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On thermal control of devices contained in inclined hemispherical cavities with dome oriented downwards and subjected to transient natural convection ☆

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ABSTRACT

In this study, relationships of Nusselt–Rayleigh–Fourier type are proposed for the case of air-filled hemispherical cavity whose dome is oriented downwards and maintained isothermal. Its disk is subjected to a constant heat flux and inclined at an angle varying between 90° (vertical position) and 180° (disk horizontal with dome oriented downwards). The numerical approach is performed in transient regime by means of the finite volume method for Rayleigh numbers in the range of $10^4 - 5 \times 10^8$. These results are confirmed at steady state by measurements done for some configurations in a previous study for the same Rayleigh and inclination ranges. Otherwise, they complete other surveys considering inclination angles varying between 0° (horizontal cavity with dome oriented upwards) and 90° (vertical cavity) for a wider range of Rayleigh numbers. The correlations allow thermal control of devices submitted to natural convection in hemispherical cavities during the time preceding the steady state after their switch on.

1. Introduction

Various devices are used for the automatic operation (OK) of different systems in many engineering domains. Some of them are programmed while others are actuated by a human presence via a control chain often using passive infrared detection sensors. The recent study of Nguyen and Aiello [1] is devoted to these aspects in the field of building. Several systems including these detectors exist, with different geometries according to their destination. Some devices are hemispherical, constituted by a disk covered with a dome. These systems are increasingly used for controlling various systems requiring different power levels for lighting, audio warning, opening shutters, ventilation, starting of the domestic boiler or air conditioning,… There is no work in the literature to quantify the transient convective exchanges that occur in these hemispherical cavities. However, other geometries have been studied. Ben Baya and Lili [2] examine numerically the influence of the inclination angle on the transient convective heat transfer occurring in a cubic cavity (3D), for wide ranges of Rayleigh and Prandtl numbers. Influence of this angle is treated with a 2D model by Basak et al. [3] at steady state. The case of parallelogrammic enclosures is considered at steady state by Hussein [4] and Costa [5]. Some transient aspects are examined for this geometry by Baïri [6] and Baïri et al. [7], leading to Nusselt–Rayleigh–Fourier type correlations. The case of triangular enclosures is treated by Oztop et al. [8] while heat transfer concerning a disk cooled by means of inclined circular jet is considered by Oztop et al. [9]. The annular cavity is treated with a numerical approach by Fu et al. [10] by adopting the SIMPLE-R with a powerlaw scheme. The work shows a similarity with the case of rectangular cavities for some aspects. The influence of nanofluids has been studied by Yu et al. [11] for transient natural convection occurring in a differentially heated square cavity, at some Rayleigh numbers and nanoparticles volume fractions.

In almost all the existing systems considering hemispherical cavities, the disk is connected to a chain of electronic and electric power device which is disposed outside the cavity. This is not the case for the hemispherical air-filled cavity considered in this work since the disc constitutes itself the power device and so it is itself the active part of the assembly.

2. The treated case. Procedure and results

This disk of radius R is covered by a transparent passive dome. This assembly shown schematically in Fig. 1 is intended to control the devices. It is switched on when the IR sensor installed in the centre of the disk detects the presence of a person.

In the numerical approach, the dome is maintained isothermal at temperature T_c. The disk may be inclined at an angle varying between 90° (vertical position) and 180° (disk horizontal with dome oriented downwards) according to the detection zone for the envisaged application. Switching on the system following detection causes the heating of

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Nomenclature

a	thermal diffusivity of the air ($\mathrm{m^2\,s^{-1}}$)
$c_{\alpha,\,Ra}$	exponent of Fourier number in Eq. (5) for a combination (α, Ra) (−)
c_α	exponent of Fo in Eq. (7) (−)
$\overline{c_\alpha}$	average value of $c_{\alpha,\,Ra}$ (−)
C_p	specific heat at constant pressure ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
Fo	Fourier number (−)
g	acceleration of the gravity ($\mathrm{m\,s^{-2}}$)
$k(\alpha)$	coefficient of the correlations $\underline{\underline{\overline{Nu}}}_\alpha = k(\alpha)Ra^{n(\alpha)}$ (−)
m	number of elements on the inner face of the disk (−)
$n(\alpha)$	exponent of Ra in the correlations $\underline{\underline{\overline{Nu}}}_\alpha = k(\alpha)Ra^{n(\alpha)}$ (−)
$\overline{Nu}_\alpha$	average transient Nusselt number at the disk from Eq. (7) (−)
$\overline{Nu}_{\alpha\ ,Ra}$	average transient Nusselt number at the disk for a combination (α, Ra) (−)
$\underline{\underline{\overline{Nu}}}_\alpha$	average steady state Nusselt number at the disk for an angle α (−)
R	radius of the disk/dome (m)
Ra	Rayleigh number (−)
S_h	total area of the hot wall ($\mathrm{m^2}$)
S_i	area of the ith element of the hot wall ($\mathrm{m^2}$)
t	time (s)
T_i	temperature of the ith element of the hot wall (K)
T_c, T_h	temperature of the cold (dome) and hot (disk) walls respectively (K)
$\overline{T_h}$	average temperature of the disk (K)
T^*	dimensionless temperature (−)

