MEASUREMENT AND IMPROVEMENT OF INDOOR AIR QUALITY IN AN INFORMATION TECHNOLOGY CLASSROOM

by

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With the rapid development of information technology equipment and its use in the teaching and learning activities, the working environment (especially indoor air quality) in which students and pupils spend a great deal of time in educational institutions has been changing. Therefore, special attention must be paid to indoor air quality and comfort. It is of great importance to maintain indoor air quality in an object, such as information technology classrooms, where a large number of students spend long periods of time. Poor indoor environment can negatively affect scholarly performances and cause discomfort and poor work performance. The problem of indoor air quality in educational institutions can be more serious than in other types of objects, because of the higher concentration of students and information technology equipment. This paper analyzes the changes in air quality in an information technology classrooms, when occupied with students, for the period from March to April. The changes of indoor air temperature, relative humidity, and carbon dioxide concentration are monitored in the classroom, as well as outdoor temperature and relative humidity. Several cases are studied: the classroom with closed windows and doors (closed classroom), the classroom with natural ventilation, the classroom cooled with a split system (cooled classroom). Responses of students are followed for each case. The analysis is performed based on the measurement results and numerical simulations using the computational fluid dynamics package, and measures are proposed to improve the indoor air quality in the considered classroom.

Keywords: *indoor air quality, information technology classroom, CFD*

Introduction

Indoor air quality (IAQ) in occupational and residential settings has generated considerable concern over the last decades [1]. In the developed world, with the rapid development of information technology (IT) equipment and its use in the teaching and learning activities, the working environment (especially indoor air quality) in which students and pupils spend a great deal of time in educational institutions has been changing, IAQ has been identified as a determinant cause of allergies and other hypersensitivity reactions, airways infections, *etc*. Recent studies have suggested that poor IAQ may directly reduce the personal ability to perform specific mental activities requiring concentration, calculation, or memory [2]. Some authors have investigated different ways of improving IAQ without increasing ventilation and suggested new emerging technologies [3].

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IAQ problems in schools may be even more serious than in other categories of buildings, due to a higher occupant density and insufficient outside air supply, aggravated by frequent poor construction and/or maintenance of school buildings [1]. The research was conducted in order to detect ventilation rates in schools and to establish the minimum acceptable level of fresh air required for the health of the occupants [4]. Since it was observed that there is an association between ventilation rates in classrooms and student performance, certain papers examined the association between student performance on standardized aptitude tests to classroom CO_2 concentrations [2, 5].

Temperature and humidity have a strong and significant impact on the perception of indoor air quality, at a constant pollution level, the perceived air quality decreases with increased air temperature and humidity [6]. The research which was conducted in order to examine specific indoor environmental quality parameters in college computer classrooms, suggested that schools should assess the functioning of air-conditioning equipment in classrooms (particularly in computer classrooms), and should determine whether ventilation rates are sufficient [7].

The available measurements of ventilation rates and CO_2 concentrations in schools suggest that, based on the current ASHRAE ventilation standard, many classrooms are not adequately ventilated. Results from the few studies in schools have been inconsistent in associating ventilation rates or CO_2 concentrations and symptoms [8]. The use of a CO_2 demand-controlled ventilation system in computer classrooms may slightly reduce headache and tiredness and improve perceived air quality, even if the mean levels of CO_2 are below current ventilation standards. This indicates that the proportion of time with CO_2 levels above 1000 ppm can be important in certain indoor environments [9]. The measurement of indoor air quality in classrooms with special emphasis on particulate matter (PM_{10}) and CO_2 and the impact of cleaning and ventilation is presented in [10].

This paper analyzes the changes in air quality in an IT classroom in a College in Nis, when the classroom is occupied with students. The changes of indoor air temperature, relative humidity, and CO_2 concentration are monitored in the classroom, as well as outdoor temperature and relative humidity. Several cases are studied: the closed classroom, the classroom with natural ventilation, the cooled classroom. Responses of students are followed for each case. The analysis is performed based on the measurement results and numerical simulations using the computational fluid dynamics (CFD) package.

