Numerical prediction of surface radiation effect on thermal comfort and indoor air quality in a ventilated cavity heated from below

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Abstract. This paper presents an investigation of the influence of surface radiation on indoor environmental parameters such as thermal comfort and indoor air quality. To achieve this objective, coupled heat transfer by mixed convection and radiation was numerically carried out inside a ventilated cavity. Air-CO\textsubscript{2} mixture was considered as the working fluid. Uniform heat and CO\textsubscript{2}-concentration were applied at the bottom wall of the cavity. The boundary conditions of other walls were fixed at the external conditions. The same emissivity value was considered for all interior surfaces. An external fresh air enters at the cavity through an opening located on the top of the left vertical wall and exits from another one located at the bottom of the opposite wall. The mass, momentum, energy and chemical specie equations, coupled with the RNG k-\varepsilon turbulence model were solved via finite volume method. The obtained results indicate that the surface radiation presents slight effect on thermal comfort indexes, while the increasing of Rayleigh number enhances them. A good indoor air quality is insured inside the studied cavity.

1. Introduction
Over the past decades, indoor environment quality in terms of thermal comfort and air quality has become crucial for the occupants' health. It is reported that global air pollution caused around seven million premature deaths in 2016, of which 3.8 million were related to indoor air pollution [1]. Indeed, several products emitting chemical compounds like building materials, furnishings and consumer products are being used. Following the energy crisis of the 1970’s, buildings have been sealed more tightly in order to reduce the associated energy consumption [2]. As a result, air exchanges between the outside and inside were greatly reduced [3]. This has allowed some successful development regarding to reducing energy costs, but has generated other problems such as confinement, poorer air quality [2], and health issues, as the sick building syndrome (SBS) and the consequent loss of productivity [4]. The occupants also contribute to the thermal discomfort and air quality degradation through their presence and activities. Further, the pollutant concentrations within indoor environments are typically much higher than that outdoor environment [5]. Moreover, in modern societies, people spend more than 80% of their time in closed spaces such as homes, schools, transports, stores or shopping centres and other indoor places where extra and leisure activities are developed [6].

The main objective of this research is to predict the effects of surface radiation on thermal comfort and indoor air quality (IAQ) indexes. The mixing ventilation mode with low inlet velocity is adopted to achieve an acceptable microclimate inside room. The room is modeled as a ventilated cavity often taken as a first approximation. A good knowledge of airflow, heat transfer and contaminant dispersion behaviors inside ventilated spaces is essential for designing ventilation systems; the aim is to create a comfortable environment where a good air velocity and temperature as well as contaminant
concentrations prevail [3]. The process for creating an adequate interior microclimate basically can be divided into two categories: ventilation to insure a good air quality and heating or cooling to achieve thermal comfort [7]. However, it is tough to enjoin conditions to comply both, owing to such conditions are usually different even for the same spaces occupied by different people. The ventilation effectiveness depends entirely on the flow pattern, the heat and contaminants sources and the location of air supplying and extracting.

2. Physical description and mathematical formulation

2.1 Physical domain of the ventilated cavity

The model enclosure are schematically shown in figure 1. It is a ventilated 2D-room (H/L = 1) filled with a transparent air-CO₂ mixture, since CO₂ plays an important role in sick building syndrome symptoms. Initially, the air-CO₂ mixture inside the cavity is at a constant temperature Tₐ and CO₂-concentration Cₐ. A uniform heat and CO₂-contaminant sources of high temperature Tₕ and high CO₂-concentration Cₕ are mounted on the floor (Tₕ > Tₐ and Cₕ > Cₐ). The other walls are maintained at a uniform temperature Tₐ and CO₂-concentration Cₐ. The interior surfaces are assumed to be opaque and diffuse-gray with identical emissivities. The fresh air-CO₂ mixture (Uₖ, Tₖ, Cₖ) is supplied via an inlet supply grid and then the polluted hot air-CO₂ exhausted naturally from an outlet one.

