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SIMULATION OF AIR-CONDITIONED OPERATING THEATRES

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ABSTRACT

A hospital is a place where we find simultaneously people whose health state is weakened, or vulnerable, and pathogenic micro-organisms able to worsen their health. The quality of the air in a hospital must be in conformity with precise criteria in such buildings in everyday usage, and in particular in the areas of the buildings where some risks of specific pollution exist such as in operating rooms.

In this paper, we present a modelisation and three dimensional numerical studies made in an operating room. Results could be used when new operating rooms must be conceived or others existing will be modified. It could be used to avoid risks and to allow all controls of any risks. The air flow modelling aim, by analysing the stream coherence, is to control the contamination in the operating area by bringing out the contamination generated within the operating room. It will allow a clear understanding of the complex coupled phenomena thanks to animation and to virtual 3D reality. The use of real data of the studied operating room (geometry, volume, extracted and blown air flow, temperature and hygrometry) will allow to determine the drainage of air, the distribution of temperature, and the zones of poor air distribution. To be able to find the exact distribution zones of the contaminants, the chosen turbulence model has to be accurate with a good ability to predict the recirculation of the air. The obtained results show that only one of the four tested models can correctly define the recirculation of the air.

Keywords: Operating theatre, aerodynamics simulation, turbulent model, comfort, Airflow, Indoor air quality.

INTRODUCTION

The air conditioning system of a hospital operating room must provide a comfortable and healthy environment for the patient and the surgical team. Thermal comfort can be achieved by controlling the temperature, the humidity, and the air flow. A healthy environment can be achieved by minimizing the risk of contamination through appropriate filtration and air distribution scheme.

To ensure these optimal conditions, a study of the aerodynamics flow in a conditioned operating room must be made, by using a digital simulation which

constitutes not only one powerful tool of anticipation, but by his possibilities of calculating in any point various aerodynamics parameters, it is presented as a genuine tool for tracing.

Our purpose in this study is to detail the control of a digital simulation for a test case of an operating room with diagonal air distribution system, to visualize the zones of recirculation and stagnation of air which supports the accumulation of contaminants, then to conclude the minimal conditions which make it possible to have a quality of indoor air without these zones of stagnation or recirculation. The choice of the turbulent model is then justified.

Table. 1. Basic equations of RNG k-ε model.

Equation of	Equations
Continuity	$\text{div}(\rho \vec{U}) = 0$
X-Momentum	$\text{div}(\rho U \vec{U}) = -\frac{\partial p}{\partial x} + \text{div}(\mu_{\text{eff}} \text{grad} U) + S_U$
Y-Momentum	$\text{div}(\rho V \vec{U}) = -\frac{\partial p}{\partial y} + \text{div}(\mu_{\text{eff}} \text{grad} V) - \rho g(1 - \beta \Delta t) + S_V$
Z-Momentum	$\text{div}(\rho W \vec{U}) = -\frac{\partial p}{\partial z} + \text{div}(\mu_{\text{eff}} \text{grad} W) + S_W$
Thermal energy	$\text{div}(\rho T \vec{U}) = \text{div}(\Gamma_{T,\text{eff}} \text{grad} T) + S_T$
RH-equation	$\text{div}(\rho RH \vec{U}) = \text{div}(\Gamma_{RH,\text{eff}} \text{grad} RH) + S_{RH}$
k-equation	$\text{div}(\rho k \vec{U}) = \text{div}(\alpha_k \mu_{\text{eff}} \text{grad} k) + G_k + G_b - \rho \varepsilon + S_k$
ε-equation	$\text{div}(\rho \varepsilon \vec{U}) = \text{div}(\alpha_\varepsilon \mu_{\text{eff}} \text{grad} \varepsilon) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon$
$\mu_{\text{eff}} = \mu_l + \mu_t, \mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \Gamma_{T,\text{eff}} = \Gamma_{RH,\text{eff}} = \frac{\mu_{\text{eff}}}{Pr_{\text{eff}}}, Pr_{\text{eff}} = 0.9,$ $C_\mu = 0.0845, C_{1\varepsilon} = 1.42, C_{2\varepsilon} = 1.68$ $S_U = \frac{\partial}{\partial x} \left(\mu_{\text{eff}} \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_{\text{eff}} \frac{\partial U}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu_{\text{eff}} \frac{\partial U}{\partial z} \right)$ $S_V = \frac{\partial}{\partial x} \left(\mu_{\text{eff}} \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_{\text{eff}} \frac{\partial V}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu_{\text{eff}} \frac{\partial V}{\partial z} \right)$ $S_W = \frac{\partial}{\partial x} \left(\mu_{\text{eff}} \frac{\partial W}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_{\text{eff}} \frac{\partial W}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu_{\text{eff}} \frac{\partial W}{\partial z} \right)$ $G_k = \mu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_j}{\partial x_i}, G_b = -g_i \frac{\mu_t}{\rho \sigma_t} \frac{\partial p}{\partial x_i},$ $R_\varepsilon = \frac{C_\mu \rho \eta^3 (1 - \eta/\eta_0) \varepsilon^2}{1 + \beta \eta^3 k} \text{ with } \eta \equiv Sk/\varepsilon, \eta_0 = 4.38, \beta = 0.012$	

