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Natural convection heat transfer from a finned sphere

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ABSTRACT

Natural convection heat transfer from a finned sphere has been studied numerically in both laminar ($10^5 \leqslant Ra \leqslant 10^8$) and turbulent ($10^{10} \leqslant Ra \leqslant 10^{12}$) regimes. Computations are done for the Nusselt number (*Nu*) by varying the fin-height-to-sphere-diameter ratio (H/D) and the fin-pitch-to-sphere-diameter ratio (P/D) in the range of 0.017–0.200 and 0.131–0.393 respectively. Five different turbulence models have been used to compute the mean Nusselt number for some cases and for the purpose of developing a general correlation for the *Nu* from our computed results we have used the k–ε model. The numerical procedure has been verified first by comparing the numerically obtained Nusselt number for a simple sphere (without fins) with that of the given correlations from the literature. For the sphere having conductive (Al) fins, with increasing number of fins, *Nu* decreases for laminar heat transfer and increases for turbulent heat transfer. For the sphere having non-conductive fins, *Nu* decreases with increasing number of fins in both laminar and turbulent heat transfer. Also, *Nu* increases with increasing fin height for conductive fins over the sphere and decreases for non-conductive fins. Finally, correlations of Nusselt number for natural convective heat transfer from a finned sphere are developed with the pertinent input parameters like *Ra*, P/D and H/D in the range stated above.

1. Introduction

Natural convection is a convenient, noise free and inexpensive way of cooling a hot surface by an adjoining fluid [1]. Several attempts have been made to analyze the natural convection over a sphere because of its theoretical interest and practical applications such as vapourization and condensation of fuel droplets, heat transfer in manufacturing systems (packed beds of spherical bodies), spherical storage tanks, spray drying, nuclear reactor design, solar energy collectors, and in many electrical and electronic components [2–8]. Numerous analytical, numerical and experimental investigations have been conducted on natural convection heat transfer from isothermal spheres. The pertinent experimental studies of heat transfer by natural convection from a sphere are given by Elenbaas [9], [10], Bromham and Mayhew [11], Kranse and Schenk [12], Amato and Tien [13], etc. Some early analytical studies were carried out by Merk and Prins [14–16], Chiang et al. [17], Potter and Riley [18], and Jafarpur and Yovanovich [6] for high Grashof number (*Gr*) cases using boundary layer assumption. However, the limiting cases of very low *Gr* were solved by using asymptotic expansion techniques by Fendell [19] and Singh and Hasan [20]. Numerical solution for the natural convection heat transfer over a sphere in air ($Pr = 0.72$) was first reported by Geoola and Cornish [21]. They have reported the local and overall Nusselt numbers for Grashof number in the range of $0.05 \leqslant Gr \leqslant 50$. In addition, temperature and streamline contours were also presented. In their subsequent paper [22], the study was extended to find transient Nusselt number for $Pr = 10$ and $Pr = 100$ while increasing the range of *Gr* to 12500. Jia and Gogos [2], [23] provided a numerical solution for steady-state and transient natural convection over a sphere for a wide range of Grashof numbers ($10^1 \leqslant Gr \leqslant 10^8$) and Prandtl numbers 0.72 and 7.0. In a more recent study by Yang et al. [3], transient results have been obtained for Grashof numbers in the range of $10^5 \leqslant Gr \leqslant 10^9$ and a wide range of Prandtl numbers ($Pr = 0.02$, 0.7, 7 and 100). Based upon a collection of theoretical and experimental results, Campo [7] proposed a correlation for calculating *Nu* for natural convection from spheres in both laminar and turbulent flow regimes. Churchill [8] also gave a correlation by collating a large literature data for free convection from spheres. Thus, there is a vast collection of analytical, numerical and experimental studies to estimate the average Nusselt number over a sphere in natural convection in both laminar and turbulent regimes.

