# Modeling of Water Vapor Sources in Enclosures

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***Abstract*—The objective of this study is to propose an approach concerning the integration of indoor humidity sources in CFD (Computational Fluid Dynamics) simulations for buildings. The numerical model is based on source terms of mass and energy, added in the conservation of water vapor equation and energy balance equation. The equation governing the conservation of water vapor is added to the basic equations dealing with turbulent non-isothermal confined air flows in CFD models. This method allows achieving values of air velocity, air temperature and air humidity (relative humidity or moisture content) all over the computational domain. The methodology is exemplified for the case study of an office with mixing ventilation system, the sources of humidity being represented by people. The results of this study can be used in analyses focused on thermal comfort and indoor air quality. Finally, the numerical description of water vapor sources proposed here can be easily extrapolated for other indoor humidity sources.**

***Index Terms*—computational fluid dynamics model, humidity sources, indoor air quality, thermal comfort, ventilation**

## I. Introduction

The indoor air humidity has multiple implications on different issues. For instance, the thermal comfort of occupants is related not only to the temperature but also on the relative humidity of the indoor air. Consequently, unpleasant sensation of dryness occurs for relative humidity less than about 30% [1], [2]. On the contrary, high relative humidity (over 70%), associated with high air temperatures, leads to feeling of heaviness, choking while high relative humidity, combined with low air temperatures, intensifies the sensation of cold [3]. On the other hand, high indoor air humidity correlated with cold weather, is causing condensation on cold surfaces or even within the materials. This situation may result in premature deterioration of these materials [4]. On the contrary, very dry indoor air leads to frequent electrostatic shocks [5]. These should be avoided in electronic industries. There are also other applications (e.g. museums, hospitals, pools, different industrial fields – printing processes, food, and pharmaceutical) where the indoor air humidity is extremely important to properly manage the indoor environment conditions for occupants or for technological purposes [3]. Finally, high levels of relative humidity in rooms (greater than 75%), with favorable conditions of temperature, contributes to mold development [6]. This is not only an aesthetic problem, but a major human health concern, clearly established nowadays [7].

Despite all the issues mentioned above, the number of studies dealing with phenomena related to indoor air humidity is relatively low. In addition, the importance of air flow for indoor air humidity is obvious as the transport due to air is the main mechanism of moisture movement inside buildings. As a result, the air flow has a major influence on humidity distribution in rooms [3]. This means that studies on moisture propagation in enclosures must be based on "air flow – humidity" coupling. Humidity is also closely related to temperature. For example, for a mass of water vapor in a given volume of air, the degree of saturation depends on the temperature of the mixture dry air – water vapor. In addition, the energy involved in phase change phenomena (condensation / evaporation) can reach extremely high values. Consequently, it is clear that the study of humidity in buildings must be also linked to energy aspects. Accordingly, the study of indoor air humidity must take into account complex physical mechanisms, particularly if the interaction with air flow and energy is represented. On the other hand, this coupled approach (heat – air flow – moisture) should integrate five main elements concerning the study of humidity in buildings: moisture transport due to air flow, diffusion of water vapor in air, water vapor condensation on cold surfaces and in the air volume, water vapor absorption / desorption phenomena in materials, and integration of water vapor sources. In this context, the CFD (Computational Fluid Dynamics) technique is appropriate for developing numerical models dealing with heat, air flow, and humidity transfer phenomena in enclosures, as this approach allows taking into account all the aspects mentioned above.

As a result, this study presents a model for integrating humidity sources in CFD simulations for buildings. It is worthwhile to mention that this approach is part of a global CFD model which is dealing with heat, air flow, and humidity transfer phenomena in rooms (e.g. condensation [8]).

## II. Humidity Sources Modeling

There are many sources of moisture in buildings. The most common are due to: people (respiration and transpiration), pets, houseplants, domestic activities (showers, dishwashing, cleaning – floor mopping, cooking, clothes washing and drying, ironing), and humidity release from construction elements (e.g. wet foundations). In these circumstances, it is preferable to

Manuscript received March 17, 2015; revised July 15, 2015.


doi: 10.18178/ijscer.4.2.212-217

develop a “universal” approach for numerical description of all these sources of moisture.