Methodology

Measuring the indoor air temperature, relative humidity and CO_2 concentration was carried out in the IT classroom in from March to April 2013. The classroom is located in an urban area with major traffic roads surrounding the college building. The classroom volume is 103 m^3 with double-glazed windows for excluding noise and equipped with one split type air-conditioner. There are 24 standard PC configurations and the same number of working places. During the IAQ investigation the classroom was occupied with 7-23 students.

The adopted methodology was similar to the research conducted by Lee *et al.* [6] and Kavgic *et al.* [11]. Lee *et al.* investigated the relationship between indoor environmental quality (IEQ) and learning performance in air-conditioned university teaching rooms via subjective assessment and objective measurement. Kavgic *et al.* evaluated IAQ in typical medium-sized mechanically ventilated theatre in Belgrade, based on the results of monitoring (temperature, relative humidity, CO_2, air speed and heat flux), modeling (CFD), and the assessment of comfort and health as perceived by occupants.

Data collection

In this research, both objective physical measurements and subjective assessments were performed. The following physical parameters affecting human thermal comfort were measured: air temperature, relative humidity and air velocity, average radiant temperature of surrounding walls. Sampling equipment was placed at a sitting person's (1.5 m above floor) head level, around the middle of the wall at the indoor location.

Having measured the environmental parameters, the two personal parameters – metabolic rate and cloth insulation – were estimated in accordance with ASHRAE standard 55-1992 [12]. The standard provides a checklist of typical activities and their corresponding metabolic rates. For this study, the metabolic rate was taken to be 1.2 met (1 met = 58.15 W/m^2), which represents the value for sedentary activities. Individual clothing articles in the survey responses were converted into their respective thermal clothing insulation in units of clo (1 clo = 0.155 km^2/W) according to ASHRAE standard 55-1992. The overall clothing insulation for each subject's entire clothing ensemble was assumed to be 1 clo, corresponding to a normally dressed person [13, 14].

Table 1. TESTO 454 probe technical data

Probe ranges and accuracy	
Measuring range	0 ÷ 5000 ppm CO_2
Accuracy	±2% at 0 ...5000 ppm ±3% at 5001 ...10000 ppm
Temperature range	–10-50 °C
Accuracy	±0.4 °C
Relative humidity range	5-95%
Accuracy	±2%
Air velocity range	0.4-40 m/s
Accuracy	±0.2 m/s

An assessment of thermal comfort in the classrooms was based on the students' responses to a questionnaire, which was administered simultaneously with the physical measurements in class. The number of respondents was 20-23, age group 18-20. Thermal sensation was defined using the ASHRAE Thermal Sensation Scale, a continuous seven-point scale (–3 cold, –2 cool, –1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot).

Each student was required to answer the questionnaire. The questionnaire consisted of two parts:

– thermal sensation before the start of the class, and
– thermal sensation at the end of the class.

The questions were:

– How would you rate the temperature in the classroom? Students were offered the following responses: cold, cool, slightly cool, neutral, slightly warm, warm and hot.
– How would you rate the humidity in the classroom? Students were offered the following responses: very wet, wet, neutral, dry and very dry.
– Is the classroom stuffy? Students were offered the following responses: yes, no.
– Have you experienced any of the symptoms in the classroom at the end of class? Students were offered the following responses: headache, difficulty breathing, excessive sweating, nausea.

The results of the survey were compared with the calculated values based on the measuring results and values obtained by numerical simulation and presented in tab. 4.

Measuring equipment

The emission of CO_2 measurement was performed using the TESTO 454 gas analyzer with ambient CO_2 probe 0632 1240. Relative humidity and air temperature were measured with adequate probe 0632 1240. Air velocity was measured with the adequate probe 0635 9540. The characteristics of the sensor used are shown in tab. 1.

Mathematical model

The estimation of the chemical species dispersion is relatively difficult for modeling. The mathematical model is based on:

– continuity equation

$$\frac{\partial(\rho)}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

– momentum (Navier-Stokes) equation

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j}(\tau_{ij}) - \frac{\partial p}{\partial x_i} + f_i \tag{2}$$