The heat transfer by natural convection can be substantially increased by making use of heat sinks of various shapes. Several investigators have focused on natural convection heat transfer by heat sinks from cylinders and vertical plates. Haldar [1] reported

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Nomenclature

A	area, m^2
D	diameter, m
g	acceleration due to gravity, m s^{-2}
Gr	Grashof number, dimensionless
h	average heat transfer coefficient, W m^{-2} K^{-1}
H	fin height, m
k	thermal conductivity, W m^{-1} K^{-1}
Nu	average Nusselt number, dimensionless
Nu_{cf}	average Nusselt number for a sphere having conductive fins
Nu_{ch}	average Nusselt number for an unfinned sphere based on correlations by Churchill [8]
Nu_{nf}	average Nusselt number for a sphere having non-conductive fins
Nu_{sph}	average Nusselt number for an unfinned sphere
Nu_{θ}	local Nusselt number, dimensionless
P	fin pitch, m
p	pressure, N m^{-2}
Pr	Prandtl number
Q	total convective heat transfer, W
R	radius, m
Ra	Rayleigh number, dimensionless
t	thickness of fin, mm
T_{∞}	ambient temperature, K
T_f	mean film temperature, K
T_s	sphere surface temperature, K
v	velocity, m s^{-1}
x	axial coordinate direction
y	radial coordinate direction

Greek symbols

α	thermal diffusivity, m s^{-2}
β	thermal expansion coefficient, K^{-1}
θ	position on the surface of the sphere, deg
μ	dynamic viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, m s^{-2}
ρ	density, kg m^{-3}

a numerical solution of laminar free convection of air around a horizontal cylinder with external longitudinal fins. An et al. [24] proposed a correlation for estimating the Nusselt number for natural convection from cylinders with vertically oriented plate fins. Free convective heat transfer from rectangular fins on a vertical base was investigated experimentally by Yazicioğlu and Yüncü [25]. In a more recent numerical study of natural convection, Cao [26] evaluated the influence of fin spacing on the power of heat sink and heat dissipation. Kim et al. [27] experimentally investigated the heat sinks with vertically oriented plate-fins.

A spherical light source is shown in Fig. 1. The most important goal of thermal design of the lighting devices is to ensure that the temperature of the device stays at a low level [28,29]. The addition of fins around a light source will serve the dual purpose of increasing the heat transfer to the surroundings and the beautification of the light source. Fig. 2 shows some possible light sources with different fin-pitch-to-sphere-diameter ratios that can be used as

Fig. 1. Spherical light source.

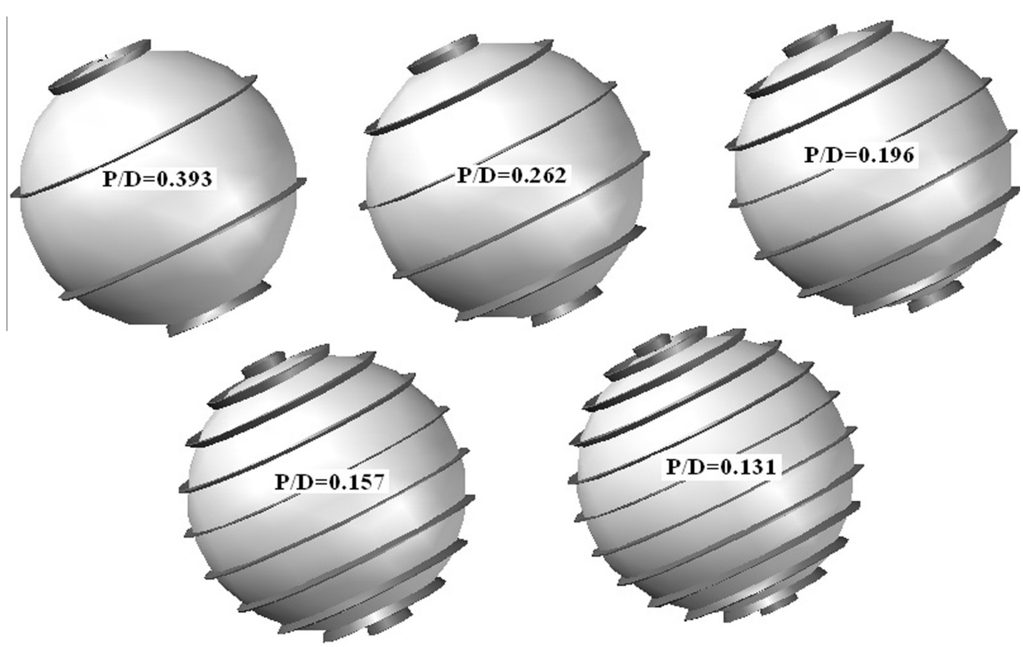

Fig. 2. Pictures of possible light sources with fins having H/D = 0.033.