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NUMERICAL MODELING OF ENERGY EFICIENCY PARAMETERS IN THE WORKING ENVIRONMENT BY T-RANS APPROACH

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ABSTRACT
The latest trends in building design lead to connections between the indoor climate and energy efficiency. Increasing energy efficiency is one of the most important mechanisms for reduction of emission of greenhouse gases, contributing to the global climate change.
The impact of indoor climate on people's wellbeing, health and performance levels requires working place design to take into account different solutions for distribution of heat sources and sinks, as well as potential sources of indoor contaminants and devices for ventilation. First, it is of most importance to determine factors make up the concept indoor climate and how they can be translated into measurable design requirements. The Time-dependent Reynolds-averaged Navier-Stockes (T-RANS) approach presented in this paper can serve as an effective tool for modeling indoor energy transport in its full turbulent form. The major transport mechanism in this type of flows is buoyancy, driven by the difference in temperature and concentration. For this reason the applied modeled equations fully satisfy the physics of the problem, since the thermal and concentration gradients remain included within the equations. The approach has been validated in a number of test cases and applied in a couple of numerical cases, simulating both indoor and outdoor real-time air movement, driven by the dominant buoyancy mechanism, and providing very good numerical results. For different combination of work place dimensions, location of heat sources, levels of room insulation and other related parameters, it is possible to obtain an optimum solution in terms of achieving satisfactory level of energy efficiency.
Keywords: T-RANS, turbulence modeling, energy efficiency, indoor climate

1. INTRODUCTION
Turbulent Transport Phenomena is the common name for processes involving transfer of mass, heat and momentum. Most fluid flows encountered in engineering practice are turbulent and therefore require different treatment. There are a number of mathematical methods that lead to the solutions of turbulent flows. All of the methods require the solution of some form of the conservation differential equations of mass, momentum, energy or chemical species. Engineering approach to the solution of fluid flow properties is based on techniques of approximating differential equations by a system of algebraic equations, which can then be solved numerically. The approximations are applied to small domains in space and time. The numerical solution of partial differential equations (PDE) can be obtained by using different discretization methods. Nowadays, there are three commonly used methods for approximation of PDEs. All the methods have been applied to the solution of wide range of cases in continuum mechanics, which deal with continuous matter including both solids and fluids. Turbulence is the most dominant transport mechanism causing indoor air movement. Regarding the physical characteristics of the air and specific imposed boundary conditions at the room walls, the

movement of air is determined with a high level of turbulence. In order to mathematically resolve flow turbulence a mathematical method applicable for such indoor climate flows, called Reynolds-averaged Navier-Stockes (RANS), has been applied. The RANS approach to turbulence resolves mean values of the turbulent flow properties, but the rest of turbulence must be modelled separately. In this work, we have applied RANS method on typical indoor air flow and introduced a turbulence model for thermal properties, in order to achieve the solution with as less computational power as possible. Previously, the model was successfully tested on a number of test cases, which proves that the solution can be obtained with the applied level of approximation. The main task of this work was to introduce a T-RANS approach suitable for complex environmental flows. 3D model of an indoor space (a typical office premise) was developed and the numerical approach applied to resolve turbulent properties describing air movement and the dispersion of cigarette smoke. The Time-dependent RANS (T-RANS) approach has been proposed by Kenjeres and Hanjalic [1], as a convenient method to compute flows with dominant coherent vertical structures at very high Reynolds and Rayleigh numbers. The latest trends in building design lead to connections between the indoor climate and energy efficiency. Increasing energy efficiency is one of the most important mechanisms for reduction of emission of greenhouse gases, contributing to the global climate change. The impact of indoor climate on people's wellbeing, health and performance levels requires room design to take into account different solutions for distribution of heat sources and sinks, as well as potential sources of indoor contaminants and devices for ventilation. This work demonstrates application of numerical flow modelling to solve problem of indoor energy efficiency.

