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Prediction of thermal conductivity of alumina water-based nanofluids by artificial neural networks

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ABSTRACT

The aims of the present study are to develop and validate an artificial neural network (ANN) approach to estimate the thermal conductivity ratio (TCR) of alumina water-based nanofluids as a function of temperature, volume fraction and diameter of the nanoparticle. The ANN parameters are adjusted by back propagation learning algorithm using 285 collected experimental data sets from various literatures. Statistical accuracy analysis confirms that a two-layer feed forward ANN model with fourteen hidden neurons is the best architecture for modeling the considered task. The developed ANN approach has predicted the experimental data with the absolute average relative deviation (AARD%) of 1.27%, mean square error (MSE) of 4.73×10^{-4} and regression coefficient (R^2) of 0.971875. Comparison of predictive capability of the proposed technique with some recommended correlations in the literatures confirmed that the ANN model is more superior to other published works and therefore can be considered as a practical tool for estimation of the thermal conductivity ratio of alumina water-based nanofluids.

1. Introduction

Thermal conductivity of dispersed solid particles in fluids has been under investigation for more than a century [1]. Since many of nanofluids have greater thermal properties than their base fluids, they can be used for heat transfer applications [2–8]. Maxwell [1] and Hamilton and Crosser [9] proposed theoretical correlations for estimation of thermal conductivity of these suspensions as a function of their particle loading, thermal conductivity of particles and base fluids. Moreover, effects of nanoparticle geometry, type of base fluids, temperature and pH on the thermal conductivity enhancement of pure base fluids have been investigated [6,10,11]. Some researchers showed an increase in thermal conductivity with temperature [6,10–13]. Brownian motion of nanoparticles is the most acceptable mechanism to explain enhancement of fluids thermal conductivity in the presence of nanomaterial [6,11]. This mechanism is dependent on fluid temperature since any increase in fluid increases particle motions and hence increases fluid thermal conductivity [6]. Increasing the nanoparticle content may also increase the collisions between fluid molecules and nanoparticles and enhance the nanofluid thermal conductivity. Enhancement of thermal conductivity of nanofluids by increasing the suspension temperature has been reported by different groups of researchers [12–15]. Effect of particle size on the thermal conductivity was extensively investigated by some researchers [2–4,12,15]. Decreasing the thermal conductivity of nanofluid has been observed under some specific circumstances [12,15]. Clustering and agglomeration of the smaller particles may result in sedimentation which can reduce the random motion of particles and thermal conductivity of nanofluids [12,15].

2. Theoretical modeling of thermal conductivity enhancement

An accurate experimental measurement of thermal conductivity of nanofluids is a very challenging and time-consuming process. In addition, cost and expense of doing properly reproducible experiments deter the measurement of nanofluid thermal conductivity over all of the desired operating conditions. Therefore, some theoretical/empirical correlations have been developed to relate the thermal conductivity of nanofluids to their easily measurable properties such as temperature, volume fractions and nanoparticle size.

In this section, some of the proposed correlations for estimation of thermal conductivity of suspensions as well as nanofluids are reviewed. While some of the proposed correlations for thermal conductivity of nanofluids are developed by modifying their associated correlations for suspension, in this section the later one is also incorporated.

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2.1. Maxwell model

Maxwell [1] was likely the first researcher who proposed a correlation for the thermal conductivity of suspensions. The model can be expressed by Eq. (1).

$$k_d = \frac{k_p + 2k_{bf} + 2\left(k_p - k_{bf}\right)\varphi}{k_p + 2k_{bf} - \left(k_p - k_{bf}\right)\varphi} k_{bf} \tag{1}$$

here k_d, k_p and k_{bf} are thermal conductivity of the suspension, particles and base fluid, respectively and φ represents the volume fraction of particles. This model can predict the amount of thermal conductivity of dilute dispersions of micro- or millimeter-sized spherical particles.

2.2. Hamilton and Crosser model

Hamilton and Crosser [9] modified the Maxwell model by including an empirical shape factor n for description of the effect of particles shape (non-sphericity) as follows:

$$k_d = \frac{k_p + (n-1)k_{bf} - (n-1)\left(k_{bf} - k_p\right)\varphi}{k_p + (n-1)k_{bf} + \left(k_{bf} - k_p\right)\varphi} k_{bf} \tag{2}$$

n is given by $3\psi^{-1}$ where ψ is the particle sphericity, $n = 3$ and $n = 6$ represent the spheres and cylindrical particles, respectively.