CASE STUDY: OPERATING THEATRE

An operating room assigned to the service of neurosurgery is selected to study. The arriving air in the room is already filtered in the station of air treatment, using primary filters of 88% and 95% effectiveness, and then in a second time on the level of the inlet diffuser using HEPA (High Efficiency Particulate Air) filters.

For our study, we consider the room empty without staff neither patient nor medical equipment, to define the air recirculation without presence of disturbance which could increase the zone number of recirculation.

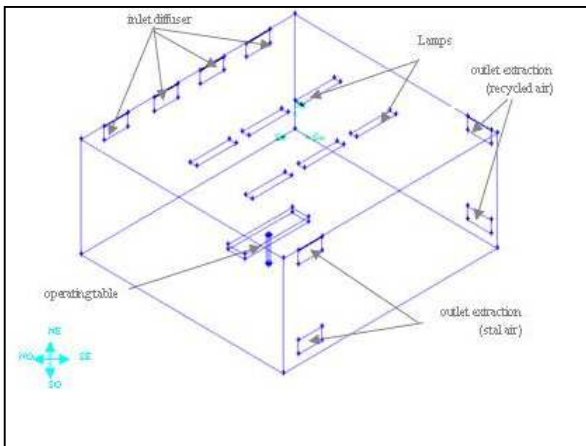


Fig. 1 .Geometry of the operating room

ADOPTED METHODOLOGIES

The first phase is the determination of our operating room characteristics:

Specific

- Area with very high risks for the patients (class 4 according to NF S 90-351 or ISO 5 according to ISO'S DIN 14644-1).

Aerodynamic

- The distribution of air is diagonal
- The renewal of air is 40% of new air and 60% of recycled air, with 6.08 ACH (Air Change by Hour)
- The air flow ventilation is equal to 1852m³ / h, with a velocity of 0.51m/s.
- The recycled flow is equal to 1110m³ / h, with a velocity of 0.61m/s.
- The stale flow is equal to 495m³ / h, with a velocity of 0.27m/s.
- The blowing temperature is 17.5°C with 40% humidity.

Geometrical

The following parameters were measured:

- Volume of the room.
- Dimensions of the walls and of the doors.
- Dimensions and positions of the various objects in the room (Sialytic- operating table -medical equipment - staffs).

- Dimensions and positions of the inlet and outlet diffuser.

The second phase consists in calculating the heat flows released by the occupants, lighting, by the machines and transmission, to be able to use them as boundary conditions.

NUMERIC SIMULATION

Choice of the turbulent model

According to literature, Nielsen P.V (1974), was one of the first researchers having used the k- ε turbulent model in 2D, to study the air movement and heat transfer in conditioned room [5].Murakami et al (1994), from the University of Tokyo quoted by [6] added to the standard k- ε model a wall function to model the air flow, in a clean room where the number of Air Change by Hour (ACH) is very high.

Chow and Yang (2003) used the standard k-ε model using eddy viscosity hypothesis for their numerical predictions on the ventilation of an operating theatre in a hospital of Hong Kong, [2]. Similarly the work made by Monika et al(2004), who used the same turbulent model and the flow near the boundaries were represented by using the standard logarithmic law [5]. They focused on the contaminant diffusion in an experimental operating room.

Chen (1995) [1] studied five modified k-ε models and compares the obtained numerical results with existing experimental results. The RNG k-ε model was found slightly better than the standard k-ε model for simulating air flow displacement.

