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Numerical investigation of transient heat and mass transfer by natural convection in a ventilated cavity: Outlet air gap located close to heat source

J. Serrano-Arellano [a,*], M. Gijón-Rivera [b], J.M. Riesco-Ávila [a], J. Xamán [c], G. Álvarez [c]

[a] Departamento de Ingeniería Mecánica, Universidad de Guanajuato, Carretera Salamanca-Valle de Santiago Km 3.5+1.8 Km, Comunidad de Palo Blanco, Salamanca, Gto. CP 36885, Mexico

[b] Tecnológico de Monterrey Campus Puebla, Vía Atlixcáyotl 2301, Reserva Territorial Atlixcayotl, Puebla, Puebla CP 72800, Mexico

[c] Centro Nacional de Investigación y Desarrollo Tecnológico, CENIDET-DGEST-SEP, Prol. Av. Palmira S/N. Col. Palmira, Cuernavaca, Morelos CP 62490, Mexico

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A transient numerical study of heat and mass transfer by turbulent natural convection of an Air–Carbon Dioxide mixture (CO_2) inside a ventilated cavity is presented. The working fluid is initially considered to be at rest at an initial temperature and concentration. The inlet air velocity is a function of the Reynolds number ($5 \times 10^2 \leqslant Re \leqslant 2 \times 10^4$) and constant CO_2 contaminant source between $1000 \leqslant C_H \leqslant 3000$ ppm is considered. The air inlet gap is located on the lower side of the right vertical wall of the cavity, whereas the air outlet is located on the right side of the upper wall. The transient governing equations of mass, momentum, heat and chemical species were solved by the finite volume method. From the results, it was found that temperatures and concentrations reached for $Re < 1 \times 10^3$ do not fulfill minimal Standards established by ISO 7730 and ASHRAE Standard 55–62, respectively. On the contrary, thermal and air quality parameters achieved for $Re = 1 \times 10^4$ satisfied all requirements in a time of 15 s.

1. Introduction

Heat and mass transfer phenomena have been deeply studied through years due to the continued presence of fluids in motion in nature. Heat and mass transfer by convection is usually presented in multiple engineering applications such as: building ventilation, drying processes, electronic cooling systems, nuclear plants, air conditioning systems, combustion engines, fires modeling, etc. In particular, building ventilation can be considered as the basic mechanism to remove heat and contaminants produced by people, equipment, and materials in exchange for providing of air fresh to the inside spaces with the aim of saving energy. Therefore, the knowledge on air movement in ventilated rooms is essential on the design of ventilation systems in order to reach acceptable indoor conditions in terms of temperature, air velocity and contaminants distribution.

On the other hand, it is important to note that human beings are the most important source of CO_2 inside buildings. Therefore, thermal and air quality appraisals considering Air–CO_2 mixtures as working fluids into buildings have to be deeply studied even for health care purposes. In this sense, it is well known that poor indoor air quality inside rooms has been linked to many physical and psychological problems such as eyes irritation, headaches, sore throats, skin hypersensitivity, tiredness, trouble concentration, respiratory problems (asthma), slumbering, among others. All these problems can produce low levels of productivity and diseases which commonly will be relieved as soon as the occupants leave the building or room [1]. Thus, good ventilation strategies can prevent and fix indoor air quality problems by fulfilling minimal requirements or Standards for acceptable indoor environments. In summary, performing transient analysis of ventilated rooms is necessary to predict contaminant removal rates and HVAC control runtimes for saving electricity consumption and healthier indoor spaces. The present study is focused on modeling a ventilated room as a cavity in transient state with different thermal and air quality conditions. A short review on heat and mass transfer in ventilated cavities in steady and unsteady state follows below.

Fang et al. [2] conducted a numerical and experimental study of the time-dependent hydrodynamic removal of a contaminated

* Corresponding author. Tel.: +52 (464) 64 7 99 40x2421; fax: +52 (464) 64 7 99 40x2311.

E-mail addresses: jserrano@cenidet.edu.mx (J. Serrano-Arellano), miguel.gijon@itesm.mx (M. Gijón-Rivera), riesco@ugto.mx (J.M. Riesco-Ávila), jxaman@cenidet.edu.mx (J. Xamán), gaby@cenidet.edu.mx (G. Álvarez).