Greek symbols

α	inclination angle of the cavity (°)
β	volumetric expansion coefficient of the air ($\mathrm{K^{-1}}$)
δ	deviation between $\overline{c_\alpha}$ and c_α according to Eq. (6) (%)
φ	heat flux imposed to the disk ($\mathrm{Wm^{-2}}$)
λ	thermal conductivity of the air ($\mathrm{Wm^{-1}\,K^{-1}}$)
μ	dynamic viscosity of the air (Pa s)
ρ	density of the air ($\mathrm{kg\,m^{-3}}$)

the disk and produces a superficial heat flux φ assumed as uniform. Local and average temperatures of its inner face are denoted by T_h and $\overline{T_h}$ respectively. The aerothermal phenomena occurring in the cavity depend on several physical parameters including φ, R and air thermophysical characteristics. The inclination angle of the disk α has also a significant effect on the heat transfer. Knowledge of natural convective heat exchange in the cavity is necessary for the thermal control of the disk and its correct operation in steady state and during the transient state following its switching on. It is indeed essential to characterize the device to comply with the technical recommendations of the manufacturer of the electronic and electrical components. For example it is important to ensure that the maximum temperature reached during operation in extreme conditions does not exceed the limit value beyond which the system may be inoperative or permanently destroyed.

The numerical approach is performed in transient regime by means of the finite volume method for Rayleigh numbers Ra in the range 10^4 — 5×10^8, corresponding to the envisaged applications. Calculated results are confirmed at steady state by measurements done for some configurations in the numerical and experimental study [12] considering the same Ra and α ranges. They complete other results obtained in [13] at steady state for $0° \le \alpha \le 90°$ and $10^4 \le Ra \le 5 \times 10^7$, and in transient regime in [14] for $10^4 \le Ra \le 3.2 \times 10^{11}$. An almost complete literature review on natural convective heat exchange in this type of cavity as well as the theoretical aspects of the problem treated in the present survey is available in [13]. The governing equations are solved in transient regime by considering the terms corresponding to the temporal derivatives in the continuity, momentum and energy equations. Convective heat transfer is laminar in all the treated range $10^4 \le Ra \le 5 \times 10^8$. Radiation is not considered by imposing a zero global IR emissivity on all the internal surfaces of the cavity. The unstructured mesh consists of triangular and tetrahedral elements on the walls and in the fluid volume respectively. The internal face of the disk whose surface is denoted by S_h is discretized into m elements whose exchange surfaces and temperatures are denoted by S_i and $T_i (i = 1, m)$ respectively. The entire domain is considered to be initially isothermal at the lower temperature T_c, air is assumed as incompressible, the Boussinesq approximation is applied and the no-slip boundary condition is assumed. The numerical code used in this work is the commercial software Fluent-Ansys [15] in combination with the SIMPLE algorithm, complemented by codes developed in LTIE laboratory. The Rayleigh and Fourier numbers based on the radius of the cavity are defined by

$$Ra = \frac{g\beta R^4 \rho}{\mu\lambda a}\varphi; Fo = \frac{at}{R^2} \tag{1}$$

In these equations, $a = \lambda/\rho C_p$ is the thermal diffusivity and t is the time, equal to zero at the beginning of the transient regime, corresponding to the switching on of the device (disk). The volumetric expansion coefficient of the air is calculated through $\beta = \left[\left(\overline{T_h} + T_c\right)/2\right]^{-1}$. The Ra value is implicitly affected by the inclination angle α through the the disk temperature distribution and its average temperature $\overline{T_h}$. Dimensionless transient temperature of the ith element of the disk calculated with

$$T_i^* = (T_i - T_c)/\left(\frac{\varphi}{\lambda/R}\right); \quad i = 1, m \tag{2}$$

allows determination of the local transient Nusselt number. The average transient Nusselt number $\overline{Nu}_{\alpha\ ,Ra}$ concerning a particular combination (α, Ra) is then calculated with

$$\overline{Nu}_{\alpha\ ,Ra} = \left[\frac{1}{S_h}\iint_{S_h} T_i^* dS_i\right]^{-1} \tag{3}$$

whose steady state value $\underline{\underline{\overline{Nu}}}_\alpha$ obtained at the end of the transient regime can be determined by means of the Nusselt–Rayleigh type correlations

$$\underline{\underline{\overline{Nu}}}_\alpha = k(\alpha)Ra^{n(\alpha)}$$
$$\text{being } \underline{\underline{\overline{Nu}}}_{180^\circ} = 1\left(\text{for } \alpha = 180^\circ\right)$$
$$\text{and}$$
$$\begin{cases} k(\alpha) = 63\times10^{-8}(\alpha-90)^3 - 78\times10^{-6}(\alpha-90)^2 + 7\times10^{-4}(\alpha-90) + 0.4334 \\ n(\alpha) = -3\times10^{-7}(\alpha-90)^3 + 2\times10^{-5}(\alpha-90)^2 - 5\times10^{-4}(\alpha-90) + 0.2154 \end{cases}$$
$$\text{for } 90^\circ \le \alpha \le 170^\circ \tag{4}$$

proposed in [12], valid for $10^4 \le Ra \le 5 \times 10^8$. This steady state value is linked to the transient one through the Fourier number with the expression

$$\overline{Nu}_{\alpha,Ra} = \underline{\underline{\overline{Nu}}}_\alpha Fo^{c_{\alpha,Ra}} \tag{5}$$

Several calculations were performed for various combinations (α, Ra) in the ranges $90° \le \alpha \le 180°$ step 10° and $10^4 \le Ra \le 5 \times 10^8$. Evolution of $\mathrm{Ln}\left(\overline{Nu}_{\alpha,\ Ra}/\underline{\underline{\overline{Nu}}}_\alpha\right)$ versus $\mathrm{Ln}(Fo)$ is presented in Fig. 2 for four representative angles α = 90°, 120°, 150° and 180° and seven specific Ra values stated in this figure. Slopes $c_{\alpha,\ Ra}$ corresponding to Fo