in this paper. The suggested model was used to solve two hypothetical scenarios. The first scenario simulates the temperature field in classroom with current energy characteristic envelope of the school building. The calculated numerical data from the first scenario were compared with in-situ measurements values of temperature and wall heat fluxes and showed satisfying accuracy. The second scenario was simulated to indicate possible improvements, which would allow energy consumption decrease and thermal quality enhancement. The analyzed results, calculated using the suggested numerical model under the second scenario conditions, showed that using appropriate set of measures, it is possible to obtain desired temperature comfort levels without need for increase in the building energy consumption.

Key words: *energy efficiency, thermal comfort, school buildings, CFD*

Introduction

In the recent years, both professional and scientific societies perform significant efforts to find a solution for present challenges regarding building energy consumption [1-3]. Large portion of utilized energy is spent on heating (cooling). The amount of energy depends on the characteristics of the heating (cooling) systems, internal heat partition and characteristics of the building's thermal envelope. Based on this, the main aim is to minimize the buildings' energy consumption, maintaining adequate indoor comfort at the same time. It is expected that achieved thermal comfort would comply with the European regulations on buildings' energy ef-

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ficiency and current indoor air quality (IAQ) standards. Occupants' desired health and comfort levels are defined by the IAQ, which is in most cases determined by the building's ventilation system characteristics and its infiltration levels. Because of this, buildings' IAQ is always actual topic. Building types of the foremost interest are residential, office and educational buildings [4-11]. It is accepted that school buildings are the most vulnerable considering the healthy environment and the indoor comfort because of the time children spent inside of them. The majority of schools in Serbia are naturally ventilated with consequent low envelope performance and thus have low IAQ. The IAQ and indoor thermal comfort in the classrooms have a prevailing effect on the teaching and learning capabilities and generally have significant influence on students' and teachers' long-term health [8, 12, 13].

Schools are one of the most complex building types in terms of energy-efficient design and construction since they need to maintain the defined performance in all environmental conditions, during accommodating periods characterized by very high occupant densities. This can be explained by the fact that a typical classroom has more occupants per square meter than a typical office building [14]. Our previous study was conducted during the heating season in five different primary naturally ventilated schools in Serbia situated both in rural and urban areas. Measurements of indoor CO_2 concentration were performed in the classrooms occupied by children of age 7-10. The obtained indoor CO_2 concentrations were higher than 1000 ppm for over 50% of the time the children were present in the classroom, pointing out very poor ventilation. It was concluded that the main reason of high indoor CO_2 concentration and low IAQ is the insufficient ventilation of the classrooms [15]. More detailed research was performed in a single school. The school was chosen based on the estimated IAQ with aim to point the sources of air pollution. The experimental campaign included measurements of the suspended particulate matter up to 10 μm (PM_{10}), respirable suspended particulate matter less than 2.5 μm ($PM_{2.5}$), polycyclic aromatic hydrocarbons in PM_{10} (PAH in PM_{10}), volatile organic compounds, formaldehyde, ozone, NO_2, and CO_2. The measurement results showed that the concentrations of PM_{10}, $PM_{2.5}$, NO_2, and PAH during classes exceeded their threshold limit values. It was concluded that increase in the indoor concentration of pollutants in school classrooms is a consequence of different factors. The most important being the inadequate and insufficient ventilation, the incomplete combustion of coal in the boiler furnace, low level of flue gas extraction, presence of old carpets and flooring in the observed classrooms and poor state of windows [16]. Recent research studies report that more than one third of children in Europe suffer from asthma or allergies and that the frequency of respiratory diseases believed to be caused by indoor air pollution is continuously increasing [15].

Although different research groups use different methods to investigate thermal comfort, it is commonly accepted to link its significance to the indoor temperature. This can be explained by the fact that all internationally accepted standards [16] recommend temperature levels inside school buildings.

Poor thermal characteristics of the building envelope are the main cause of the building heat losses. Modelling tools for estimating building energy consumption can be used to perform a detailed simulation of the current state and to point to the possible improvements of the building thermal comfort levels. Thus, it is possible to simulate different scenarios that would allow deeper insight into the possible energy consumption reduction mechanisms and consequently to a possible increase in the living space quality.

The most important parameters in assessing building energy efficiency are the characteristics of the building envelope which is also an important factor in the indoor building thermal comfort.