– energy equation

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}(j_{i,h}) + S_h \tag{3}$$

– passive scalar (CO_2) transport equation

$$\frac{\partial(\rho c)}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i c) = \frac{\partial}{\partial x_i}(j_{i,c}) + S_c \tag{4}$$

where ρ is the density, u_i are the three main velocity components, p is the pressure, f_i are the body forces and any additional momentum sources, h is the enthalpy, c – the scalar contaminant and S_h and S_c represent the generation/destruction rate of energy and species, respectively, $\tau_{i,j}$ – the momentum shear stress tensor, $j_{i,h}$ – the diffusion flux of energy transport and $j_{i,c}$ is the diffusion flux of species transport. In the energy equation, the diffusion flux of energy transport term ($j_{i,h}$) includes the energy transfer due to conduction, species diffusion and viscous dissipation. Similarly, in the CO_2 transport equation the diffusion flux ($j_{i,c}$) arises due to the concentration of gradients. Finally, they are calculated as:

$$j_{i,h} = \Gamma_T \frac{\partial T}{\partial x_i} - \sum_j h_j j_{j,c} + \Phi \tag{5}$$

$$j_{i,c} = \Gamma_c \frac{\partial c}{\partial x_i} - \Gamma_{i,h} \frac{\partial T}{\partial x_i} \tag{6}$$

where the factors Γ_T and Γ_c are the diffusion coefficients for the enthalpy (Fourier's law) and species (Fick's law) transport, respectively. The second term of the right hand side in eqs. (5) and (6) represents the energy transport by diffusion of species and the Soret-effect species diffusion transport, respectively. The term Φ is the viscous dissipation defined as:

$$\Phi = 0.5\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2 - \frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\frac{\partial u_l}{\partial x_l} \tag{6}$$

As the former equations represented the system averaged equations, it was needed to implement a turbulent model in order to close the system and to convert the given set of differential equations into algebraic ones, which were solved using the PHOENICS software package, FLAIR module. FLAIR is a special-purpose version of PHOENICS, designed to provide an air-flow and thermal-simulation facility for the Heating, Ventilating and Air-Conditioning community. It predicts air-flow patterns and temperature distributions in buildings and other enclosed spaces. FLAIR can be used during the design process to detect and avoid uncomfortable air velocities or temperatures. For the simulation the standard k-ε turbulent model was adopted. The details are given in the tab. 2.

Table 2. Standard k-ε turbulent model transport equations and constants

Transport equation	Φ	Γ_Φ	S_Φ
Turbulent kinetic energy	k	ν_t/σ_k	$\rho\,(G - \varepsilon)$
Turbulent kinetic energy dissipation	ε	ν_t/σ_ε	$\rho\,(\varepsilon/k)(C_{\varepsilon1}G - C_{\varepsilon2}\varepsilon)$
$G = \nu_t\,(\partial_k U_i + \partial_i U_k)\,\partial_k U_i$		$\nu_t = C_\mu k^2/\varepsilon$	
$(\sigma_k, \sigma_\varepsilon, C_{\varepsilon1}, C_{\varepsilon2}, C_\mu) = (1.0, 1.314, 1.44, 1.92, 0.09)$			

Constant temperature boundary conditions

The temperature of walls, floor and sealing was measured with an infrared camera, which showed that the surface temperature of walls was 24 °C for the inner walls, floor and sealing and 22 °C for the outer wall, and those were approximately constant. The walls were simulated with constant temperature *plate* elements [15].

Heat and humidity sources

In the simulation, people were simulated with *people* elements, as presented in the fig. 1 [15]. Each individual was set as a source of heat and humidity. CO_2 emission was presented with the people element simulating an exhalation cloud around every simulated individual. In adition to the people in the room, computers and radiators were identified as heat sources. For each computer a constant heat flux was set, and a constant temperature for a heater in the case when heating was active.

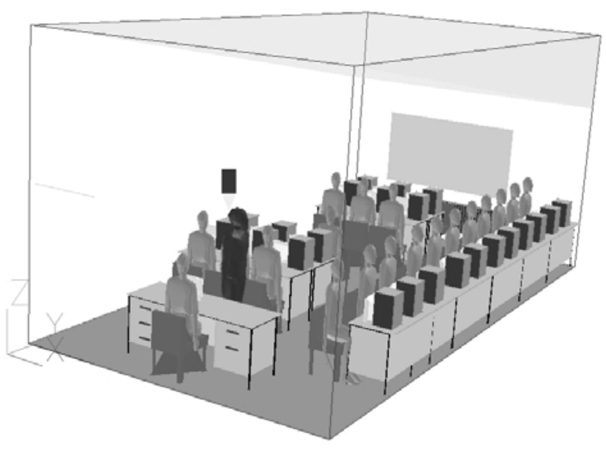

Figure 1. Numerical model of the classroom [15]

Inlet and outlet to domain

There are two inlets into domain: leakage around the door and the window (fig. 1). The measurments and calculations showed up to 0.6 h^{-1} changes of air occur through the gap between the door and the floor. By measuring, it was noticed that the upper third of the open window acted as an outlet, while the lower two thirds acted as inlets.

