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Numerical investigation of natural convection heat transfer from vertical cylinder with annular fins

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ABSTRACT

Natural convection heat transfer from a vertical cylinder with annular fins has been studied numerically by varying the Rayleigh number (Ra) in both laminar ($10^4 \le Ra \le 10^8$) and turbulent ($10^{10} \le Ra \le 10^{12}$) regimes. The computations were carried out by varying the fin to tube diameter ratio (D/d), fin spacing to tube diameter ratio (S/d) in the range of 2–5 and 0.126–5.840 respectively. In the present study, numerical simulations of full Navier-Stokes equation along with the energy equation have been conducted for a vertical cylinder with annular fins of constant thickness using the algebraic multi-grid solver of FLUENT 15. Optimization study of the conjugate heat transfer characteristics has been carried out to find the best fin spacing for maximum heat transfer for the turbulent flow. With the addition of fins to the heated isothermal tube surface, heat transfer goes on increasing for laminar flow and turbulent flow heat transfer first increases and gets a maximum value then starts to decrease. The optimum fin spacing for maximum heat transfer for the cases of turbulent flow varies between $S/d = 0.28$ to 0.31 (7.0 mm –7.7 mm) for the turbulent regime. The effect of parameters like D/d, S/d and Ra on Nu are analyzed, and correlations for average Nusselt number has been developed for both laminar and turbulent regimes.

1. Introduction

Among the cooling methods of natural convection and forced convection, natural convection systems are convenient and inexpensive due to lack of any extra components. The inherent advantage of using a natural convection cooling systems arise out of not having any additional components which make the system free of extra moving parts, and no further designing of the cooling system may be needed. Lack of spare parts makes the operation of the system noise-free and free of any extra maintenance. However, the main shortcoming of such a natural convection based cooling system is that the rate of heat transfer achieved is quite small as explained by Bejan [1] and Kreith et al. [2]. Use of fins is one of the simplest ways of overcoming this shortcoming of low heat transfer rates while keeping the system noise-free and maintenance-free. Use of fins to enhance heat transfer was extensively studied by Guvenc and Yuncu [3] and Yazicioglu and Yuncu [4].

The shape of the fin is an important consideration for heat transfer enhancement since the entire surface of the fin may not be equally effective. Hence, the basic job of the designers is to improve the rate of heat transfer by effectively designing the fins. One has to consider factors such as the shape of the primary surface, application of the system and location of the system to design efficient fins. Use of natural convection systems with fins are quite large in number which includes heat exchangers, cooling of electronic components, internal and external combustion engines, annular finned heat sinks, utilization of natural circulation for energy storage systems for space heating (e.g. baseboard heating), air cooling systems for air conditioning and refrigeration. For a cylindrically shaped primary surface, one of the most popular choices among shape of fins to enhance the rate of heat transfer are annular fins because of their inherent ease of manufacturing and also simplicity in the analysis due to radial symmetry.

There is plenty of existing literature in the field of natural convection heat transfer which includes Churchill and Chu [5] and Churchill [6], where the authors experimentally developed a correlation for average Nusselt number as a function of Rayleigh number and Prandtl number for natural convection from the horizontal cylinder and vertical flat plate respectively. Relevance of the study of natural convection over a vertical flat plate while considering natural convection over vertical cylinder comes due to the fact that a vertical cylinder (at least for thick cylinder) may be

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Nomenclature

A	area of convection surface, m^2
A_{fin}	area of annular circular fin, m^2
d	diameter of horizontal cylinder, mm
D	fin diameter, mm
D/d	fin-to-tube diameter ratio
e	Linear eccentricity, mm
g	acceleration due to gravity, m/s^2
h	average heat transfer coefficient, W/m^2-K
k	thermal conductivity of fin material, W/m-K
L	length of the horizontal cylinder, mm
N_{fin}	number of fins
Nu	average Nusselt number
p	pressure, N/m^2
p_{atm}	atmospheric pressure, N/m^2
Q	convection heat transfer, W
R	Specific gas constant, J/kg K
Ra	Rayleigh number
R_{fin}	fin radius, mm
S	inter-fin spacing, mm
S_{opt}	optimum fin spacing for maximum heat transfer, mm
S/d	fin spacing to tube diameter ratio or non-dimensional fin spacing
$(S/d)_{opt}$	optimum fin spacing to tube diameter ratio for maximum heat transfer
t	thickness of fin, mm
T_∞	ambient temperature, K
T_f	fluid temperature at the contact surface, K
T_{film}	mean film temperature, K
T_S	temperature at solid surface, K
T_w	cylinder surface temperature, K
u, v, w	velocity components in x, y, z directions respectively, m/s
x, y, z	Cartesian coordinates