According to Serbian Regulations on Energy Efficiency of Buildings, the indoor air design temperature during the heating season for schools' buildings should be 20 °C [17]. In cases where the energy performance of the building's envelope is not satisfactory, a large amount of energy consumption is required to achieve the adequate air temperature. The CFD simulation has become a widely accepted method for indoor environment quality assessment. The CFD simulations can calculate temperature distribution in any classroom. Thus, CFD helps us to identify the location and causes of the possible heat loss sources. Numerical results obtained by the performed CFD simulations allows us to define the best-case scenarios for building energy efficiency increase. Undoubtedly, among the available research methods, real scale measurements are the most reliable for the accurate description of the IAQ and building energy efficiency. However, full-scale measurements are often expensive, time-consuming, and often difficult to execute. The CFD is well established tool for simulation of ventilation and ventilation systems [18, 19] and smoke extraction systems [20, 21]. The CFD is also an important tool in improving building health and safety [22-24], thermal comfort for the occupants' spaces [25, 26], testing energy-efficient designs [27, 28]*, etc.* The CFD modelling has been frequently applied for the thermal comfort and energy efficiency assessment within the IAQ studies of school buildings.

Wang *et al.* [29] showed that natural ventilation is an effective method to simultaneously improve IAQ and reduce energy consumption in buildings, especially when the indoor temperature is close to the ambient temperature. The same authors in [30] showed that the enhancement of classroom air quality and reduction of school building energy consumption could be simultaneously achieved with the appropriate operation of heat recovery heat pump and ventilation system. Campano *et al.* [31] performed an analysis of thermal emissions of a typical classroom heated by radiators situated under the windows. Karimipanah *et al.* [32] carried out many CFD simulation cases to provide additional information on IAQ and comfort conditions inside a single classroom. The effects of ventilation flow rate, air exchange, radiation influence, and supply temperature value on thermal comfort and air quality were assessed.

The main subject of this paper is to research the influence of building energy efficiency on indoor air temperature using a 3-D CFD simulation of a naturally ventilated classroom inside a typical primary school building in the eastern Serbia region during the heating season.

The first step is to examine the current classroom energy efficiency using the numerically obtained temperature field. Numerically calculated temperature values are being compared to the corresponding experimentally determined temperature values in order to establish the CFD model accuracy. Based on the obtained results, a novel scenario with a proposed set of measures for energy efficiency increase is determined. The validated CFD model used to calculate temperature distribution within the school classroom under the new scenario conditions. Numerically calculated results are being used to verify the effectiveness of proposed measures.

Experimental measurements

Indoor temperature comfort and energy efficiency a typical school classroom in Serbia are analyzed in the framework of this study. The school building, built in 1970 is in the city of Zaječar (43° 90′ N, 22° 29 ′ E). The building was renovated twice (1988 and 2008) and critical parts were fixed. The building has three levels: basement, ground floor, and first floor, total area of 4438.09 m^2 and usable area of heated space 3878.45 m^2. A local solid fuel boiler (lignite) is used for the heating system. The boiler room is located in the basement of the building. The heating of the school building was performed by radiator heating, which was carried out throughout the building. The school building does not have an air-conditioning and ventilation system.

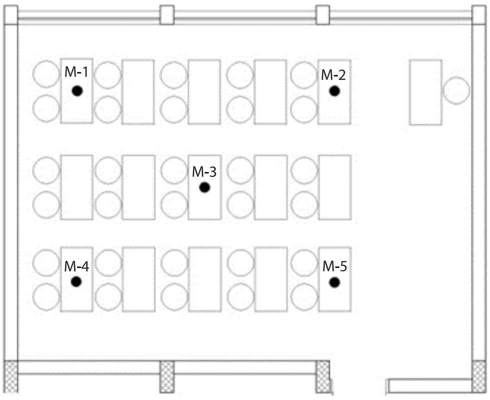

Figure 1. Position of temperature probes with loggers

The classroom measurement campaign was conducted to determine indoor air temperatures and heat flux values of different building envelope elements. To determine school building energy efficiency the infiltration measurement campaign conducted at three measuring points in school.

The indoor air temperature was measured at five different positions inside the classroom, located under the school desks, as shown in fig. 1. The campaign lasted for five working days (from Monday morning to Friday evening), during the heating period.

The school building has a local heating system and natural ventilation. The selected classroom in which measurements were performed has one external wall, one internal wall, which is in contact with an indoor corridor, two internal walls and ceiling in contact with the adjacent classrooms, and one floor surface.

Heath flux, air temperature, and surface temperature were measured every 10 minutes using the instruments Testo 435 with heat flux sensor and Testo 435 with temperature sensors. Measured values of the envelope's heat flux, air temperatures, and surface temperatures were used to calculate walls, windows, and door's thermal conductivity coefficients. The same values were also used for the calculation of the heat transfer coefficient of the overall building envelope.

