International Communications in Heat and Mass Transfer 59 (2014) 174–177

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

A synthesis of correlations on quantification of free convective heat transfer in inclined air-filled hemispherical enclosures ☆

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ARTICLE INFO

Available online 23 October 2014

Keywords:
Steady state and transient natural convection
Nu–Ra–Fo correlations
Nu–Ra correlations
Hemispherical cavity
Thermal engineering
Wide Rayleigh number range
Neumann and Dirichlet thermal boundary condition

ABSTRACT

Recent works have examined the thermal and dynamical aspects of natural convection occurring in tilted hemispherical cavities whose disk constitutes the hot active wall. The influence of some important aspects on the natural flows have been considered such as the Rayleigh Number, the disk inclination angle with respect to the horizontal plane and the thermal boundary condition on the disk (Dirichlet, Neumann). Combinations of these parameters have been treated in steady state as well as is transient regime. Correlations of Nusselt–Rayleigh type (steady state) and Nusselt–Rayleigh–Fourier type (transient regime) that allow quantifying the heat transfer are proposed in these surveys. The objective of this paper is to synthesize and summarize these works in order to facilitate their implementation in engineering applications.

1. Introduction

The aim of the present review is to synthesize the results obtained in the recent works [1–10] dealing with the quantification of the convective heat transfer occurring in hemispherical enclosures as sketched in Fig. 1(a). The notations and symbols adopted for all the parameters involved in these papers are unified in order to facilitate their implementation in engineering applications. Only the data needed for the understanding of this synthesis will be presented. Details of the numerical and experimental approaches as well as the procedure adopted to establish the correlations are available in the corresponding papers.

The hemispherical cover (dome) of radius R is maintained isothermal at temperature T_c. The circular base (disk) constituting the hot active wall is thermally insulated on the external face. Its internal area may be subjected to one of two typical thermal boundary conditions (i) maintained at constant temperature $T_h > T_c$ (Dirichlet condition) or (ii) subjected to a uniform heat flux φ (Neumann condition), depending on the intended application. The disk can be inclined with respect to the horizontal plane at an angle α varying between 0° (horizontal disk with dome upwards) and 180° (horizontal disk with dome downwards), $\alpha = 90°$ being the vertical position. Some positions are represented in Fig. 1(b). The numerical as well as the experimental approaches are done in both steady state and transient regimes. For this last case, the entire system (dome, disk, air) as well as the ambient external environment are initially at the lowest temperature T_c. The disk is then suddenly subjected to one of the two thermal boundary conditions presented above.

2. The Rayleigh range and some applications

Depending on the considered thermal boundary condition, two definitions are adopted for the Rayleigh Number, both based on the radius R, expressed as

$$Ra_{\varphi} = \frac{g\beta R^4 \rho}{\mu\lambda a}\varphi; Ra_T = \frac{g\beta R^3 \rho}{\mu a}(T_h - T_c) \quad (1)$$

for the Neumann and Dirichlet-type condition respectively.

The combination of the radius R with the temperature difference $(T_h - T_c)$ or the heat flux φ lead, for the most known applications, to a wide Rayleigh Number range, varying between about 10^4 and 10^{15} depending on the considered application area. The larger values concern the nuclear techniques where the hemispherical enclosures can constitute the cover plants (EPR case with dome upwards, $\alpha = 0°$) or the reactor basin (dome downwards, $\alpha = 180°$). Building is also concerned by such large Rayleigh values. The upwards-facing dome has indeed inspired many architects and obviously smart thermal and civil Engineers (Iken). This is highlighted by the cupolas and domes of various monuments such as those of the Academy, the Pantheon, the Val-de-Grâce or the Hôtel des Invalides in Paris. This is the case for igloos which present the well-known thermal properties suitable for the environment in which they are installed. Large Rayleigh numbers also concern solar stills whose horizontal disk constituting the absorber is covered with a transparent dome in which a greenhouse effect takes place. Some solar thermal collectors are equipped with a hemispherical transparent cover, the absorber disk being installed on a horizontal or inclined plane. Lighting techniques involving projectors for spectacle plateaux as well as for roads and monuments lighting, sometimes

☆ Communicated by W.J. Minkowycz

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2014.10.013
0735-1933/

Nomenclature

a	thermal diffusivity ($m^2\ s^{-1}$)
$C_\varphi(\alpha)$	exponent of Fo in $\overline{\overline{Nu}}_\varphi(\alpha)Fo^{C_\varphi(\alpha)}$ for Neumann condition (–)
$C_T(\alpha)$	exponent of Fo in $\overline{\overline{Nu}}_T(\alpha)Fo^{C_T(\alpha)}$ for Dirichlet condition (–)
C_p	specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
Fo	Fourier number (–)
g	gravity acceleration ($m\ s^{-2}$)
$k_\varphi(\alpha)$	coefficient of the correlation $\overline{\overline{Nu}}_\varphi(\alpha) = k_\varphi(\alpha)Ra_\varphi^{n_\varphi(\alpha)}$ (–)
$k_T(\alpha)$	coefficient of the correlation $\overline{\overline{Nu}}_T(\alpha) = k_T(\alpha)Ra_T^{n_T(\alpha)}$ (–)
$n_\varphi(\alpha)$	exponent of Ra_φ in the correlation $\overline{\overline{Nu}}_\varphi(\alpha) = k_\varphi(\alpha)Ra_\varphi^{n_\varphi(\alpha)}$ (–)
$n_T(\alpha)$	exponent of Ra_T in the correlations $\overline{\overline{Nu}}_T(\alpha) = k_T(\alpha)Ra_T^{n_T(\alpha)}$ (–)
$\overline{\overline{Nu}}_\varphi(\alpha)$	average steady state Nusselt number on the disk for Neumann condition (–)
$\overline{\overline{Nu}}_T(\alpha)$	average steady state Nusselt number on the disk for Dirichlet condition (–)
$\overline{Nu}_\varphi(\alpha)$	average transient Nusselt number on the disk for Neumann condition (–)
$\overline{Nu}_T(\alpha)$	average transient Nusselt number on the disk for Dirichlet condition (–)
R	radius of the cavity (m)
Ra_φ, Ra_T	Rayleigh number for Neumann and Dirichlet condition respectively (–)
$Ra_{\varphi L}$, $Ra_{\varphi C}$	Rayleigh number delimiting the transitional heat transfer for Neumann condition (–)
Ra_{TL}, Ra_{TC}	Rayleigh number delimiting the transitional heat transfer for Dirichlet condition (–)
t	time (s)
T_c	dome (cold wall) and ambient environment temperature (K)
T_h	internal face temperature of the disk (hot wall) (K)