2. GOVERNING EQUATIONS

In this work, RANS approach was applied. In such approach to turbulence, all of the unsteadiness, as regarded as a part of turbulence, is averaged out. RANS equations contain all conservation laws in their specific form. First of them is the law of conservation of mass, which RANS form for fluid flows is presented with following transport mass equation: $\frac{\partial \langle U_j \rangle}{\partial x_j} = 0$ (1)

The conservation of momentum is a major fundamental concept of physics. The law of the momentum balance states that, within some problem domain, the amount of momentum remains constant; momentum is neither created nor destroyed, but only changed through the action of forces as described by Newton's laws of motion. For the turbulent fluid flow that is approached by RANS method, the law of conservation of momentum can be expressed in the form of momentum transport equation.

$$\frac{\partial \langle U_j \rangle}{\partial t} + \frac{\partial \left(\langle U_i \rangle \langle U_j \rangle \right)}{\partial x_i} = -\frac{1}{\rho} \frac{\partial \left(\langle P \rangle - P_{ref} \right)}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial \langle U_i \rangle}{\partial x_j} \right) - \tau_{ij} \right] + g_i \beta \left(\langle T \rangle - T_{ref} \right) \quad (2)$$

Here, the averaged part of instantaneous variables of velocity components, temperature and pressure is denoted with $\langle \ \rangle$, but the rest of the turbulence is hidden in τ_{ij}, which represents turbulent stress. The third conservation law of interest is energy conservation law, in its RANS form given with energy transport equation (3).

$$\frac{\partial \langle T \rangle}{\partial t} + \frac{\partial \left(\langle U_j \rangle \langle T \rangle \right)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\alpha \frac{\partial \langle T \rangle}{\partial x_j} - \tau_{\theta_i} \right) \quad (3) \qquad \frac{\partial \langle C \rangle}{\partial t} + \frac{\partial \left(\langle U_j \rangle \langle C \rangle \right)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{\nu}{Sc} \frac{\partial \langle C \rangle}{\partial x_j} - \tau_{Ci} \right) \quad (4)$$

where the turbulent part is expressed with $\tau_{\theta i}$, which is called turbulent heat flux. Since this mathematical model aims to determine movement and concentrations of pollution within the domain, it has to consider another conservation law. Here, pollutant concentration is considered as a scalar property. According to this assumption, the mathematical model included transportation equation of scalar property with scalar concentration as a variable, given by eq. (4), where, the turbulence part is represented with turbulent concentration flux τ_{Ci}. So far, the mathematical model included all transport equations necessary for obtaining the solution without considering turbulence. In comparison with ordinary Navier-Stockes equations, RANS method introduces new unknown turbulent variables τ_{ij}, $\tau_{\theta i}$ and τ_{Ci}, which cause the system impossible to be solved. In order to reach the closure of the system, a number of additional equations have to be included. For this reason, turbulent heat flux is modelled by reducing to the algebraic form and expressed with

$$\tau_{\theta_i} = -\frac{1}{C_{1\theta}} \frac{\langle k \rangle}{\langle \varepsilon \rangle} \left[\tau_{ij} \frac{\partial \langle T \rangle}{\partial x_j} + \left(1 - C_{2\theta}\right) \tau_{\theta_j} \frac{\partial \langle U_i \rangle}{\partial x_j} + \left(1 - C_{3\theta}\right) \beta g_i \left\langle \overline{\theta^2} \right\rangle \right] \quad (5)$$

Similar to this, turbulent concentration flux is given with equation (6), and turbulent stress with (7).

$$\tau_{c_i} = -\frac{1}{C_{1c}} \frac{\langle k \rangle}{\langle \varepsilon \rangle} \left[\tau_{ij} \frac{\partial \langle C \rangle}{\partial x_j} + \left(1 - C_{2c}\right) \tau_{c_j} \frac{\partial \langle U_i \rangle}{\partial x_j} \right] \quad (6) \qquad \tau_{ij} = -\nu_t \left(\frac{\partial \langle U_i \rangle}{\partial x_j} + \frac{\partial \langle U_j \rangle}{\partial x_i} \right) + \frac{2}{3} \langle k \rangle \delta_{ij} \quad (7)$$