Experimentally determined heat flux and temperature values used to calculate heat transfer coefficients (*U*-values) of the glass wall, external wall, ground floor, and ceiling surfaces are shown in the fig. 2. It was concluded that data obtained from daily measurements are not quasi-stationary, mainly due to solar radiation influence. Based on this conclusion, it was decided to use data obtained from nightly measurements for all further calculations. The calculation of *U*-values of building envelops was performed using the expression given in ISO 9869 standard [33]:

$$U = \frac{\sum_{i}^{n} q_i}{\sum_{j}^{n} \left(T_{ij} - T_{ej} \right)} \tag{1}$$

where q [Wm^{-2}] is the heat flux through the building element, T_i [°C] – the indoor temperature of the air in the boundary-layer, and T_e [°C] – external surface temperature of the building element.

The number of air changes per hour was determined measuring the concentration of CO$_2$ at the measuring points and in the external environment, using the gas tracer method [34]:

$$n = \frac{\ln\left[C(t_2) - C_s \right] - \ln\left[C(t_1) - C_s \right]}{t_2 - t_1} \; [\text{hour}^{-1}] \tag{2}$$

where t [hour] is the time, $C(t)$ [ppm] – the concentration of CO$_2$ in the room at time t, C_s [ppm] – the concentration of CO$_2$ in the external environment, and Δt – the time of record of measuring device, which is 10 min in the case under consideration.

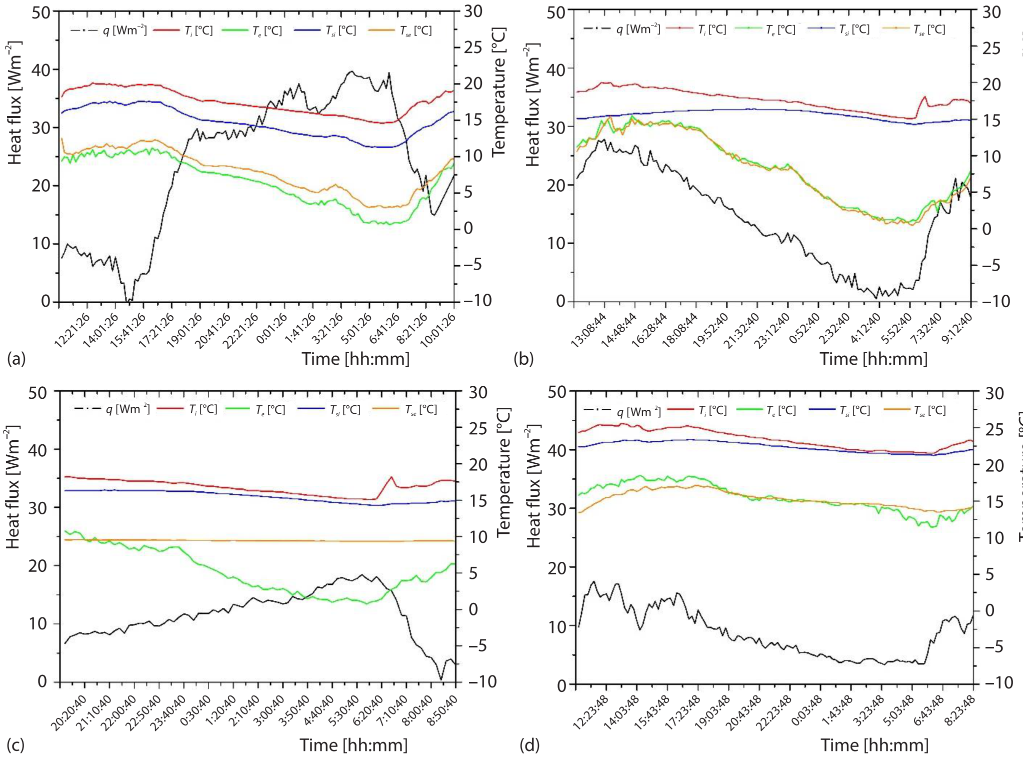

Figure 2. Measured parameters used for calculation of *U*-values for buildings envelope; (a) window, (b) external wall, (c) ground floor, and (d) ceiling (*for color image see journal web site*)

Time period for determining Δt is time period after children left classroom, when CO_2 concentration is the highest, until equilibrium with outdoor concentration. In the considered case, this time period for calculating Δt is between 90-120 minutes.

The number of changes was calculated as the mean value of the calculated ten-minute CO_2 values at the three measuring points in this school.

Combined measurement uncertainty of experimental measurement:

$$\delta = \sqrt{\delta_i^2 + \delta_{S_d}^2} \tag{3}$$

where δ_i is the measurement uncertainty of the device used for measurement ($i = 1, 2\ldots N$), which depends on the number of devices and δ_{S_d} – *the* measurement uncertainty of measurement results

Extended measurement uncertainty:

$$\delta_{\text{ext}} = k\delta \tag{4}$$

The value of the factor ($k = 2$) was adopted, because the probability is 95% that the obtained result will be found in this area.