As illustrated in figure 1, the flow through the inlet supply grid is purely horizontal forming a wall jet along the ceiling. The parameters of this stream (i.e., velocity, temperature and concentration) are uniform over the cross section of the inlet port. The inlet normal velocity is assumed as constant Uₖ = 0.57 m.s⁻¹ and the inflow value of tangential one is set to zero. The supply temperature (Tₖ) and CO₂-concentration (Cₖ) are those from outside (Tₖ = 288 K and Cₖ = 350 ppm). The turbulent kinetic energy and its dissipation rate for the incoming air-CO₂ mixture (kₖ and εₖ) are given in Ref. [10].

On all the solid walls, non-slip condition is imposed. Both normal and tangential velocity values are set to zero. The heating temperature (Tₕ) is varied between 303 K (Ra = 1.9×10⁹) and 313 K (Ra = 3.2×10⁹) with an increment of 5 K. The CO₂-polluting concentration (Cₕ) is set 2000 ppm. The ceiling and vertical walls are maintained at cold temperature and low CO₂-concentration (Tₐ = 288 K and Cₐ = 350 ppm). At the air outlet grid, zero gradient outflow boundaries are adopted for all the variables.

2.2 Governing equations and boundary conditions

A steady state 2D-model was considered to perform the coupled heat transfer by mixed convection and radiation in the whole cavity using the commercially available CFD software scStream [8]. To simplify analysis, the following assumptions are made in the mathematical model: (1) the flow is fully developed, turbulent, and viscous; (2) the air and the CO₂-contaminant gases are perfectly mixed; (3) the air-CO₂ mixture is Newtonian, incompressible and obeying the Boussinesq approximation; and (4) the dissipation and pressure forces' work are assumed to be negligible. The thermo-physical properties of the mixture were evaluated according to the methodology shown by Poling et al. [9].

2.3 Radiation between gray surfaces

The radiation heat exchange between gray surfaces is computed by the radiosity-irradiance method. The walls of the cavity are subdivided into 4000 elementary segments. The view factors are obtained by the crossing strings method reported by Hottel [11]. The air inlet and outlet are assumed to be open.
space ($\varepsilon = 1$). The Air-CO$_2$ mixture is assumed to be transparent (the level of CO$_2$-concentration is low, the amount of CO$_2$ is much lower than air (0.02%). In the transparent body, the radiation energy is directly transferred from surface to a boundary, from the boundary to the surface, or from the surface to the surface. The radiosity equation for the $i$-th element of the cavity may be written as:

$$ J_i = \varepsilon_i \sigma T_i^4 + (1 - \varepsilon_i) \sum_{j=1}^{N} F_{ij} J_j $$

where $J_i$, the radiation energy flux, $\varepsilon_i$, the surface emissivity, $\sigma$, the Stefan-Boltzmann constant, $N$, the number of segments, and $F_{ij}$, the view factor between segments $i$ and $j$. It should be noted that the view factors depend only on the geometry. Their calculation is done before initiating the computation.

### 2.4 Thermal comfort and indoor air quality parameters

To evaluate the thermal comfort, Standard ISO 7730 provides Predicted Mean Vote (PMV) index proposed by Fanger [12]. This index relates to warm and cool sensation. It is related to the human thermal loading which derived by the comfort equation calculating non-equilibrium between human body and his environment. It is calculated from temperature, humidity, flow velocity, radiation temperature, clothing, and metabolic rate. In practical applications, the seven-point ASHRAE thermal sensation scale (PMV: -3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm and +3 hot) is adopted to correlate PMV values and human thermal sensation [13]. However, the PMV index predicts the mean value of the thermal votes of a group of people exposed to the same environment. Individual votes are scattered around this mean value and it is useful to able to predict the number of people likely to feel uncomfortably warm or cool. In this way, the Predicted Percentage of Dissatisfied (PPD) index is proposed. It describes the percentage of occupants that are dissatisfied with the given thermal conditions.