Consequently, the methodology proposed in this study is based on source terms of mass and energy, added in the conservation of water vapor equation and energy balance equation, respectively. This approach can be simply implemented for any kind of humidity source, if its moisture release rate is known. In fact, based on the mass flow rate of source water vapor (representing the mass source term), the energy source term is given by the following equation:

$$H_{water\ vapor} = M_{water\ vapor}\,(C_{pwater\ vapor}\, t_{water\ vapor} + L_{water}) \qquad (1)$$

where $H_{water\ vapor}$ represents the total enthalpy of water vapor and $M_{water\ vapor}$ is the mass flow rate of water vapor. The energy source term is taking into account both the sensible heat of water vapor (by means of $C_{pwater\ vapor}$ – specific heat of water vapor, and $t_{water\ vapor}$ – temperature of water vapor) and latent heat of water vapor (based on $L_{water}$ – water latent heat).

## III. Integration of Humidity Sources in CFD

In order to integrate in CFD simulations the humidity sources model briefly described above, an equation for the conservation of the water vapor must be added to the equations expressing a turbulent non-isothermal airflow. This equation can be formulated in a similar manner to classical transport CFD equations, taking into account transport and diffusion phenomena for the water vapor mass fraction:

$$\rho \frac{\partial}{\partial x_i}\left(u_i m_{i'}\right) + \frac{\partial}{\partial x_i} J_{i',i} = S_{i'} \qquad (2)$$

where the left-hand side terms stand for the convective term ($\rho$ - density of the humid air, $x_i$ - spatial coordinate, $u_i$ – velocity component in $i$ direction, $m_{i'}$ - water vapour mass fraction) and diffusion term respectively ($J_{i,i'}$ – water vapour diffusion flux), while the right-hand side term $S_{i'}$ represents source terms.

Regarding the term source, its value is based on the moisture release rate of humidity source, as explained above.

The diffusion term in (2) takes into consideration both molecular diffusion and turbulent diffusion mechanisms, as presented below:

$$\frac{\partial}{\partial x_i} J_{i',i} = \rho \frac{\partial}{\partial x_i}\left(D_{i',m} \frac{\partial m_{i'}}{\partial x_i}\right) - \frac{\partial}{\partial x_i}\left(-\overline{u_i' m_{i'}'}\right) \qquad (3)$$

where $D_{i',m}$ is the water vapor molecular diffusion coefficient and $u_i'm'_{i'}$ is the turbulent mass flux of water vapor, $u_i'$ being the velocity fluctuation.

The molecular diffusion in (3) is represented by Fick’s first law (diffusion flux is proportional to the concentration gradient). The value of water vapor diffusion coefficient in air is considered constant in the model because its variations with temperature and viscosity are negligible [5].

The turbulent diffusion in (3) is taking into account through the turbulence model used to describe the flow of the humid air. Consequently, the turbulent mass flux of water vapor is predicted using a methodology similar to that of the Reynolds analogy: the turbulent mass diffusivity ($D_t$) is associated with the turbulent viscosity ($\mu_t$) using the turbulent Schmidt number ($Sc_t$) – see (4) and (5).

$$-\overline{u_i' m_{i'}'} = \frac{\mu_t}{Sc_t}\frac{\partial m_{i'}}{\partial x} \qquad (4)$$

$$Sc_t = \frac{\mu_t}{\rho D_t} \qquad (5)$$

where ρ is the density of the humid air.

Equation (2) is solved by the same numerical methods used for other equations describing in the CFD model the conservation of a variable in the computational domain (e.g. mass, momentum, energy, turbulent parameters).

Finally, the convection and diffusion phenomena related to humidity are studied in the developed CFD model using the following assumptions:

- Fluid taking into account (humid air): mixture (ideal gas) of two perfect gases: dry air and water vapor
- Mixture: incompressible Newtonian fluid
- There is no chemical reaction between the constituents of the mixture
- Heat and mass transfer mechanisms in the mixture are negligible
- Mixture density, ideal gas law formulation (based on the mixture temperature and the concentration of each component in the mixture)
- Mixture specific heat capacity: mixing law formulation, based on mass fraction average of the two species (air and water vapor) heat capacities
- Mixture thermal conductivity and viscosity: determined by means of kinetic theory
- Diffusion coefficient of water vapor in air: constant value, $2.55 \times 10^{-5}$ $m^2/s$ [5]

## IV. Case Study

The indoor humidity sources model and its integration in CFD simulations for buildings are applied in this study for a small office (6.2 x 3.1 x 2.5 $m^3$) equipped with mixing ventilation system, Fig. 1.