While Luo (2003) [3] compared three turbulent models, RNG k-ε, realizable k-ε and SST k-ω, where an enhanced treatment near the walls was used for the two k-ε models. The study of the 3D displacement ventilation shows that the SST k-ω model predicts better the velocity profiles in the vicinity of floor.

For our study the choice of the turbulent model is crucial to well predict the air recirculation. Such recirculation will be favourable for the accumulation of the contaminants. Four turbulent models (two equations) were studied:

- The standard k- ε model with walls function
- The realizable k-ε model with non equilibrium walls function ;
- RNG k- ε model with non equilibrium walls function;
- SST k- ω model.

The choice of the treatment associated to walls of these models is taken from the results of the literature search [3].

Validation study of turbulent model

To further evaluate the performance of different turbulence models for the prediction of 3D ventilation flows, an isothermal ventilation flow in 3D partitioned room was chosen as a test case. Buchanan (1997) quoted by [3] studied experimentally a ventilated room, their experiment was carried out in a reduced room model at 1/10 scale, with a dimension of (width × depth × height) = (0.915 × 0.46 × 0.3) m with one inlet and outlet, and partition wall at the middle of the room which is the half room height.

Measure and conditions

The Reynolds number of the inlet airflow was determined to be 1600, based on the vertical inlet velocity U_y . Measurements were carried out along the inlet jet center line and along a line on the symmetry plane at the half height of the partition wall at $y = 0.075\text{m}$, only the vertical velocity components (Y Velocities) at different locations were measured.

Prediction with different turbulent models

Four turbulent two-equation models associated to wall treatments: the standard $k-\epsilon$ model with standard wall function, the RNG $k-\epsilon$ model the realizable $k-\epsilon$ model with both non-equilibrium wall function and SST $k-\omega$ model; were simulated and numerically tested for the same configuration given by Buchanan and compared to his experimental results in the two planes: the mid height line and the jet center line Figure 2 and Figure 3.

We obtained these results:

From the locations : $x = 0\text{ m}$ to $x = 1\text{ m}$, both the RNG $k-\epsilon$ and the realizable model yielded smooth predicted velocity profile that agree with the experiment data well, but for the inlet plane, we can see that the RNG $k-\epsilon$ model is correctly predicted than the realizable $k-\epsilon$ model.

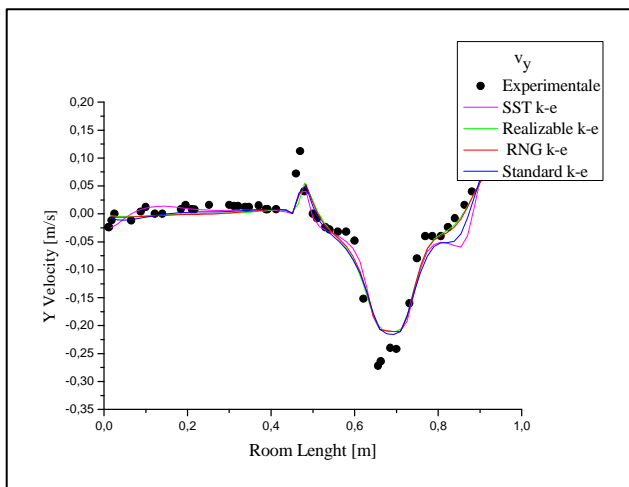


Fig.2. Comparison of the predicted velocity profiles with measurements at the mid height line

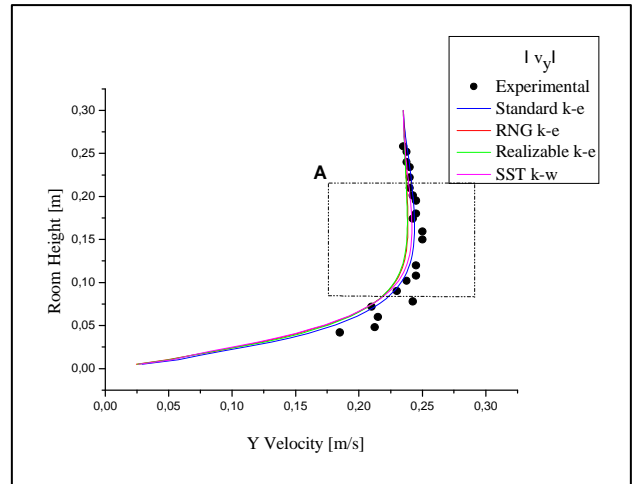


Fig.3. Comparison of the predicted velocity profiles with measurements at the jet center line