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Nomenclature

C	concentration of chemical species, kg/m^3, ppm
C_∞	concentration of reference chemical species, kg/m^3, ppm
C_{inlet}	concentration of chemical species at the mixture inlet, kg/m^3, ppm
C_{outlet}	concentration of chemical species at the mixture outlet, kg/m^3, ppm
C_{source}	contaminant source of the chemical species, kg/m^3, ppm
Cp	specific heat of the air, J/kg K
Cp_m	specific heat of the conductive wall, J/kg K
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, C_μ	constants of the turbulence model
D_{AB}	diffusion coefficients of the chemical specie from A to B, m^2/s
g	acceleration due to gravity, m/s^2
h_{ext}	external convective heat transfer coefficient, W/m^2 K
H_i	aperture height at the mixture inlet, m
Hx	cavity width, m
Hy	cavity height, m
Le	Lewis number, $Le = \alpha/D_{AB}$
n	normal direction
P	fluid pressure, N/m^2
Pr	Prandtl number, $Pr = \upsilon/\alpha$
q	imposed heat flux on the exterior of the opaque wall, W/m^2
$q_{conv\text{-}ext}$	convection heat flux towards the exterior of the cavity, W/m^2
$q_{conv\text{-}int}$	convection heat flux towards the interior of the cavity, W/m^2
$q_{rad\text{-}ext}$	radiation heat transfer towards the exterior, W/m^2
Re	Reynolds number, $Re = (u_{inlet})(\rho)(H_i)/\mu$
$S\varphi$	source term
Sh	average Sherwood number
T	temperature, °C or K
$T_{average}$	average temperature of the mixture (Air–CO_2) inside the cavity, °C
T_m	temperature of the conductive wall, °C
T_{inlet}	temperature of the mixture (Air–CO_2) at the inlet, °C
T_{outlet}	temperature of the mixture (Air–CO_2) at the outlet, °C
u	velocity in the horizontal direction, m/s
u_{inlet}	velocity in the horizontal direction at the inlet, m/s
v	velocity in the vertical direction, m/s
W_m	thickness of the opaque wall, m
x, y	coordinate x or y
Greeks	
α	thermal diffusivity, m^2/s
β	coefficient of thermal expansion, $\beta = 1/T_{prom.}$, K^{-1}
β_C	coefficient of concentration expansion, $\beta_C = 1/C_{prom.}$ (kg/m^3)$^{-1}$
Γ	diffusion coefficient
ε^*	emissivity
ε	rate of dissipation of turbulent kinetic energy, m^2/s^3
$\bar{\varepsilon}_t$	overall effectiveness coefficient for temperature distribution
$\bar{\varepsilon}_C$	overall effectiveness coefficient for contaminant distribution
κ	turbulent energy kinetic, m^2/s^2
λ	thermal conductivity of the mixture (Air–CO_2), W/m K
λ_m	thermal conductivity of the conductive wall, W/m K
μ	dynamic viscosity of the mixture (Air–CO_2), kg/m s
μ_t	turbulent viscosity
υ	kinematic viscosity of the mixture (Air–CO_2), m^2/s
ρ	density of the mixture (Air–CO_2), kg/m^3
σ	Stefan–Boltzmann constant, 5.67×10^{-8}, W/m^2 K^4
σ_t	turbulent Prandtl number
ϕ	dependent general variable (u, v, P, T)

fluid from a cavity on the floor of duct. The Reynolds number under study was between 50 and 1600. The study was focused on the convective transport of the contaminated fluid out from the cavity and the effect of duct flow acceleration on the cleaning process. The results showed that the cleansing of the cavity was more pronounced during the unsteady start-up of the duct flow and the rate of cleaning decreases as the flow reached a steady state. A continuation of this numerical study [3] showed that that the change in Grashof number causes a dramatic difference in the observed flow patterns and cleaning efficiency. Later, Papakonstantinou et al. [4] reported a numerical study of the prediction of carbon monoxide (CO) concentration inside a typical garage in Athens urban area. The study focused on identifying the appropriate ventilation system for an adequate indoor air quality (with and without mechanical ventilation). The results of the simulation were compared with experimental measurements on the CO level inside garage. They showed that under the proper ventilation conditions the levels of CO concentration decrease and remain below the health based indoor air quality criteria. In 2004, Zhaoa et al. [5] conducted a 3-D numerical study in order to propose a uniform parameter: integrated accessibility of contaminant source (IACS). This parameter combines the accessibility of contaminant source (ACS) and occupied density (OD) to protect indoor environment. The results showed that ACS is a distributed index to scale the accessibility of suddenly released contaminant indoors in a finite period of time. By the IACS analysis in this study, displacement ventilation was more effective than mixing ventilation. Tian et al. [6] conducted a numerical study of particles concentration in the air flow inside a room, for which they used three models of turbulence: the $k-\varepsilon$ model, the re-normalized $k-\varepsilon$ model (RNG) and the large eddy simulation (LES). The CFD computational model was solved using FLUENT. The results were compared to those reported in literature. The authors concluded that the three models have a good agreement with experimental data, but the best result was obtained with the simulation performed by LES. Chang et al. [7] investigated a three-dimensional flow in a cavity using large-eddy simulation (LES), the study included laminar and turbulent regimes (Re = 3360). The results showed that laminar inflow case becomes unstable but remains laminar as it is convected over the cavity. For turbulent inflow case the fluctuation of the shear layer on top of the cavity by the incoming near-wall coherent structures strongly influences the formation and convection of the eddies inside the separated shear layer. Brahim and Taieb [8] conducted an unsteady double diffusive mixed convection study based on the steady study of Qi-Hong et al. [9]. The buoyancy ratio was constant with the value of 1. The results showed that the period of oscillations decreases whereas the main heat and transfer rates increase monotonously with increasing Gr. Other result was that the average Nusselt number for periodic flow is shown to be higher than that of steady case. In 2008, Liu et al. [10] carried out a study in order to remove two contaminants from a three dimension cavity with an inlet and outlet flow; the purpose of the study was to identify an adequate air conditioning system that provides a comfortable environment at the lowest energy cost. Inside the cavity, a contaminant source emitting two contaminants carbon dioxide (CO_2) and formaldehyde (HCHO) was located at the center. The