For the turbulent stress tensor the simple isotropic eddy diffusivity formulation (SGDH) was used. For the closure problem three additional transport equations are needed. For this reason, equations for turbulent kinetic energy <*k*>*,* its dissipation rate <*ε*>, and temperature variance $\left\langle \overline{\theta^2} \right\rangle$

$$\rho \frac{\partial \langle k \rangle}{\partial t} = \frac{\partial}{\partial x_j} \left(\frac{\mu_{ef}}{\sigma_k} \frac{\partial \langle k \rangle}{\partial x_j} \right) + \rho g \beta_T \tau_{\theta_i} - \rho \langle \varepsilon \rangle \quad (8)$$

$$\rho \frac{\partial \langle \varepsilon \rangle}{\partial t} = \frac{\partial}{\partial x_j} \left(\frac{\mu_{ef}}{\sigma_\varepsilon} \frac{\partial \langle \varepsilon \rangle}{\partial x_j} \right) + \rho g \frac{\langle \varepsilon \rangle}{\langle k \rangle} C_{\varepsilon_3} \beta_T \tau_{\theta_i} - C_{\varepsilon_2} f_\varepsilon \rho \frac{\langle \varepsilon \rangle \tilde{\varepsilon}}{\langle k \rangle} \quad (9)$$

$$\rho \frac{\partial \left\langle \overline{\theta^2} \right\rangle}{\partial t} = \frac{\partial}{\partial x_j} \left(\frac{\mu_{ef}}{\sigma_{\overline{\theta^2}}} \frac{\partial \left\langle \overline{\theta^2} \right\rangle}{\partial x_j} \right) - 2\rho \tau_{\theta_i} \frac{\partial \langle T \rangle}{\partial x_j} - \frac{1}{C_{T'}} \rho \frac{\langle \varepsilon \rangle}{\langle k \rangle} \left\langle \overline{\theta^2} \right\rangle \quad (10)$$

have been included into the mathematical model. This system of ten partial three-dimensional differential equations makes the closure problem solved. Here, the information on pressure distribution is still needed and it is obtained numerically. Contrary to other transport quantities (velocity, temperature, concentration, etc.) pressure does not have its own equation and must be derived from continuity (1) and momentum (2) equation, like in [3]. To obtain the necessary information about pressure, the SIMPLE (Semi-Implicit-Method-for-Pressure-Linked-Equations) algorithm was applied. Once the mathematical model is defined, one can approach to the numerical solution.

3. PROBLEM DEFINITION AND RESULTS

In order to apply proposed numerical approach to interior design streaming to increasing energy efficiency by properly designing of air circulation devices, we assumed a calculation domain suited in a furnished room with realistic heating bodies (radiators), windows, doors, and walls. In addition to this, having in mind that the mathematical model contains an equation for approximating concentration transport, we implied sources of cigarette smoke within the room, aiming to numerical results of smoke dispersion. A numerical grid in size of 122x122x60 cells was applied to the domain (Figure 2). The grid also includes 300 passive cells acting as obstacles to air circulation by simulating room furnisher and human bodies. In order to follow a realistic situation, three room windows were set to be thermally active with implied constant temperature of 15 ^{o}C. Heat sources, the 3 radiators, were set also to thermally active with temperature of 45 ^{o}C. The rest of the numerical domain boundary surfaces, which are room ceiling, floor and other walls are assumed to be ideally insulated and numerically treated as adiabatic walls. The temperature filed within the whole domain was set to an initial value of 20 ^{o}C. The temperature difference between side walls and inner space is quite enough to cause the main transport mechanism, buoyancy. Boundary conditions are applied in a way to simulate a realistic situation that often occurs in residential and office premises. With such disposition of room elements that can cause a way the air circulates, the model will bring information on the air path that dynamically changes and values of the all parameters which are important to describe the nature of this specific flow. In addition to the implied mechanical and thermal air properties, the model simulates cigarette smoke spreading within the room. For this reason, two smoke sources were assumed and a relative concentration value of 1 is given. Taken by the main flow smoke particles are being spread out through the domain where in all points it is possible to determine ratio between the levels of concentration in comparison with the source. The main objective of this work is application of proposed numerical approach to the solution of main flow parameters in interior design. A number of different combinations of elements disposition can help in choice of the best option in terms of installing air circulating equipment and reaching energy efficiency improvements.