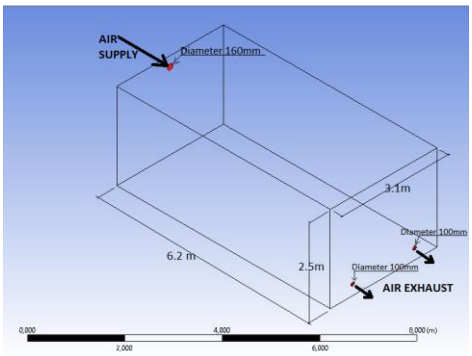


Figure 1. Office with mixing ventilation system

The sources of humidity in this office are represented by moisture released from 4 persons. The total moisture generation rate (respiration and transpiration) taken into account for an occupant was 60 g/h. This value corresponds to the metabolic rate of an average adult who performs typical office work [9].

As a result, the source term introduced in (2), according to humidity source model, is based on the value mentioned above. This value is also used to determine the corresponding source term of energy, according to (1).

In order to methodically study the behavior of the proposed CFD model - dealing with heat, air flow, and humidity transfer phenomena in enclosures (including the description of moisture sources), several configurations were taken into consideration. These test conditions include the following situations (Table I): isothermal air supply, cold air supply, and warm air supply in the enclosure (according to mean air room temperature).

TABLE I. CASE STUDY CONDITIONS (AIR INLET CHARACTERISTICS)

| Test | Air changes per hour ($h^{-1}$) | Inlet moisture content (g/kg) | Inlet air temperature (°C) |
|---|---|---|---|
| Isothermal air supply | 2.0 | 5.3 | 22.0 |
| Cold air supply | 2.0 | 5.3 | 15.0 |
| Hot air supply | 2.0 | 1.0 | 30.0 |

The main issues of the proposed CFD model are shown in Table II. This numerical model was built using a general-purpose, finite-volume, Navier-Stokes solver (Fluent version 15.0.0).

## V. RESULTS

We present below air velocity, air temperature and humidity distributions in the office for each situation taken into account (isothermal air supply, cold air supply, and hot air supply). These results are reported in two vertical planes of the room, normal to the air terminal devices: the median plane and another plane which includes the moisture sources (the centerplane of the occupants, 45 cm. from the median plane).

TABLE II. CFD MODEL - PRINCIPAL ELEMENTS AND HYPOTHESIS

| Fluid | Air – water vapor mixture |
|---|---|
| Flow | Three-dimensional, steady, non-isothermal, turbulent |
| Computational domain discretization | Finite volumes, unstructured mesh (tetrahedral elements): 5,787,819 |
| Turbulence model | Shear Stress Transport (SST) turbulent kinetic energy-specific turbulent dissipation rate (k-ω), with low-Reynolds corrections |
| Numerical resolution | Second-order upwind scheme<br>Velocity-pressure coupling: SIMPLE algorithm<br>Convergence acceleration: algebraic multigrid |

Concerning the isothermal case, Fig. 2 shows the air velocity contours in the median plane, while Fig. 3 and Fig. 4 show the distribution of the relative humidity and moisture content in the plane including the humidity sources (centerplane of the occupants).

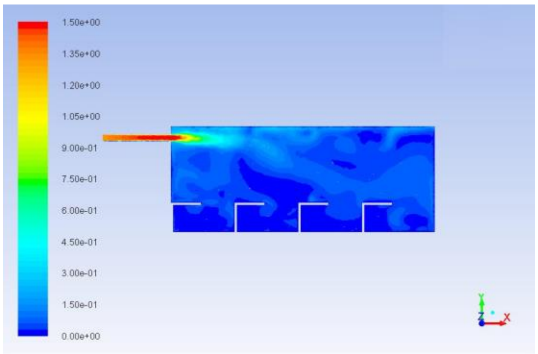


Figure 2. Air velocity (m/s) – isothermal air supply case

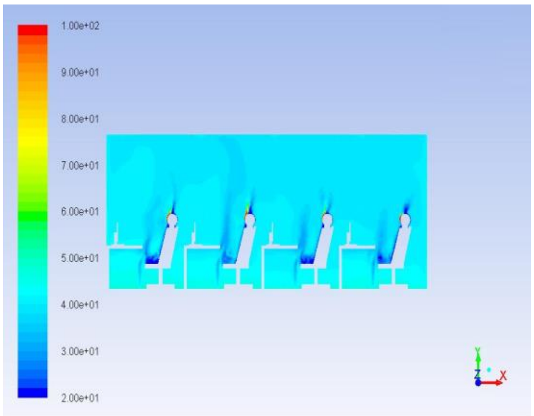


Figure 3. Relative humidity – isothermal air supply case (centerplane of the occupants)