Greek symbols

α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, 1/K
ΔT	base-to-ambient temperature difference, K
ε	Eccentricity ratio
ξ	fin-to-tube diameter ratio, D/d
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

treated as a vertical flat plate due to similarity in correlation of Nusselt number as investigated by Gebhart et al. [7] and has been explained in Ozisik [8] and Holman [9]. However, for the slender vertical cylinder, the curvature effect cannot be neglected, and the correlation will be different as explained by Popiel et al. [10]. LeFevre and Ede [11] proposed an integral heat transfer solution that accounts for the effect of wall curvature in the laminar range. Minkowycz and Sparrow [12] developed a local non-similarity solution method which was applied to solve natural convection on a vertical cylinder with large curvature. Fujji and Uehara [13] compared the heat transfer rates by laminar natural convection along the outer surface of a vertical cylinder with the same along a vertical flat plate. Kuiken [14] investigated the radial curvature effects on axisymmetric free convection boundary-layer flow for vertical cylinders and cones with non-uniform temperature differences between the surface and the ambient fluid. Bejan and Lage [15] investigated the Prandtl number effect on the transition in natural convection along a vertical surface. Day et al. [16] revisited the topic of laminar natural convection from isothermal vertical cylinders.

There is extensive experimental literature when considering the effect of fins on natural convection over cylinders Natural convection from a vertical cylinder with vertically oriented plate fins have been studied experimentally by An et al. [17], where the authors have proposed a correlation for estimating the Nusselt number. Park et al. [18] have studied experimentally the effect of natural convection over branched fins fitted with a vertical cylinder. Recent advances in semiconductor technology have led to a significant increase in the power density threshold of microelectronic devices suggested by Bar-Cohen [19] and Oktay et al. [20]. This higher power density leads to an increase in the junction temperature, which is harmful to device performance and reliability. Therefore, a highly efficient cooling mechanism is needed to achieve reliability of electronic equipment. Many cooling methods for thermal management have been proposed; among those natural convective heat transfer has been proven to be appropriate for these devices, because of their simplicity, long-term low cost, and minimum maintenance. There is some literature readily available on how the use of fins on light sources not only helps in efficient cooling but also helps for the beautification of the light sources, and the literatures are as An et al. [17], Park et al. [18] and Kim et al. [21]. Literature is readily available for natural convection heat transfer over a horizontal cylinder with concentric annular fins such as Littlefield and Cox [22], Kraus et al. [23], Tsubouchi and Masuda [24], Edwards and Chaddock [25]. There is some literature available on experimental study of natural convection heat transfer from inclined cylinders (here, the angle of inclination varies from 0° (vertical cylinder) to 90° (horizontal cylinder)) by Al-Arabi and Salman [26] and Al-Arabi and Khamis [27].

Numerical studies of natural convection over finned surfaces are relatively rare. For example, natural convection heat transfer from finned sphere has been investigated numerically by Singh and Dash [28]. Senapati et al. [29] numerically investigated heat transfer over a horizontal cylinder with concentric annular fins. Senapati et al. [30] also numerically investigated the effect of eccentricity on heat transfer from a horizontal cylinder with annular fins. Considering the above literature survey, it would indeed be useful to study numerically natural convection heat transfer from a vertical cylinder with annular fins. The lack of experimental or numerical study is the reason for the incomplete picture of such a system. Numerical investigation of natural convection over an annular finned vertical cylinder with equal fin spacing is of relevance to industrial applications.

In the present study, numerical simulation of full Navier-Stokes equation along with energy equation has been conducted for the natural convection over a vertical cylinder with annular fins of constant thickness for both laminar and turbulent flow regimes. Computations have been performed by varying the parameters such as Rayleigh number, the fin to tube diameter ratio, the number of fins (fin spacing). The effect of the aforementioned parameters on Nu is analyzed, and correlations for average Nusselt number for finned vertical cylinder have been developed for both laminar ($10^4 \le \mathrm{Ra} \le 10^8$) and turbulent ($10^{10} \le \mathrm{Ra} \le 10^{12}$) flows (transition to turbulence occurs at Rayleigh number 10^8 for natural convective flow over a vertical cylinder) when the fin to tube diameter ratio, fin spacing to tube diameter ratio are in the range of 2–5 and