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Flow of nanofluid plane wall jet and heat transfer

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HIGHLIGHTS

- The momentum layer shape factor indicates decay regarding the velocity field.
- The shape factor explains why the nanofluid Ag most enhances the skin friction.
- An explicit correlation between the skin friction and the rate of heat transfer.
- Without solving the energy equation, the rate of heat transfer is enhanced.
- The Maxwell–Garnett model and the Patel model lead to the same conclusions.

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ABSTRACT

The traditional laminar plane wall jet is studied when the medium is filled with nanoparticles of Ag, Cu, CuO, Al_2O_3 and TiO_2. It is aimed to understand the effects of several nanofluids on the heat and flow behaviors of the wall jet. Momentum and thermal integral flux relations are obtained initially. Later on, some important shape factors are defined designing the momentum boundary layer, shear layer as well as the thermal boundary layer when the wall is subjected to either adiabatic or isothermal wall constraints. By means of these parameters, the flow field is shown to be decelerated and as a consequence the shear stress on the wall is enhanced. Without solving the energy equation, the thermal layer shape factor enables one to fully seize the cooling effect of considered nanofluids for both adiabatic and isothermal wall cases. As a result, the heat transfer rate is found to be greatly enhanced by the presence of nanoparticles. Same conclusions are reached by two different popular nanofluid models made use in the recent nanofluid researches.

1. Introduction

Plane wall jets are very important, in particular application of the jet nanofluids impingement during the personal computer cooling process [1]. Five nanofluids types; namely Ag, Cu, CuO, Al_2O_3 and TiO_2 and their effects on the flow and heat characteristics owing to the two-dimensional laminar plane wall jet are targeted in the present paper.

Finding an effective route of cooling is utmost significant in the design procedure of mechanical components of a physical system. Taking into account a base fluid, such as the water, ethylene glycol or oil together with some colloidal suspensions of nanoparticles, is the best suited for this purpose [2]. The main ingredients of nanoparticles employed in nanofluid mixtures can be oxides and metals due to their enhanced thermal conductivity [3], refer to the articles [4,5] for boiler gas application. The reader may also view the articles, for further applications, like to the radiators [6,7], to the solar collectors [8], to the rotating disk [9] and to the magnetohydrodynamic influences [10].

In fully hydrothermal equilibrium state, the single phase assumption of nanofluids is perfectly valid making it possible to consider the thermo-physical properties as a function of uniform concentration [11]. However, in the case of non-equilibrium, the variation of concentration through the boundary layer may not be uniformly distributed and hence it may change from the wall up to the outer boundary (free stream). In this case, two-phase nanofluid model of Buongiorno which further takes into account the Brownian and thermophoresis effects is generally used in the simulations [12]. It is worthy of mentioning that the general trend of the conclusions from the both approaches may be the same as far as the impacts of nanoparticles, see for instance the usage of both methods in condensation problem [13].

The problem of a symmetric plane jet in two dimensions spreading out from a nozzle into a stationary fluid has found many applications in industry, such as paper manufacturing [14], since the quality of the final paper sheet is highly affected by the states

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of the headbox and jet. Plane liquid jets are also used in controlling fuel atomization, in film coating, in materials processing, in blades of turbines and in boundary-layer control of airfoils and flaps. The initial attempts applied the boundary layer approximation to jet flows to achieve self-similar solutions, see for instance [15,16]. Jets in an atmosphere were studied in [17]. Schwarz in [18] studied the radial free jets. Successful models of a laminar two-dimensional free jet and its analogous laminar circular free jet issuing into a medium at rest and admitting exact flow solutions were presented by Schlichting in [19]. The wall jet on an axisymmetric body was analyzed in [20]. The heat transfer characteristics of a wall jet flow over a convex surface were explored by Chiou and Kao in [21]. Non uniformities were also investigated in [22]. Sanchez-Sanza et al. in [23] examined by means of asymptotic methods the behavior of hydrogen laminar jet. Two-dimensional MHD jets with power law fluids were numerically solved by Jat and Kulhari in [24]. Algebraically decaying counterpart of the classical wall Glauert-jet was discovered in [25]. Blasius wall jet was compared to experiments in [26]. The use of conservation laws was made in [27]. The hydrogen jet within the atmosphere was analyzed in [28]. Cooling of computer equipments was experimentally investigated via jet nanofluids impingement in [1]. A numerical computation by Fourier series was recently implemented in [29]. Laminar mixing phenomenon was illuminated in [30]. Some exact temperature results concerning the laminar free and circular jets were presented in [31].

It is an inevitable fact that there is no consensus on the relation of the nanofluid thermal conductivity, since it may change depending on the flow medium under consideration. For this reason there appears to be a collection of empirical thermal conductivity formulae in the open literature, see [32,33]. Even so, the Maxwell–Garnett model [34] is generally acknowledged since it yields highly sufficient agreement with the available experiments. According to the semi-empirical thermal conductivity model proposed in [35], in nanofluid flow investigations concerning the micro-convection, the Brownian motion and the specific surface area should not be neglected implying a two-component nanofluid, even though the same viscosity relation as for the Maxwell–Garnett model is at the disposal. This model was shown to be specifically good for estimating the anomalous thermal conductivity variation of nanofluids. Making use of such a model, successful solutions consistent with the experimental data were presented in the articles [9,36,37].