According to the T-RANS approach which serves as an identification method for large coherent structures (used for pollutant dispersion in atmosphere modeling [2]), air circulation within the room can be well recognized within simulation results. The time evolution of temperature field given in Figure 1, shows how T-RANS identifies large eddy structures very well. Due to unsteadiness caused by turbulence the situation is constantly changing. The air path can be effectively visualized by putting massless particles in the air stream. The levels of cigarette smoke concentrations can be visualized by scalar iso-surface (Figure 3). Here we have shown that model applied to the environmental flows [2], with small adaptation can be used for an indoor space modelling (a typical office premise).

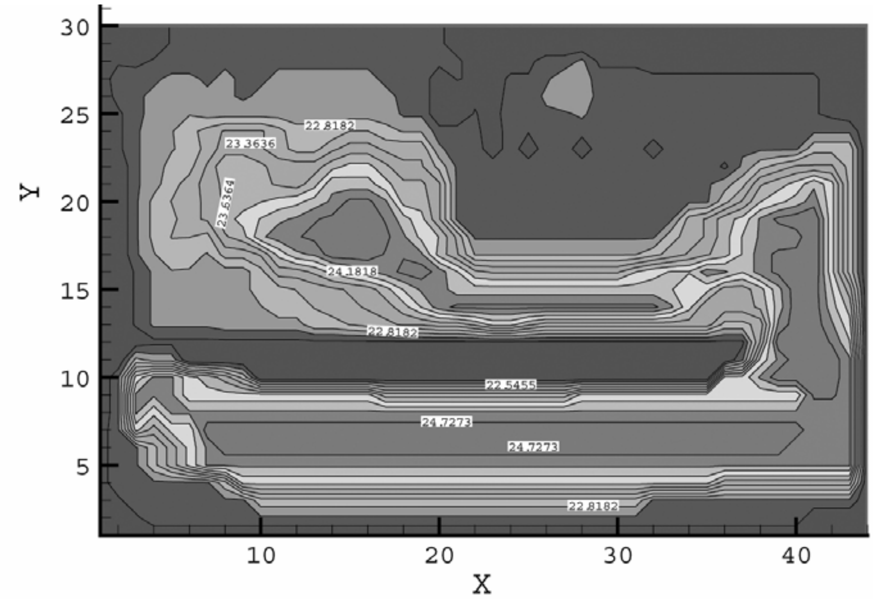

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Figure 1: Temperature field in vertical plane 30 cm from radiator

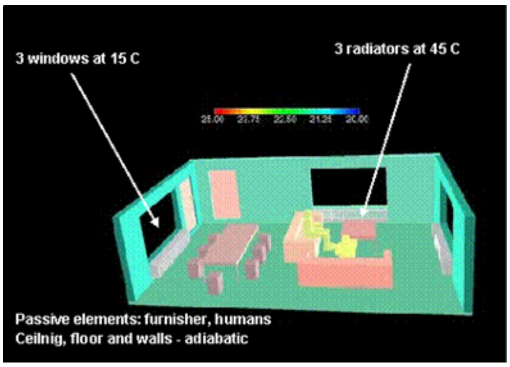

Figure 2: Boundary conditions

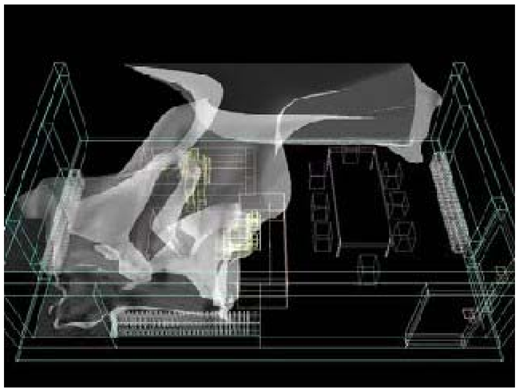

Figure 3: Smoke spreading in the room/office

4. REFFERENCE

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