To assess the IAQ with respect to a pollutant, i.e., CO$_2$, the local IAQ index ($I_{IAQ}$) is used. It is defined as:

$$ I_{IAQ} = \frac{C - C_\infty}{C_{Th} - C_\infty} $$

where $C$, the local contaminant concentration, $C_\infty$, the outdoor contaminant concentration, and $C_{Th}$, the contaminant concentration threshold.

### 3. Numerical procedure and validation

The computation analysis using the specified boundary conditions described in the above section were solved employing a finite-volume method. To avoid possible artificial diffusion, a QUICK scheme and a second-order central differencing scheme were involved in approximating the advection and diffusion terms, respectively. A SIMPLEC algorithm was chosen to couple the momentum and continuity equations. To ensure convergence, the criteria was set at $10^{-7}$ for the residual error of each variable. The computation of equation (1) was achieved using the Gauss-Seidel method.

The numerical approach has been successfully checked and validated in recent studies [14, 15] against experimental and numerical results for natural and mixed convection. Thanks to availability of interesting and accurate experimental data concerning turbulent natural convection coupled with radiation, two comparisons were added here (Clergent [16] and Saury et al. [17]).

Clergent [16] experimentally analyzed the turbulent natural convection in a rectangular filled with argon and subjected to heat flux conditions. The left vertical wall is coated with a shiny of low emissivity ($\varepsilon = 0.07$) while the opposite wall is painted in matte black ($\varepsilon = 0.9$). The horizontal walls have a non-treated surface and their emissivity is 0.7. Table 1 gathers comparisons of temperature evaluated in the middle of the cavity for different points (Ra = $3.1 \times 10^8$). As we can see, the results from the simulation show a good agreement. Figure 2 depicts the comparative achieved in terms of dimensionless temperature ($\theta$) plotted at $Z = 0.5$ with the results of Saury et al. [17]. The vertical surfaces have low emissivity ($\varepsilon = 0.1$). The emissivity of horizontal surfaces varied between 0.1 and 0.6. It demonstrates that our findings corroborate the experimental data.
Table 1. Comparison of temperature at vertical mid-plane for $Ra = 3.1 \times 10^8$.

| $x$ (mm) | $z$ (mm) | Temperature (K) |
|----------|----------|-----------------|
|          |          | Present work    | Clergent [16] |
| 320      | 83       | 294.34          | 294.35        |
| 318      | 173      | 294.67          | 294.65        |
| 314      | 265      | 295.47          | 295.45        |
| 315      | 355      | 295.99          | 295.95        |
| 316      | 445      | 296.20          | 296.15        |

Figure 2. Comparison of dimensionless temperature at vertical mid-plane.

4. Results and discussions

The impact of surface radiation and Rayleigh number on PMV, PPD and I$_{IAQ}$ is discussed in the current section. It should be noted that the grid independency was checked by employing series of quadratic and uniform grids with high density mesh in regions where high gradients are expected. We put up several grids ranging from $176 \times 176$ to $216 \times 216$ for $Ra = 3.2 \times 10^9$. It was observed that there are no noticeable differences in the solutions when the number of cells is greater than $196 \times 196$-cells.

Figure 3 depicts the distribution of PMV index for different values of emissivity ($\varepsilon = 0.3$, 0.5 and 0.85). To compute the PMV index, the Mean Radiant Temperature (MRT) of space is handled following the relationship (3). The relative humidity, the levels of occupant activity and clothing are considered as a constant, i.e., 50%, 1.0 met and 1.0 clo, respectively. The convective heat transfer coefficient is also computed and considered in PMV index calculating.

$$MRT = \sqrt{\frac{1}{\varepsilon}}$$

From the results of figure 3, it is observed that near the upper and right vertical walls the thermal sensation is cool (PMV $\sim -2$) nay cold near the air inlet (PMV $\sim -3$) due to the flow of ventilation. Unlike the left side of the lower wall, the thermal sensation is rather hot (PMV $\sim 3$). This is induced by the thermal stratification caused by the heating. The lower part of the cavity presents an index of PMV that varies between -1 (slightly cool) and 1 (slightly warm). In the center of the cavity, it is found that the PMV is close to -1. According to ASHRAE [13], the comfort zone is defined as conditions falling within and including PMV levels from $-0.5 \leq PMV \leq 0.5$. Therefore, the obtained PMV does not comply with the recommendations of the ASHRAE standard 55 in the most of the occupied zone. This remains valid regardless of the emissivity value.