Results and discussion

Using the described measuring equipment and the presented matematical model, the results were obtained and the comparison was performed. Table 3 shows the values of temperature, relative humidity, absolute humidity and CO_2 concentration obtained by measuring and numerical simulation. The differences between the measured value and the value obtained by numerical simulation are presented by ε in tab. 3.

Table 3. Values IAQ parameters obtained by measuring and numerical simulation

	CO_2 [ppm]	t [°C]	φ [%]	ω [g/kg]
Closed classroom				
Numerical simulation	4,149	28.30	64.90	15.56
Measurement	3,897	28.70	57.50	13.10
ε [%]	6.47	1.39	–	19.10
Classroom with an opened window				
Numerical simulation	1,453	21.38	43.84	6.89
Measurement	925	23.60	39.70	6.90
ε [%]	57	9.41	–	0.15
Cooled classroom				
Numerical simulation	5,611	25.99	41.1	8.52
Measurement	5,197	27.50	46.00	8.96
ε [%]	7.97	5.81	–	5.16

There is no fundamental difference between the closed classroom and cooled classroom case studies in CO_2 concentration, because in both cases the door and windows were closed. The difference of CO_2 concentration of 1,210 ppm, in these case studies, could be explained by different seating, movements of students, air flow (especially in case of the cooled classroom), *etc*. The high difference between the measured value and the value obtained by numerical simulation in CO_2 concentration, in the case of the classroom with an opened window, could be explained by wind influence. The difference between the measured value and the value obtained by numerical simulation in temperature and humidity content (ω) is less than 10% and 20%, respectively.

Thermal comfort indicators: Predicted Mean Vote (PMV) which predicts the mean response of a larger group of people and Predicted Percentage Dissatisfied (PPD) which is a quantitative measure of the thermal comfort of a group of people at a particular thermal environment were considered. These values were calculated, read from numerical simulation and obtained from the survey. Calculated values were obtained on the basis of the measured data (air temperature, relative humidity and air velocity) and the assumed data (clothing insulation and metabolic rate). The results are compared and presented in tab. 4.

Table 4. Thermal comfort indicators: predicted mean vote (PMV) and predicted percent of dissatisfied (PPD)

Case study	Closed classroom		Classroom with an opened window		Cooled classroom	
	PMV	PPD	PMV	PPD	PMV	PPD
Calculated	1.16	33.7	0.33	7.3	0.78	18
Simulated	0.95	24.96	0.13	7.21	0.46	10.2
Survey	1.65	100	0.1	10	0.82	45.2

Although CO_2 is not a pollutant, concentrations higher than 1500 ppm strongly indicate poor ventilation (fig. 2, tab. 3). This could be easily seen in the case of the closed classroom, when only 60 m^3/h of fresh air was supplied. The low rate of fresh air also results in high temperature of 28.7 °C in the classroom (fig. 3, tab. 3), and humidity (figs. 4 and 5) causing a high dissatisfaction rate (tab. 4).

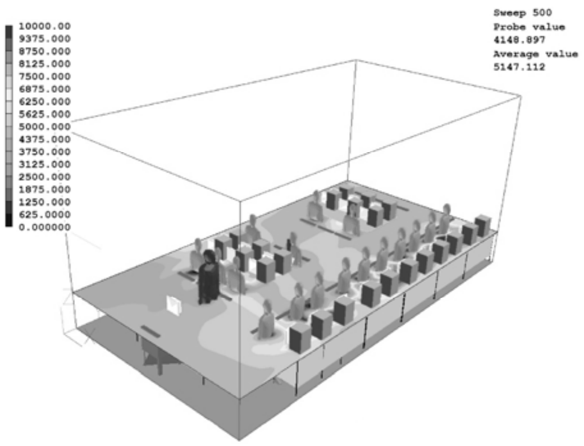

Figure 2. The visualization of CO_2 field in the case of the closed classroom [15]

In the case of the classroom with an opened window the situation was better in terms of the classroom temperature, which decreased from 28.7 °C to 23.6 °C (tab. 3), as well as the significantly lower CO_2 concentration of 925 ppm, compared to the closed unventilated classroom. As a result, survey respondents marked PMV with the almost neutral value of 0.1, which corresponds to PPD of about 6%. According to the survey results, students response was 10% of dissatisied.