The *U*-value measurement uncertainty for all measurement cases:

$$\delta = \sqrt{(\delta T_i)^2 + (\delta T_e)^2 + (\delta T_{si})^2 + (\delta T_{se})^2 + (\delta q)^2 + (\delta u)^2} \tag{5}$$

Table 1 shows the measured and calculated values of measurement uncertainty.

Table 1. Measured and extended values of measurement uncertainty

Measured	Uncertainty of measurement	Extended uncertainty of measurement
External wall	0.88 %	1.76 %
Ceiling	0.91 %	1.82 %
Ground floor	0.88 %	1.76 %
Window	0.89 %	1.78%
Air changes*	5%	10 %

* for air changes uncertainty of measurement is uncertainty of device used for measurement

Based on the previously presented measurements and data on the geometries of the building, a calculation of energy consumption was made only for heating according to [18, 19], since the school has natural ventilation.

Geometrical model of the investigated classroom

The geometry model of the classroom has an inner area of 55 m^2 designed to accommodate 28 students and one teacher. The main dimensions of the modeled classroom are 8.6 m in length, 6.4 m in depth, and 3.7 m in height. Classroom tables are arranged in three columns and five rows, fig. 3. It is assumed that each student generates averaged heat load of 75 W, while the standing teacher generates averaged heat load of 100 W. Physical shape of all occupants in the investigated model is represented by the hexaedars. Although this may seem like quite a big simplification in terms of geometry, it enables the generation of a high quality structured computational grid consisting of all hexagonal elements. Since the focus of performed CFD simulations is to calculate the heat transfer and temperature distribution near-walls, which requires high grid quality in this region, and not the flow near the classroom's occupants, this simplification is also physically justified. The classroom is equipped with a radiator heating system without any mechanical ventilation. This allows uncontrolled infiltration through the door and windows. The energy exchange radiator system consists of three radiator panels placed under the windows, with a temperature difference of 20 °C in the water in/out (I/O). Previously calculated heat transfer coefficients (*U*-values) of building envelope components are used as input for CFD simulations, tab. 3.

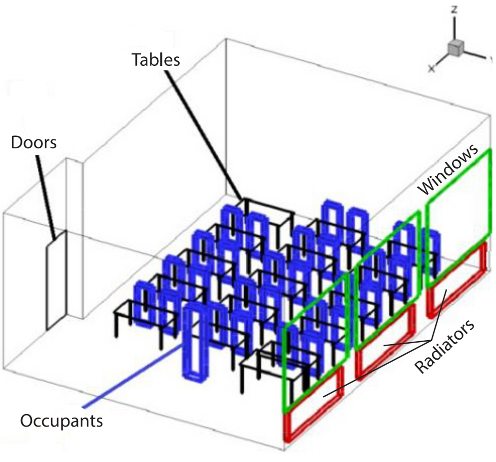

Figure 3. Geometry model with main elements

The CFD model

The main equations for mass, momentum, and energy conservation are solved in Eulerian manner on a co-located finite volume grid consisting of 854002 computational cells, fig. 4. The main transport equations have the following general steady-state RANS form:

$$\frac{\partial\left(\rho u_j f\right)}{\partial x_j}=\frac{\partial G_j}{\partial x_j}+S_\Phi \tag{6}$$

Expressions for diffusion terms, G_j, and source terms, S_Φ, are given in tab. 2.

Table 2. Sub-grid and source terms in steady-state RANS equations

Equation	f	G_j	S_Φ
Continuity	0	0	0
Momentum	u_i	τ_{ij}	$-\frac{\partial p}{\partial x_i}+\frac{\partial \sigma_{ij}}{\partial x_j}$
Energy	H	H_j	$\frac{\partial}{\partial x_j}\left(\frac{\mu}{\mathrm{Pr}}\frac{\partial H}{\partial x_j}\right)+S_r$
Species mass fraction	f	Φ_j	$\frac{\partial}{\partial x_j}\left(\frac{\mu}{\mathrm{Sc}}\frac{\partial f}{\partial x_j}\right)+S_r$