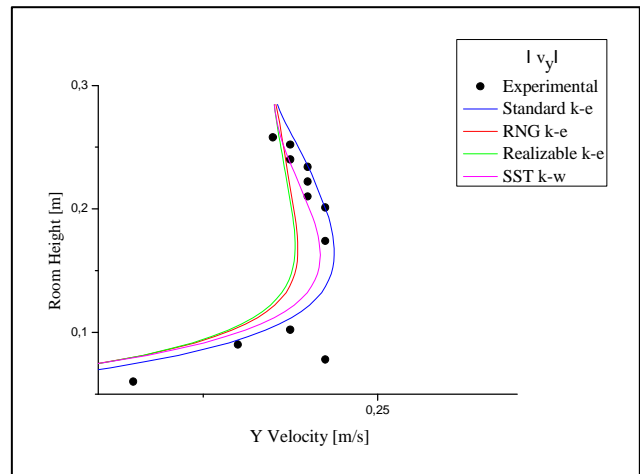


Fig.4. Zoom part A of Fig.3.

We can conclude that the two equations of RNG $k-\epsilon$ model with the non-equilibrium wall function, a performed good agreement has been achieved between predictions and measurements.

Current study

The RNG $k-\epsilon$ model were used as the computational tools in the current study. The basic equations are listed in Table 1.

A non uniform grid (1037497 tetrahedral cells) was used too with a refinement on the level of the inlet and outlet diffuser of the lamps and the operating table; the following heat flows were taken into account:

Table. 2. The heat dissipation

Item	Heat flux [w/m^2]
wall NE	1.3565
wall SO	0
wall SE	0
wall NO	2.7409
ceiling	7.8576
floor	6.6687

The fluid is supposed incompressible and a second order scheme is used to discretize the diffusion terms. The solution is obtained in primitive variable P-V and the pressure and velocity coupling is obtained by the SIMPLEC algorithm.

The convergence criterion was based on the maximum error less than a prescribed value taken equal to 10^{-6} for energy, and 10^{-4} for the other equations.

Four planes were selected, each one is localised in the middle of the inlet diffuser represented on Figure 5 and localised at:

- $z = 1.13m$ in the medium of the first inlet diffuser.
- $z = 2.54m$ in the medium of the second inlet diffuser.
- $z = 3.95m$ in the medium of the third inlet diffuser.
- $z = 4.47m$ in the medium of the fourth inlet diffuser.

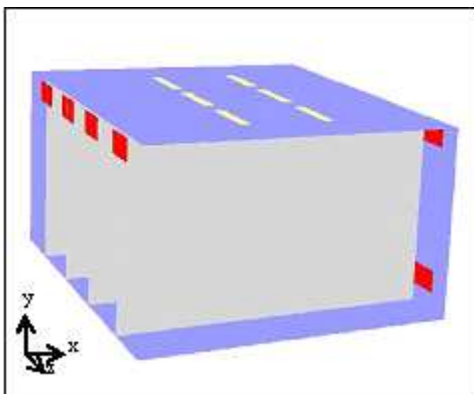


Fig.5. Planes of study

RESULTS AND DISCUSSION

The velocities vectors and the mean velocities lines are represented on Figure 6: (a) (b) (c) (d) for the four vertical planes located at central vertical axis of each inlet diffuser.

We notice on each explored studied plane, the presence of two zones:

- The one is showing a correct circulation of the air between the inlet and the outlet and.
- The other is showing a recirculation area, in addition to stagnation zone of air.