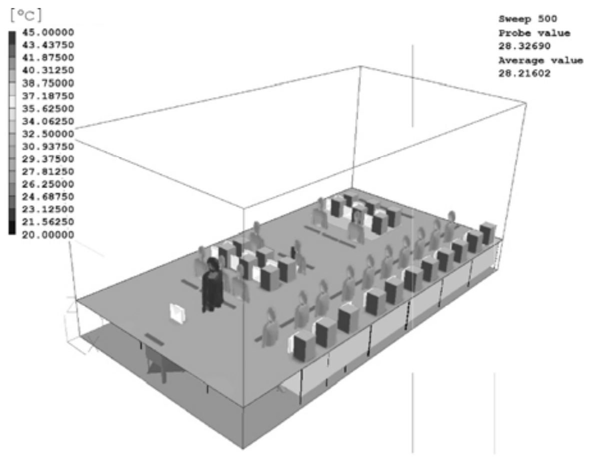

Figure 3. The visualization of temperature [°C] field in the case of the closed classroom [15]

In the case of the cooled classroom, the air conditioner was set to 16 °C with the approximate flow rate of 350 m^3/h. The measured values did not vary significantly from the ones measured in the closed unventilated classroom. The temperature was a bit lower (tab. 3), but the concentration of CO_2 was higher. The dissatisfaction rate of survey respondents was high with 45.2%.

The case of the classroom with an opened window proved to be the most effective as far as thermal comfort is concerned.

The result of numerical simulation for the worst case scenario – winter time, when windows cannot be opened, pointed out that the average temperature in this case would be 28.08 °C, relative humidity 62.93%, PMV value of 0.93, and PPD level 24.9%. The clothing insulation is assumed to be 1.1clo.

Limitations about the lack of options for distributing the centralized HVAC system led to a solution in which the fresh air would be introduced with two axial fans with the capacity of 250 m^3/h each. The specific amount of fresh air would be 20 m^3/h per person. In order to provide better flow rate, a small opening would be set on the opposite wall, behind the teacher's desk, just above the floor. The fresh air temperature was assumed to be 0 °C with relative humidity of 90%, corresponding to the average conditions in the period from February to April when the minimal average temperature is from 1.4 °C to 6.4 °C, and when the computer classroom lecture is carried out [16]. For the proposed solution, according to the numerical simulation, the average temperature would be 18.1 °C leading to a neutral PMV value of –0.11, and with a low level of PPD – 5.3%.

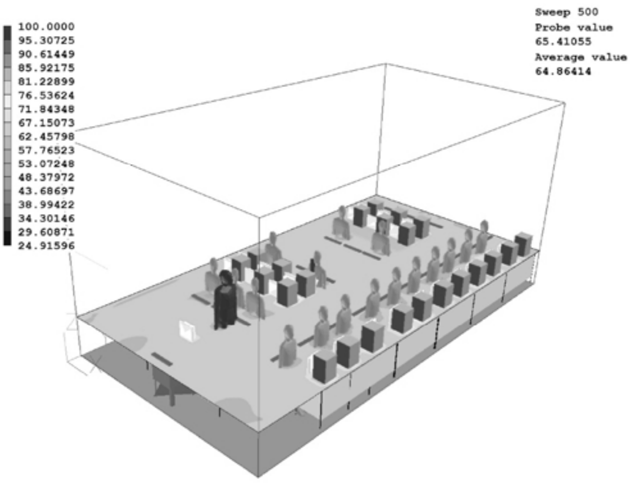

Figure 4. The visualization of relative humidity field in the case of the closed classroom [15]

Evaluating the uncertainty of numerical simulation results

The mean cell size of the numerical grid was 5 cm. Probes for CO_2, temperature and humidity with temperature were aligned at an overall distance of approximately 30 cm. According to this probe position, the error was around 5 cm. The errors of simulation in comparison to the measured values are presented in tab. 3. The error of CO_2 concentration needs to be discussed in more detail. The imposibillity of accurate simulation of the exhalation proces could lead to a significant error of up to 50 or more percent. On the other hand, measurements of average CO_2 concentration in the closed unventilated classroom yielded the value of 4,812 ppm, in comparison with 3,878 ppm, a value of CO_2 gained from the numerical simulation. This would lead to an error of 24% for the average concentration.