Greek symbols

α	disk inclination angle (°)
β	volumetric expansion coefficient (K^{-1})
φ	heat flux imposed to the disk for Neumann condition (Wm^{-2})
λ	thermal conductivity ($Wm^{-1}\ K^{-1}$)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
θ	angle ($\alpha - 90$) (°)

involve significantly high power leading to large Rayleigh number values. Food, chemical and petroleum industries use also such hemispherical enclosures for different applications (storage of various products, chemical reactors, …). The smaller Rayleigh number values concern the instrumentation used to measure the solar irradiation. Global solar components are measured by means of pyranometers that are installed either horizontally or on inclined planes depending on the intended application. Other components of solar and terrestrial irradiation are measured by means of instruments using these hemispherical enclosures (albedometer, pyrgeometer, pyrradiometer). It is also the case in the safety and security field where hemispherical enclosures are often used as sensors to control various devices, in lighting and electrical industry (beacons, light bulbs, lamps, ...); in electronics (some electronic components), electronic assemblies enclosures; in aeronautics (embarked elements), … In these applications, the maximum Rayleigh number values are generally associated with inclinations $0° \le \alpha \le 90°$ while the $90° \le \alpha \le 180°$ range often concern lower Rayleigh Number values. The ranges considered in the works of this synthesis reach 3.2×10^{11} and even 2.55×10^{12} for $0° \le \alpha \le 90°$, and they are limited to 5×10^8 for $90° \le \alpha \le 180°$.

3. Correlations

The correlations obtained in studies [1–10] are presented in the single Table 1.

3.1. Steady state

The average convective heat transfer on the disk can be calculated by means of correlations of $\overline{\overline{Nu}}_\varphi(\alpha) = k_\varphi(\alpha)Ra_\varphi^{n_\varphi(\alpha)}$ type for the Neumann condition denoted as (N) and $\overline{\overline{Nu}}_T(\alpha) = k_T(\alpha)Ra_T^{n_T(\alpha)}$ type for the Dirichlet condition, denoted as (D). All the results are presented in the upper part of Table 1 where the Rayleigh Number ranges are specified for all the disk inclination angle values and the corresponding boundary conditions. These results identify three specific heat transfer zones corresponding to particular trends of $\overline{\overline{Nu}}_\varphi(\alpha)$ and $\overline{\overline{Nu}}_T(\alpha)$:

(i) laminar $10^4 \le Ra_\varphi \le Ra_{\varphi L}$ (N) and $10^4 \le Ra_T \le Ra_{TL}$ (D);
(ii) transitional $Ra_{\varphi L} \le Ra_\varphi \le Ra_{\varphi C}$ (N) and $Ra_{TL} \le Ra_T \le Ra_{TC}$ (D);
(iii) turbulent $Ra_{\varphi C} \le Ra_\varphi \le 2.55 \times 10^{12}$ (N) and $Ra_{TC} \le Ra_T \le 2.55 \times 10^{12}$ (D).

The values of $Ra_{\varphi L}$, $Ra_{\varphi C}$, Ra_{TL} and Ra_{TC} corresponding to these ranges clearly depend on the inclination angle α. They increase systematically with increasing α for both boundary conditions. The transitional and turbulent zones systematically begin at Rayleigh numbers greater for the (N) condition. However, direct comparison of these Rayleigh Number values must be made carefully. They are largely based on the air thermophysical characteristics, which are evaluated at the mean temperature and associated to not negligible uncertainties.

3.2. Transient regime

The average convective heat transfer on the disk during the transient regime can be calculated by means of $\overline{Nu}_\varphi(\alpha) = \max\left[\overline{\overline{Nu}}_\varphi(\alpha), \overline{\overline{Nu}}_\varphi(\alpha)Fo^{C_\varphi(\alpha)}\right]$ correlations for the Neumann condition

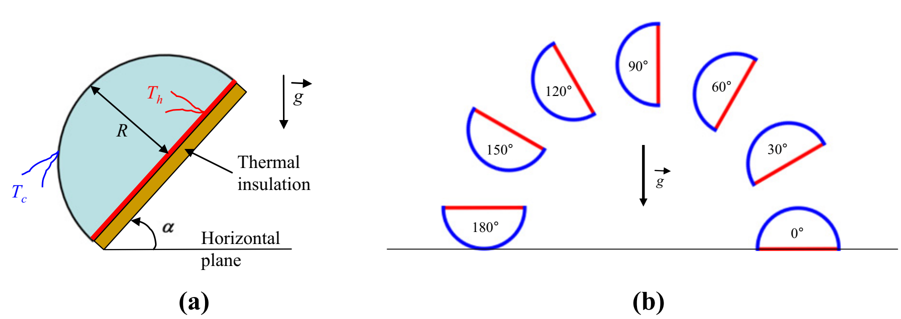

Fig. 1. (a) the considered enclosure (b) some configurations.