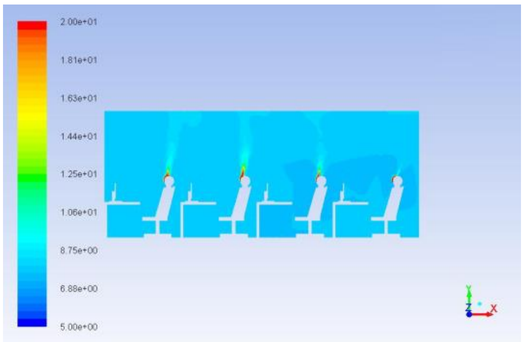


Figure 4. Moisture content (g/kg) – isothermal air supply case (centerplane of the occupants)

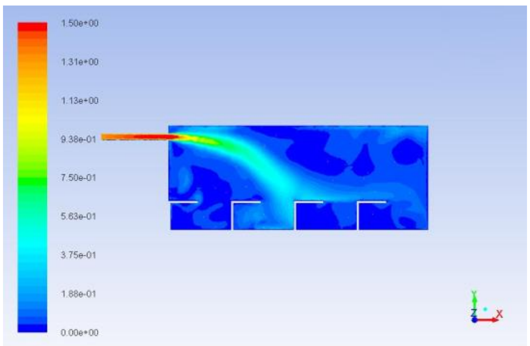


Figure 5. Air velocity (m/s) – cold air supply case

The predicted values for velocity, temperature and relative humidity in the case of the cold jet supplied in the room are shown in Fig. 5- Fig. 7 for the median vertical plane of the enclosure.

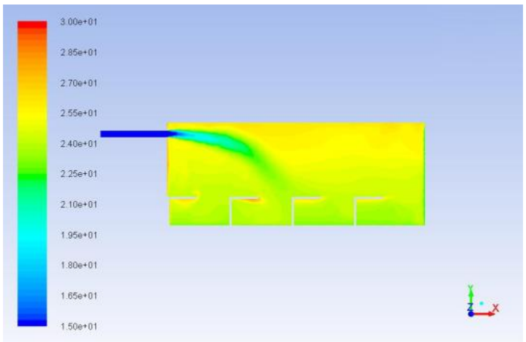


Figure 6. Air temperature (℃) – cold air supply case

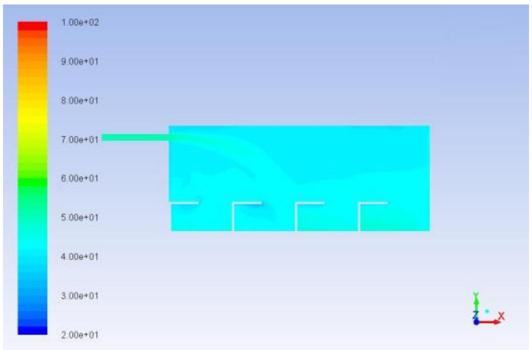


Figure 7. Relative humidity – cold air supply case

As can be observed, there are important momentum, energy and mass (vapor) diffusion mechanisms in the jet area due to complex air flow which occurs in this case.

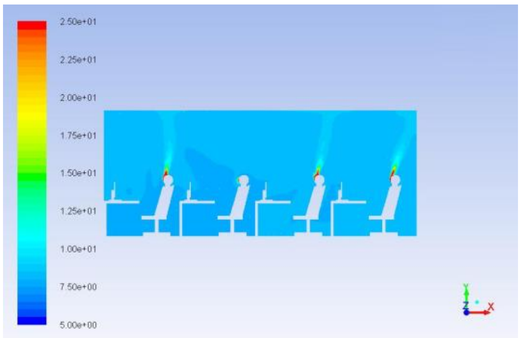


Figure 8. Moisture content (g/kg) – cold air supply case (centerplane of the occupants)

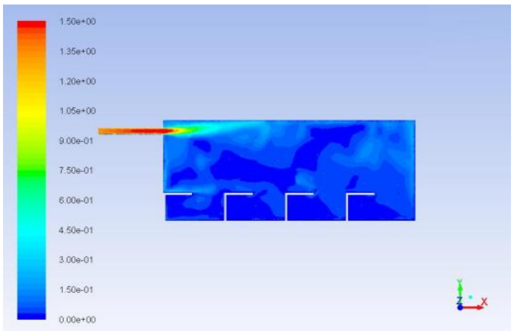


Figure 9. Air velocity (m/s) – hot air supply case

On the other hand, the distribution of the moisture content in the centerplane of the occupants (Fig. 8) highlights in this case the strong interaction between the main air flow in the enclosure and thermosolutal convection phenomena that occur above the sources of humidity (people). This is most evident in the region around the second person in the direction of the supply air, where the cold air jet penetrates into the occupied zone.