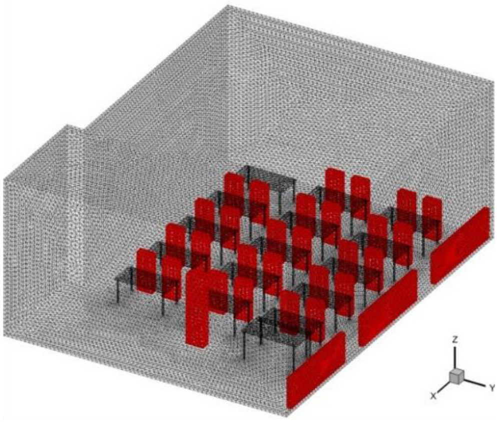

Figure 4. Illustration of the generated computational grid

The computational mesh was locally refined near classroom walls setting six layers inside the near-wall region capture the temperature gradient effects in this part of the computational domain [35]. Although it is expected that velocity magnitude values are small, flow nature is turbulent. Turbulence was modeled using the realizable *k-ε* model, as recommended for inner flows with re-circulation [35]. Air was assumed as an incompressible fluid composed of 21% of O_2 , and 79% of N_2 on a molar basis. Classroom tables were modeled as adiabatic walls. Radiator and occupants were modeled as separate solid domains with wall temperatures 65 °C and 23 °C for radiator and occupants, respectively. Their contribution the overall heat transfer inside the classroom was taken into account setting appropriate energy source values: 29221 W/m^3 and 957 W/m^3, for radiator and occupants, respectively. Heat transfer due to convection and radiation from walls to classroom interior was also taken into account by the proposed model. Discrete ordinates model with equal quadrature divisions in all four directions (4 × 4) was chosen for radiation modelling [36]. The weighted sum of grey gases (WSGG) model with default coefficients was used to calculate gas emissivity [37]. Wall emissivity was set to 0.82 for radiator walls, and 0.18 for all other walls [37]. Heat transfer coefficient values were set separately for each wall surface based on the calculation procedure described in the previous paragraph. The obtained convective heat transfer coefficients were used as boundary values for wall convection in the CFD calculations.

Numerical simulations of the existing classroom temperature conditions were performed for four grids with different computational cell numbers to establish a grid-independent solution. The solution was calculated on coarse, medium, fine, and very fine computational grids consisting of 100588, 407665, 854002, and 1039952 computational cells, respectively. The fine mesh was selected for all simulations since the solution did not change switching to very fine mesh, as can be seen in the fig. 5.

The model validation was done using a relative error examination between the measured values and the numerically calculated values. It is considered that the experimental and

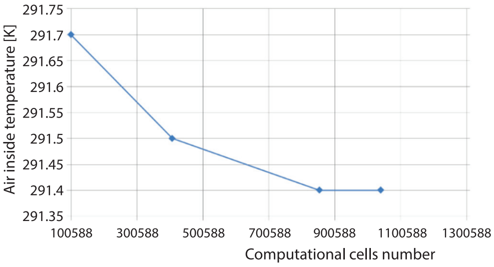

Figure 5. Relationship between indoor air temperature of the computational cells number

numerical results are in satisfying agreement if the relative error is less or equal to 5%, which enables quantitative utilization of the developed CFD model.

The relative error is expressed [38]:

$$\text{Error} = \left| \frac{\Phi_{\text{exp}} - \Phi_{\text{CFD}}}{\Phi_{\text{exp}}} \right| \times 100 \tag{7}$$

where Φ_{exp} is the measured value and Φ_{CFD} is the simulated value.

Results and discussion

Calculated heat transfer coefficient *U*-value for the building envelope, eq. (1), are summarized in the tab. 3. The obtained *U*-values for different building envelope components are higher compare to the recommendations in the Serbian Regulations on Energy Efficiency of Buildings [19].

Table 3. Heat transfer coefficients (*U*-values)

	U [Wm^{-2}K^{-1}]	
Element	Measured	Recommendations by [19]
External wall	1.36	0.4
Indoor wall	1.56	–
Ceiling	0.58	0.4
Ground floor	1.11	0.4
Door	2.3	1.6
Windows	2.73	1.5

The tab. 4 shows the number of air changes per hour for the three measuring points *i.e.* three different classrooms.

Table 4. The number of air changes per hour

Measuring point	n [hour^{-1}]
1	2.10
2	1.68
3	1.36
Average value	1.71

The calculation of energy consumption for heating was done according to [18, 19]. The following results were obtained:

- annual energy required for heating is 715924 kWh,
- annual consumption per square meter is 184.6 kWh/m^2, and
- the energy class of the building is *F* [19].

In order to validate the adopted model, a CFD simulation was performed, where the values of the required quantities, calculated using the presented measurements, were taken as the input values for Scenario 1. Table 5 gives the values of the relative error between numerically calculated temperature values and experimentally measured temperature data obtained for the first scenario.