Figure 4 illustrates the distribution of PPD index with an emissivity ranging between 0.3 and 0.85. It is found that the PPD index is high ($> 10\%$) in the main part of the cavity. These results state that this cavity discords with the ISO 7730 standard recommendations, which advises a PPD lower than 10% for a comfortable thermal environment. This value corresponds to the range $-0.5 \leq PMV \leq 0.5$.

CO$_2$-concentration of 1000 ppm is used as a threshold to assess the IAQ. We note that good IAQ corresponds to an index I$_{IAQ}$ less than unity. The analysis of figure 5 shows that a good IAQ is insured inside the cavity, unless in lower left corner. Indeed, the fresh air is heated and charged on CO$_2$-contaminant as it passes near the bottom wall. Then, it branches to ascend to the upper part of the cavity. It is for this raiso that there is an important CO$_2$-concentration in this area (i.e., I$_{IAQ} > 1$).
Regarding the effect of surface radiation on thermal comfort, figures 3 and 4 state that there are slight changes on PMV and PPD only in the hot wall vicinity. This indicates that the radiant temperature variations related to the radiation are slight compared to the other parameters governing the fluid motion (i.e., velocity and temperature gradient). It should be noticed that the radiant temperature is a key parameter for the PMV index computation. Concerning IIAQ, no variation could be established with the increasing of the emissivity on the distribution of CO₂-contaminant (see figure 5). This means that the radiation contribution on fluid motion is negligible compared to the mixed convection, which is the main motor in this case.

![Figure 3. PMV index, (left) ε = 0.3, (middle) ε = 0.5, and (right) ε = 0.85 for Ra = 2.6×10⁹.](image)

![Figure 4. PPD index, (left) ε = 0.3, (middle) ε = 0.5, and (right) ε = 0.85 for Ra = 2.6×10⁹.](image)

![Figure 5. IIAQ index, (left) ε = 0.3, (middle) ε = 0.5, and (right) ε = 0.85 for Ra = 2.6×10⁹.](image)

![Figure 6. Indoor environment parameters, (top) Ra = 1.9×10⁹, (bottom) Ra = 3.2×10⁹ for ε = 0.85.](image)

To visualize the effect of Rayleigh number on thermal comfort and IAQ, the heating temperature has been decreased/increased by 5 K. The corresponding Rayleigh numbers are 1.9×10⁹ and 3.2×10⁹.
The emissivity of interior surfaces was taken equal to 0.85. The distributions of PMV, PPD and $I_{IAQ}$ are illustrated in figure 6. The obtained results show that the increasing of Rayleigh number leads a clear improvement of PMV and PPD. This means that the thermal stratification is improved. Regarding $I_{IAQ}$, it is observed a slight changes caused by the increasing of temperature gradient near the hot wall. This indicates that the movement of the fluid is accelerated implying a better CO$_2$ distribution.

5. Conclusions

Based on the obtained results, the following conclusions and recommendations can be drawn:

- The analysis of the effect of the emissivity on indoor environment quality exhibited that slight changes occur on PMV and PPD, but no variations on $I_{IAQ}$. This means that the contribution of radiation is low compared to the mixed convection which is the most motor of fluid motion in the case of this study;
- In terms of thermal comfort, the considered cavity does not comply with the recommendations of the ASHRAE standard 55 and the ISO 7730 standard;
- Regarding indoor air quality, the configuration provide an index of indoor air quality inferior to the unity, which means that an acceptable level of air quality is insured;
- From the influence of the heating temperature, it was found that the increasing of Rayleigh number enhances the indoor environment quality parameters;
- Finally, the considered mixing ventilation mode with the specified boundary conditions is unfavorable to maintain an acceptable thermal comfort. It seems interesting to study the influence of air inlet velocity and temperature, and test other scenarios of ventilation.

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