Although there exists a sufficient number of literature concerning the flow and temperature character of a wall jet, its properties subjected to suspended nanoparticles have not yet been adequately studied in the literature when different nanofluids, like Ag, Cu, CuO, Al_2O_3 and TiO_2 in wall jet are concerned. Motivated by this need, we perform a mathematical analysis on both flow and energy equations. Similar to the integral conditions existing in the literature in the absence of nanofluids, the corresponding momentum and thermal fluxes in terms of integrals are derived for the nanofluid wall jet under consideration. Nanofluids are found to reduce the momentum layer thickness, with an opposite effect on the shear layer due to a shape factor defined in this study. More importantly, without fully solving the energy equation, the cooling effect of the considered nanofluids under the operating conditions of adiabatic or isothermal walls can be straightforwardly understood by means of a thermal layer shape factor defined again in this study. Moreover, the presence of nanofluids greatly enhances the rate of heat transfer. The reached conclusions are supported even when two different nanofluid models recently used in nanofluid researches are adopted for the present physical problem.

The following strategy of presentation is adopted in the rest of the paper. Mathematical modeling of the physical problem is introduced in Section 2, in which both the flow and temperature derivations are laid down. Results and discussions are then presented in Section 3 which associate with the momentum and thermal layers. Eventually, concluding remarks are made in Section 4.

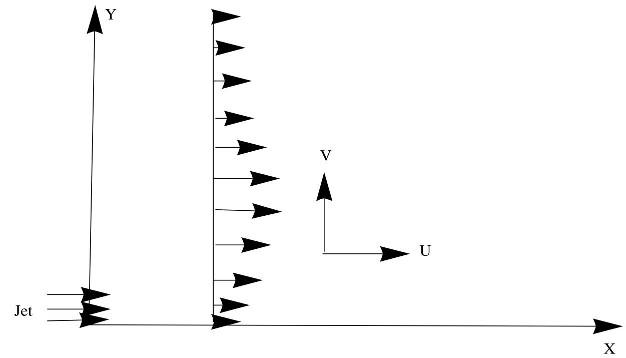

Fig. 1. Basic nanofluid jet configuration.

2. Mathematical modeling

Let us consider a static fluid possessing a temperature T_∞, upon which a jet fluid is superimposed from a narrow slit, as depicted in Fig. 1. The plane wall may be maintained at the same constant temperature T_∞ or, alternatively it can be adiabatic. This facilitates the use of a new temperature $\bar{T} = T - T_\infty$, we then drop the bar in the subsequent analysis. As seen in Fig. 1, the origin of jet is set in the slit having the coordinate axis x and y. The fluid is a water based nanofluid containing five distinct types of nanoparticles: Ag, Cu, CuO, Al_2O_3 and TiO_2, whose thermo-physical properties are summarized in Table 1. In the case of a regular fluid, the analysis of a two-dimensional plane wall jet can be found in several sources, see for instance [30,38].

2.1. Laminar nanofluid wall jet

The motion of a traditional two-dimensional laminar wall jet when composed with nanofluids is governed by the following flow and energy equations

$$\begin{aligned} u_x + v_y &= 0,\\ \rho_{nf}(uu_x + vu_y) &= \mu_{nf} u_{yy},\\ (\rho Cp)_{nf}(uT_x + vT_y) &= k_{nf} T_{yy} + \mu_{nf} u_y^2. \end{aligned} \tag{1}$$

We assumed that the dissipation is only due to the friction. Eqs. (1) are accompanied with the boundary conditions arising from the wall and far field decay conditions

$$\begin{aligned} &u(x,0) = 0, \quad v(x,0) = 0, \quad T_y(x,0) = 0 \quad (\text{Adiabatic}),\\ &T(x,0) = 0 \quad (\text{Isothermal}),\\ &u(x,\infty) = 0, \quad T(x,\infty) = 0. \end{aligned} \tag{2}$$

The subscript nf stands for the nanofluid property, and additionally the parameters appearing in (1) are respectively,

$$\begin{aligned} \mu_{nf} &= (1-\phi)^{-2.5}\mu_f,\\ (\rho)_{nf} &= (1-\phi)\rho_f + \phi\rho_s,\\ (Cp)_{nf} &= (1-\phi)Cp_f + \phi\rho Cp_s,\\ k_{nf} &= k_f \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + 2k_f + \phi(k_f - k_s)}, \end{aligned} \tag{3}$$

with ϕ the volume fraction of nanoparticles, ρ_f and ρ_s denoting the pure fluid and nanoparticle densities, likewise, $(\rho C_p)_f$ and $(\rho C_p)_s$ denoting the pure fluid and nanoparticle specific heats and, k_f and k_s denoting the base fluid and nanoparticle thermal conductivities.