Table 5. Measured and simulated air temperature in the classroom and relative error

Position index	Measured [°C]	Simulated [°C]	Relative error [%]
1	18.0	18.6	3.33
2	18.1	18.8	3.88
3	17.5	18.2	4.00
4	17.2	17.7	2.90
5	17.2	17.9	4.07

It is considered that the experimental and numerical results are in satisfying agreement because the maximum relative error is 4.07%, which is less than to 5% which enables utilization of the developed CFD model.

Air temperature distributions in characteristic horizontal and vertical planes are shown in figs. 6 and 7. The obtained numerical results showed that the highest heat losses occur through the windows and ground floor surfaces, as can be seen in fig. 7. It can be seen that heat losses, colored by blue color, are accumulated near the bottom of fig. 7, which corresponds to classroom floor. Significant heat losses also occur through external walls, as well as classrooms door, fig. 6, marked with blue color. The highest temperature values (about 21 °C) are located near the radiator surfaces, fig. 6, marked with red color. Temperature values decrease further from the radiator panels. This temperature drop is more extensive near the ground floor surface, where the temperature is about 17 °C, fig. 6(a). Temperature drop decreases with height increase, thus establishing a more uniform temperature field of about 20 °C, fig. 6(b). This temperature distribution is a result of high heat losses to the floor surface, fig. 7.

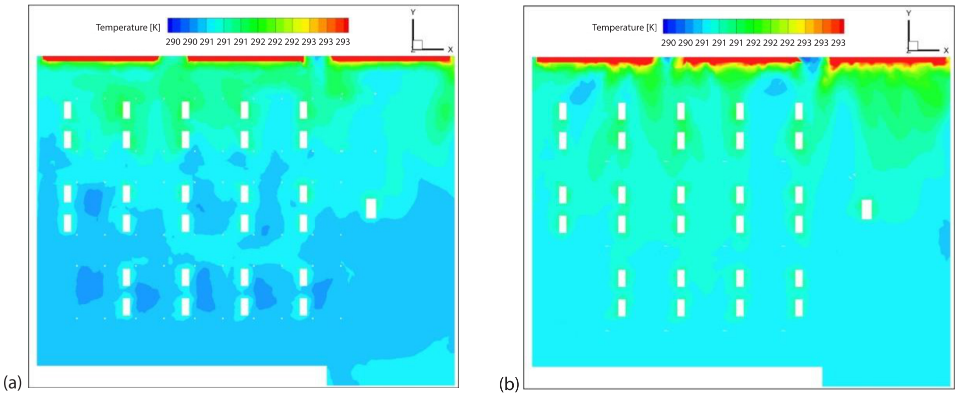

Figure 6. Contours of static air temperature at horizontal plane – Scenario 1; (a) z = 0.5 m and (b) z = 0.8 m (*for color image see journal web site*)

Heated air from the radiator panels is directed towards the classroom ceiling, as can be seen in figs. 7(a)-7(c). Natural-convection forces hot air-flow in direction of the left inner wall, opposite from cool windows' surfaces. High windows' infiltration of outer cold air contributes to the described flow patterns and causes the creation of a re-circulation zone located near the left classroom wall in the near celling region. The presence of the re-circulation zone causes a downward flow by which a significant portion of the hot air is redirected towards the floor surface, as shown in fig. 7(a).