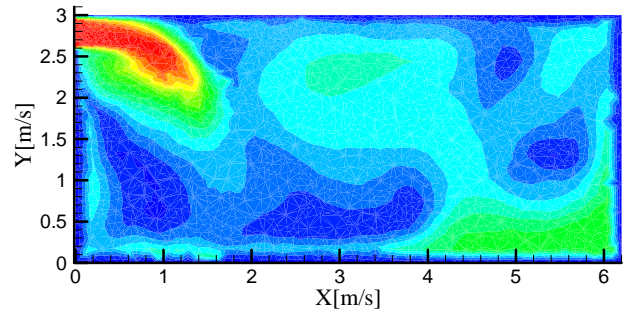
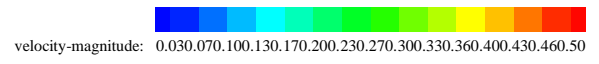
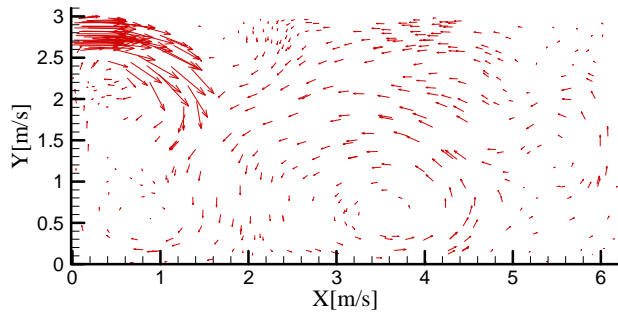
This image is perceptible through each examined plane and particularly over that containing the operating table where its presence can disturb the air jet and separates the room in two parts, creating two zones of recirculation. We can see a very intense area of stagnation on the left side and close to the corner of the right part.

The danger is that, the stagnation zones are a potential sources of pollution, the air which is originally clean, can become contaminated and this situation can increase, because the microbes are in the majority enclosed in this area, that would be in favour of their germination which represents a real danger for patients, the medical personnel, as well as the sterilized material.

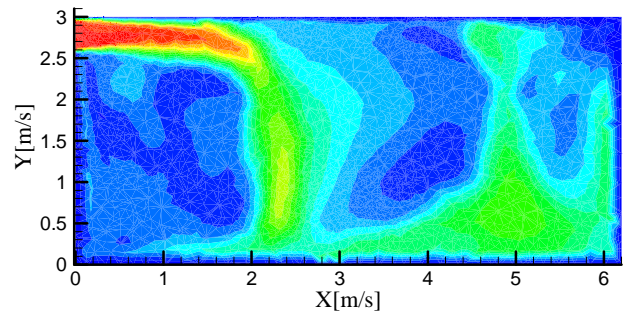
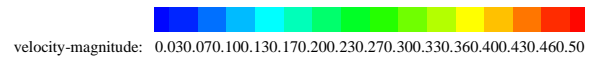
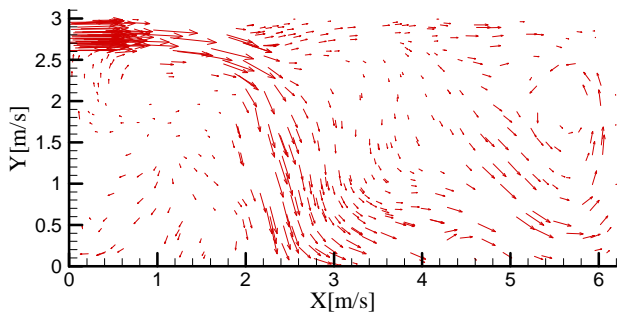
Nevertheless, the air is in good exchanges, on the top of table and on its right side.

On Figure 6: (a) and (d) the situation becomes more alarming since the recirculation zones occupy an increasingly large volume and only a very little space permitted to the air change. We are constrained to say that the air is rather very badly distributed and consequently, this type of diffuser does not agree with an operating room.

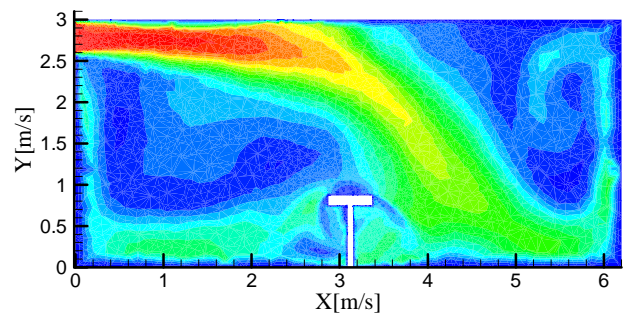
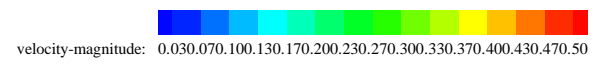
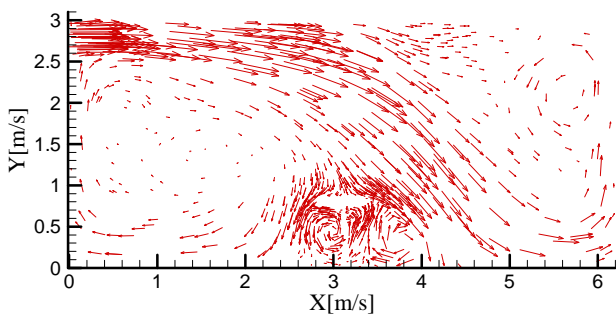
- (a) : At the plane $z = 1.13\text{m}$