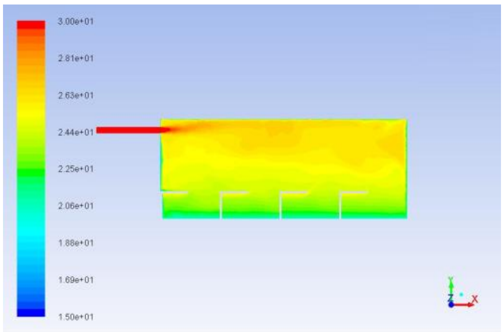


Figure 10. Air temperature (℃) – hot air supply case

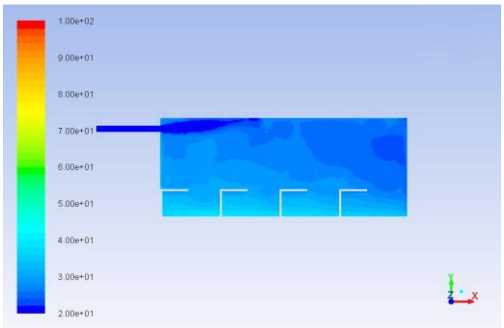


Figure 11. Relative humidity – hot air supply case

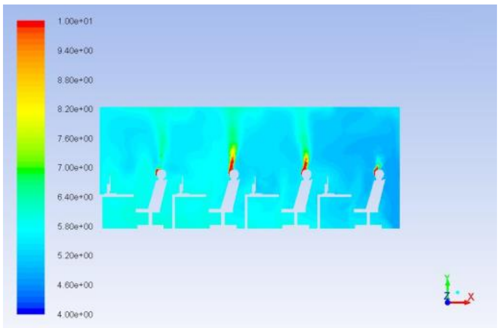


Figure 12. Moisture content (g/kg) – hot air supply case(centerplane of the occupants)

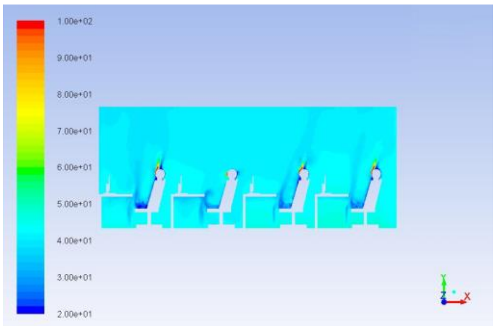


Figure 13. Relative humidity – cold air supply case (centerplane of the occupants)

The results for the hot air supply case are reported in Fig. 9- Fig. 12. The relative humidity in the office is also in this case in the normal range (40-50%).

There are regions where the relative humidity reaches 100% but this happens only near the sources of moisture (Fig. 3, Fig. 13, and Fig. 14). The numerical model integrates in these zones the vapor release from people.

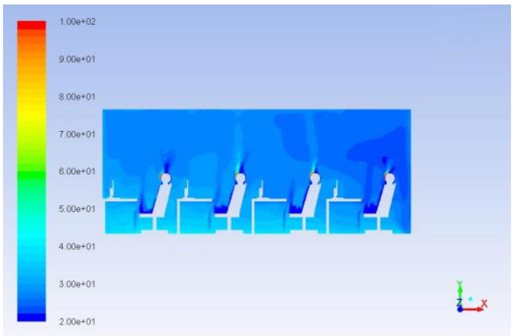


Figure 14. Relative humidity – hot air supply case (centerplane of the occupants)

## VI. Conclusion

The developed model allows describing the air velocity, air temperature and air humidity in enclosures, taking into account sources of moisture. Consequently, the model can be successfully applied in studies of thermal comfort and IAQ.

The numerical description of water vapor sources for CFD modeling proposed in this study can be easily extended for other indoor moisture sources (e.g. plants). Another perspective of our numerical model is to take into account the variation of moisture generation of different sources with the indoor conditions (air velocity, air temperature and air humidity).

In addition, the model presented here can be used in conjunction with models dealing with condensation phenomena for humid air in rooms and water vapor absorption / desorption phenomena in construction materials in order to achieve comprehensive CFD simulations of humidity in buildings.

Finally, it is worthwhile to mention that experimental studies on full scale test cell were initiated to validate the model of moisture sources.

## Acknowledgment

This work was supported by a grant of the Romanian Ministry of Education and Research, CNCS– UEFISCDI, project number PN-II-ID-JRP-RO-FR-2012-0071.

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