2.3. Nan et al. model

Nan et al. [16] incorporated the effect of particle geometry and finite interfacial resistance into the Maxwell's model and presented the following correlation for measuring the ratio of thermal conductivity of nanofluids (k_{nf}) to the base fluids.

$$\frac{k_{nf}}{k_{bf}} = \frac{3 + \varphi[(2\beta_{11}(1-L_{11}) + \beta_{33}(1-L_{33})]}{3 - \varphi(\beta_{11}L_{11} + \beta_{33}L_{33})} \tag{3}$$

L_{11}, L_{33} and β_{ii} can be mathematically expressed by following equations.

$$L_{11} = \frac{p^2}{2(p^2-1)} - \frac{p}{2(p^2-1)^{3/2}} \cosh^{-1} p \tag{4}$$

$$L_{33} = 1 - 2L_{11} \tag{5}$$

$$p = \frac{a_{33}}{a_{11}} \tag{6}$$

$$\beta_{ii} = \frac{k_{ii} - k_f}{k_f + L_{ii}\left(k_{ii}^c - k_f\right)} \tag{7}$$

$$k_{ii}^c = \frac{k_p}{1 + \gamma L_{ii}\frac{k_p}{k_f}} \tag{8}$$

$$\alpha = \frac{a_k}{a_{11}} = \frac{R_{bd}k_f}{a_{11}/2} \tag{9}$$

where a_{ii}, a_{11}, L_{ii}, p, φ, k_{ii}^c and c are the diameter of the ellipsoid, Kapitza radius, geometrical factors dependent on the particle shape, aspect ratio of the ellipsoid, volume fraction, equivalent thermal conductivities and interfacial thermal resistance, respectively.

2.4. Yu and Choi model

Yu and Choi [17] performed some modifications on the Maxwell model and derived a model to calculate the nanofluid thermal conductivity as a function of effective thermal conductivity of particles as expressed by Eq. (10):

$$k_{nf} = \frac{k_{pe} + 2k_{bf} + 2\left(k_{pe} - k_{bf}\right)(1+\beta)^3\varphi}{k_{pe} + 2k_{bf} - \left(k_{pe} - k_{bf}\right)(1+\beta)^3\varphi} k_{bf} \tag{10}$$

here k_{pe} is the effective thermal conductivity of the particles and can be defined by Eq. (11).

$$k_{pe} = \frac{\left[2(1-\gamma) + (1+\beta)^3(1+2\gamma)\right]\gamma}{-(1-\gamma) + (1+\beta)^3(1+2\gamma)} k_p \tag{11}$$

$\gamma = k_{lr}/k_p$ represents the ratio of nanolayer thermal conductivity (k_{lr}) to the thermal conductivity of particle (k_p) and $\beta = h/r_p$ is the ratio of nanolayer thickness (h) to the particle radius (r_p).

2.5. Xie et al. model

Xie et al. [18] investigated the effect of interfacial nanolayer on the effective thermal conductivity of nanofluids. The model includes thermal conductivities of base fluid (k_{bf}), nanoparticles (k_{nf}) and nanolayer (k_{ir}), thickness of nanolayer (h), the volume fraction (φ) and the size of nanoparticle (r_p). At low particle loadings, their model can be expressed by Eq. (12)

$$\frac{k_{nf} - k_{bf}}{k_{bf}} = 3\theta\varphi_T + \frac{3\theta^2\varphi_T^2}{1 - \theta\varphi_T} \tag{12}$$

where $\theta, \beta_{pl}, \beta_{fl}, \beta_{lf}, k_l, \varphi_T, \beta, \varepsilon_p$ and M can be defined by Eqs. (13)–(21):

$$\theta = \frac{\beta_{lf}\left[(1+\beta)^3 - \frac{\beta_{pl}}{\beta_{fl}}\right]}{(1+\beta)^3 + 2\beta_{pl}\beta_{lf}} \tag{13}$$

$$\beta_{pl} = \frac{k_p - k_l}{k_p + 2k_l} \tag{14}$$

$$\beta_{fl} = \frac{k_f - k_l}{k_f + 2k_l} \tag{15}$$

$$\beta_{lf} = \frac{k_l - k_f}{k_l + 2k_f} \tag{16}$$

$$k_l = \frac{k_f M^2}{(M-\beta)\ln(1+M) + \gamma M} \tag{17}$$

$$\varphi_T = \varphi(1+\beta)^3 \tag{18}$$

$$\beta = h/r_p \tag{19}$$

$$M = \varepsilon_p(1+\beta) - 1 \tag{20}$$

$$\varepsilon_p = \frac{k_p}{k_{bf}}. \tag{21}$$

2.6. Xuan et al. model

Xuan et al. [19] took into account the physical properties of both fluid and nanoparticles in their model. The authors tried to