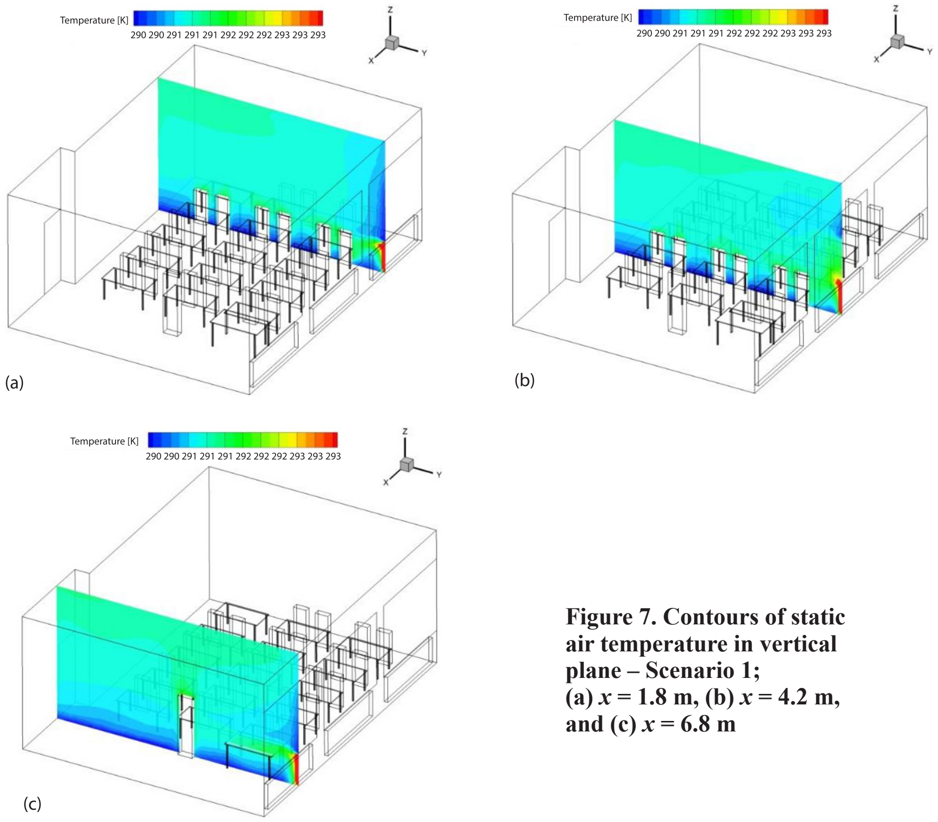

Figure 7. Contours of static air temperature in vertical plane – Scenario 1; (a) x = 1.8 m, (b) x = 4.2 m, and (c) x = 6.8 m

It can be concluded that uniform temperature distribution is achieved in a large portion of the classroom interior, especially at students' seating places. However, the obtained results showed that the temperature comfort and temperature values are not in the appropriate range for the school buildings in the heating period, which is defined by the Regulations on energy efficiency of buildings in Serbia and the indoor comfort conditions.

One of the possible measures for temperature comfort improvement is to achieve suggested (following Serbian standards and regulations) values for heat transfer coefficient and air infiltration. To maintain low energy consumption, while keeping the desired heat transfer coefficient and infiltration levels, it is necessary to implement extensive and higher quality insulation. Although this may require significant costs, it is expected that the suggested procedure will be cost-effective in mid- and long-term periods. The investment in insulation will provide the desired conditions for a healthy children's environment. To confirm the suggested improvements, the second CFD simulation (Scenario 2) was performed. Calculations were done for infiltration and U-values which correspond to the high quality insulation materials, recommended by Serbian standards and regulations, tab. 6: additional insulation of parts of the building envelope (facade, floor and roof), and replacement of existing windows and entrance doors with those that are more efficient.

Table 6. Heat transfer coefficients calculated for Scenario 2 (*U*-values)

Element	U [Wm^{-2}K^{-1}]
External wall 0.4	
Indoor wall	1.56
Ceiling	0.4
Ground floor	0.4
Door	1.6
Windows	1.5

The adopted value of air changes per hour number is 0.5 1 per hour.

The calculation of heating energy consumption for scenario two gave the following results:

- annual energy required for heating is 229909 kWh,
- annual consumption per square meter is 59.3 kWh/m^2, and
- energy class of the building is *C* [19].

The newly obtained numerical results are shown in figs. 8. and 9. Air temperature distribution at horizontal and vertical planes for the second simulated scenario are shown in figs. 8 and 9. Numerical results showed that, same as in the previous scenario, the highest heat loss occurs near the ground floor surface and through the windows, figs. 9(a)-9(c). However, this loss is significantly lower than in the previously investigated scenario. Heat losses through the external walls and the classroom door, fig. 8, are lower compared to the first scenario. The highest temperature values are again located near the radiator surfaces. Infiltration in the second CFD simulation is lowered to the recommended values of 0.5 1 per hour. This contributes to more uniform air temperature distribution inside the classroom. The average temperature is increased for about 2 °C, as can be seen in figs. 8 and 9. Higher average temperature values increases the classroom temperature comfort.

The air temperature difference between horizontal planes is not as intensive as in the previous case, which can be contributed to the smaller heat losses through the floor surface, figs. 8(a)-8(b).

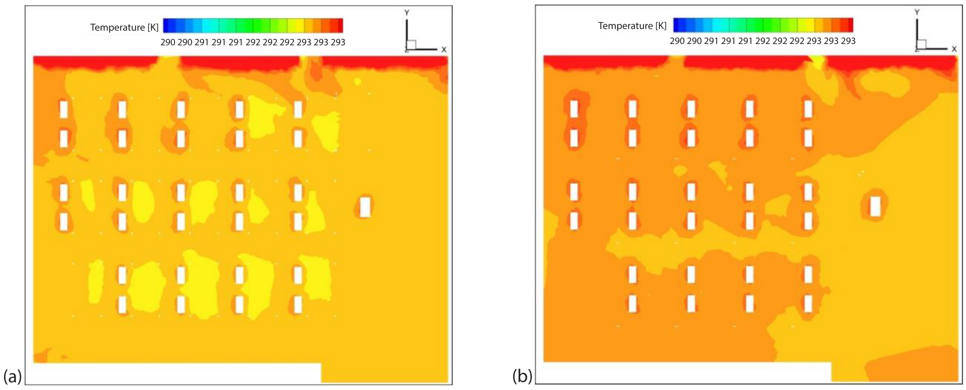

Figure 8. Contours of static air temperature at horizontal plane – Scenario 2; (a) z = 0.5 m and (b) z = 0.8 m