Conclusions

This paper analyzed the changes in air quality in IT classrooms. The changes of indoor air temperature, relative humidity, CO_2 concentration were monitored in the classroom for the period from March to April, and a survey was conducted among students. The measured values are complemented by numerical simulation which resulted in the visualization of scalar fields. An assessment of thermal comfort in the classrooms was based on the students' responses to a questionnaire, which was administered simultaneously with the physical measurements in class. Three case studies were investigated in the paper: the closed classroom, the classroom with an opened window and the cooled classroom. Measurements and simulation of indoor CO_2 concentrations have shown that in the case of the closed classroom and in the case of the cooled classroom, the indoor CO_2 level reached 5,200 ppm, indicating inadequate ventilation. Main thermal comfort indicators (obtained by measurements, numerical simulations and the survey) showed an unfavorable working environment in both cases, resulting with high PPD and relatively high PMV. In the case of the classroom with an opened window, thermal comfort indicators were far more favorable with a close to neutral value of PMV.

Finally, the error analysis evaluation of the uncertainty of numerical simulation results was conducted. The acceptable error level of computer models developed the possibility of detailed analyses and predictions on thermal comfort in buildings, which would be of real use for the design and research activity. Also, the survey results correspond to the values obtained on the basis of the measurements and values calculated in the numerical simulation. Those results showed an unfavorable working environment in cases of the closed classroom and cooled classroom, resulting with high PPD and relatively high PMV and in the case of the classroom with an opened window, showed low dissatisfaction rate and close to neutral value of PMV.

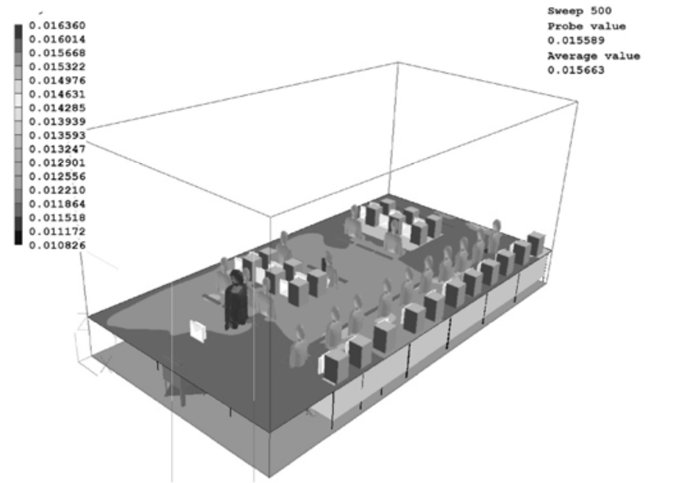

Figure 5. The visualization of humidity mass fraction field in the case of the closed classroom [15]

On the basis of these three cases, the authors suggested the solution where fresh air would be introduced directly into the classroom from two openings on the outer wall. The results of numerical simulation showed that in this case PMV and PPD values would be acceptable.

Nomenclature

- c – scalar contaminant, [ppm]
- f – body forces, [Nm^{-3}]
- h – enthalpy, [Jkg^{-1}]
- j – flux,
- p – pressure, [Pa]
- S – source term,
- T – temperature, [K]
- t – time, [s]
- u – velocity, [ms^{-1}]
- x – spatial coordinate, [m]

Greek symbols

- Γ – diffusion coefficient
- μ – dynamic viscosity, [Pa·s]
- ν – kinematic viscosity, [m^2s^{-2}]
- ρ – density, [kgm^{-3}]
- τ – shear stress, [Pa]

Subscripts

- c – contaminant
- h – enthalpy
- i, j, k, l – co-ordinates

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