- (b) : At the plane $z = 2.54\text{m}$



- (c) : At the plane $z = 3.95\text{m}$



- (d) : At the plane $z = 5.47\text{m}$

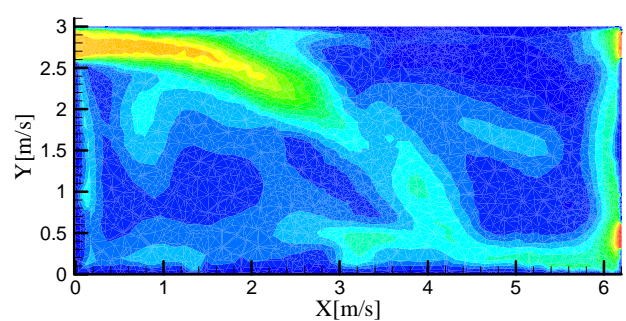
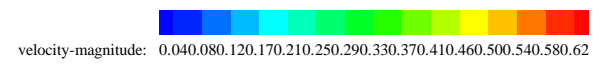
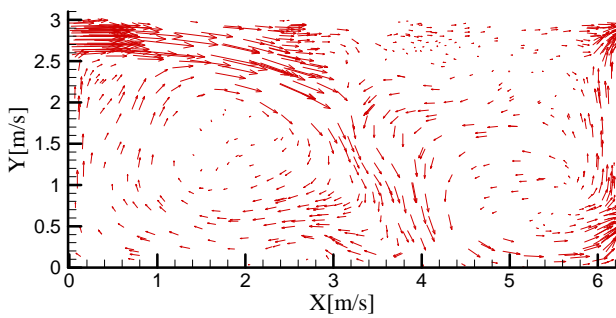


Fig.6. Different case of study: vector and iso-velocity

CONCLUSION

The modelling of airflow in a closed room and its Aeraulic simulation makes it possible to optimize the ways of the airflow distribution according to the various parameters (operating table, patient, staff, medicals material...) in order to decrease, for the patient and the medical personnel, the risks of contamination. For this, we adopted turbulent model RNG k- ϵ after having carried out the tests with other models (standard k- ϵ , realizable k- ϵ and SST k- ω). This model can enables us to better locate the various zones of recirculation and the localization of the zones of low velocities. We can then recommend certain modifications or new solutions in order to obtain better distributions of inlet air and to avoid as much as possible the causes of contamination.

NOMENCLATURE

$C_{\mu, 1\epsilon, 2\epsilon}$	constants of two –equation turbulent model
G_k	generation of turbulent kinetic energy due to the mean velocity gradients
G_b	production of turbulent kinetic energy due to buyancy
g	gravitational acceleration, m^2/s
k	turbulent kinetic energy, m^2/s^2
p	pressure, Pa
Pr	Prandtl number effectif
RH	relative humidity, %
S_ϕ	source term of entity ϕ , $\phi = U, V, W, T$
T	absolute temperature, °K
t	celsius temperature, °C
U	velocity in x direction, m/s
V	velocity in y direction, m/s
W	velocity in z direction, m/s

Greek Letters

$\Gamma_{T, RH}$	diffusion coefficients for energy and relative humidité
α_k	inverse effective Prandtl numbers of k
α_ϵ	inverse effective Prandtl numbers of ϵ
β	coefficient of thermal expansion
ϵ	turbulence dissipation rate, m^2/s^3
μ	absolute viscosity of air, kg/ms
ρ	density, kg/m^3

Subscripts

effe	effective property
l	laminaire
t	turbulent

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