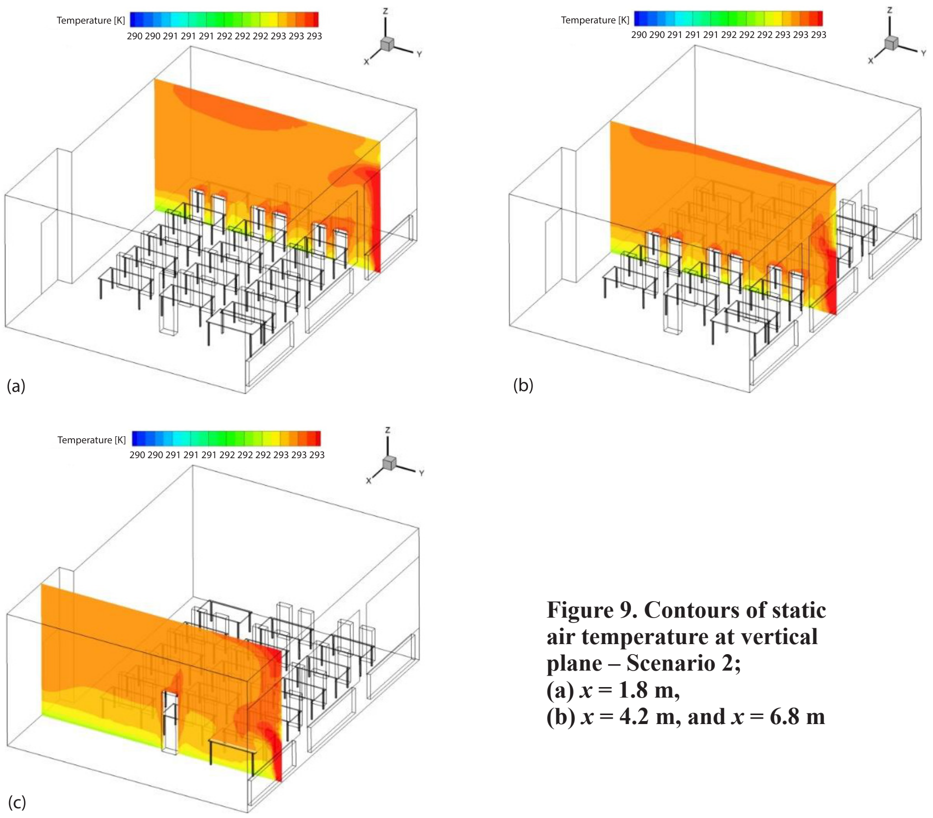

Figure 9. Contours of static air temperature at vertical plane – Scenario 2; (a) $x = 1.8$ m, (b) $x = 4.2$ m, and $x = 6.8$ m

The obtained numerical results in figs. 8 and 9 shows that the desired air temperature (20 °C), is achieved near the classroom space occupied by students, which additionally increases temperature comfort conditions. Most importantly, CFD simulations performed for the recommended *U*-values (Scenario 2) shows that the thermal comfort improvement can be achieved without increased power consumption, implementing a set of recommended measures that would reduce the heat transfer through the building envelope.

Conclusions

Regarding schools, thermal comfort is important indicator because it affects children's health and their learning ability. This study consists of experimental and numerical investigation of naturally ventilated primary school in Serbia situated in the urban area, during the heating season. The classroom measurement campaign was conducted to determine indoor air temperatures and heat flux values of different building envelope elements. To determine school building energy efficiency the infiltration measurement campaign was conducted at three measuring points in the school. The measurement was used to validate the CFD simulation. Two scenarios were performed:

- Scenario 1 for CFD model validation and
- Scenario 2 with improvements of the school building (infiltration and *U*-values which correspond to high quality insulation materials, recommended by Serbian standards and regulations).

Used CFD simulation model shows satisfactory agreement with the measurements: maximum relative error between numerically calculated temperature values and experimental temperature data obtained for the first scenario is 4.07%. Simulated results (according to the Scenario 2) showed that air temperature is on average 2 °C higher than in Scenario 1 and temperature distribution in the classroom is more uniform. This study showed that desired temperature comfort level can be obtained without energy consumption increase, but improvements to the building envelope are necessary.

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