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Nanofluids in Liquid Cooling System: Mathematical Model and Effect on Efficiency

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Abstract- Effects on efficiency for using Nanofluids in a liquid cooling system is investigated. A Mathematical model is established for a closed system in which the coolant liquid flows in an enclosed tube while exchanging heat with the tube's wall. The mathematical model predicts the rate of cooling and is equally valid for both laminar and turbulent flow. The model was tested with data for both, water based Tio_2 and water based Al_20_3 Nanofluids. Under the specified test conditions, the model predicts an 39.87% increase in the rate of cooling for Tio_2 and an 36.79% increase in the rate of cooling for Al_20_3. The result obtained in the case of Al_20_3 is consistent with the experimental value 40%, which was obtained for the same test conditions by C. T. Nguyena, & Co, in 2007. Such an increase in rate of cooling can make liquid cooling system extremely helpful in the defence sector where overheating issues in weapons like rocket launcher causes discomfort and forces the operator to take periodic breaks to cool down the launcher.

Highlights:

- A model for Nanofluids in forced convention closed system tubular flow is proposed.
- 37% to 40% increase in efficiency was predicted for TiO_2 & Al_2O_3 Nanofluids (under optimal conditions).
- Model was tested with data from experiment by C. T. Nguyena, & Co for Al_2O_3 Nanofluids.
- The obtained value 36.79% deviated from the experimental value 40% by less than 8%.

Keywords- *Nanofluids, Forced convection, Liquid cooling system enhancement,Mmathematical model, Efficiency increase*

I. INTRODUCTION

Certain Nanofluids can influence the rate of heat transfer immensely. It is because of this property that they are now been considered in multiple fields like solar thermal collectors [1][2][3] and liquid cooling systems [4][5][6]. In this case, we investigate the aspect of using Nanofluids in a closed liquid cooling system which is a case of tubular forced convection. "Nanofluid" essentially means a two phase mixture of fine sized dispersed Nanoparticles in a continuous base fluid. In general, Nanofluids possess high thermal conductivity and low specific heat. Notably, the thermal efficiency of Nanoparticles has been found to increase with the decreasing size of the particles [7][8][9] and the thermal conductivity was found to increase significantly over a volume fraction range of 0.1%–5% [10][11][12][13][14][15][16][17].

It is because of these properties of Nanofluids and the lack of a proper mathematical model that satisfies the experimental results done on them so far, that the need of a mathematical model is so great.

In the present work, I have theoretically established a mathematical model for Nanofluid based forced convective tubular flow system (NFCTF). The model was tested with data from already published experimental work and the model demonstrated a great degree of consistency.

TABLE I. NOMENCLATURE

Symbol	Property	Unit
Q	Rate of heat transfer	watt
H	Heat transfer coefficient	$w/m^2 k$
T_s	Inner surface temperature	k
T_b	Bulk fluid temperature	k
D	Diameter of the tube	m
R	Radius of the tube	m
L	Length of the tube	L
K	Thermal conductivity	w/m k
A_{eq}	Equivalent lateral surface area	m^2
P	Density of the fluid	Kg/m^3
C	Specific heat capacity	J/kg k
U	Velocity of the fluid	m/s
Ŋ	Efficiency	-

II. MATHEMATICAL MODEL: BANERJEE-DZUBUR MODEL FOR NFCTF

Considering the radial conduction (neglecting axial conduction) and axial enthalpy transport in the annular element, the rate of cooling for such a system comes out to be,

$Q = h\,A_{eq}(T_s - T_b)$ eq(i) (1)

This is the primordial equation of this model. This equation can now be solved for both laminar and turbulent flow.

III. SOLUTION FOR LAMINAR FLOW

Assuming a fully developed pipe flow [18], we get,

$h = \acute{\Upsilon}\frac{48K}{11D}$ eq(ii) & $t_b = t_s - \frac{11U_{max}\rho cR^2}{96K}\frac{\partial T}{\partial x}$ eq(iii). Where $\acute{\Upsilon}$ is the correction factor and T is the temperature function. Substituting the values of equation (ii) & (iii) in equation (i), we get the equation for the rate of cooling in case of laminar flow which is, $Q = \acute{\Upsilon}\frac{\pi}{8}D^2LU_{max}\,\rho c\,\frac{\partial T}{\partial x}$ eq(iv). This is the equation for the rate of cooling in case of laminar flow.

IV. SOLUTION FOR TURBULENT FLOW

One can use the Stanton Number or the Reynolds analogy [19][20][21] from where, we get, $h = \rho CU\frac{C_{fx}}{2}$ eq(v) where, C_{fx} is the local skin friction coefficient derived from Blasius exact solution for laminar boundary layer flow [22]. Therefore, substituting the value of eq(v) in eq(i), the equation becomes, $Q = \acute{\Upsilon}\rho CU\frac{C_{fx}}{2}\pi DL(T_s - T_b)$ eq(vi). This is the equation for turbulent flow.

V. SOLUTION FOR BOTH, TURBULENT ALONG WITH LAMINAR FLOW

In this case, modifying Colburn analogy [23][24], We get, $h = \frac{K}{L}(Pr)^{1/3}[.036(Re)^{0.8} - 836]$ eq(vii) where Pr is the Prandtl number and Re is the Reynolds number. Therefore, substituting the value of eq(vii) in eq(i), the equation becomes, $Q = \acute{\Upsilon}\frac{K}{L}(Pr)^{1/3}[.036(Re)^{0.8} - 836]\pi DL\,(T_s - T_b)$ eq(viii).

The solutions of Banerjee-Dzubur Model for (NFCTF) are thus tabulated below:

TABLE II. SOLUTIONS OF BANERJEE-DZUBUR MODEL FOR (NFCTF)

Laminar flow	$Q = \acute{\Upsilon}\frac{\pi}{8}D^2LU_{max}\,\rho c\,\frac{\partial T}{\partial x}$
Turbulent flow	$Q = \Upsilon\rho CU\frac{C_{fx}}{2}\pi DL(T_s - T_b)$
Both laminar & turbulent flow	$Q = \acute{\Upsilon}\frac{K}{L}(Pr)^{1/3}[.036(Re)^{0.8} - 836]\pi DL\,(T_s - T_b)$

VI. USING NANOFLUIDS

When using Nanofluids the changes will be in density, the specific heat and the temperature function. The change in density will be according the equation:

$P_{nf} = \varphi\rho_p + (1-\varphi)\rho_f$ eq(ix) (2)

And the specific heat will change according the equation:

c_{nf} (J/kg k) $= \frac{(1-\varphi)(\rho c)_f + \varphi(\rho c)_p}{(1-\varphi)\rho_f + \varphi\rho_p}$ eq(x) (3)

From the law of mixtures as used by Zhou, L in [25], here φ is the volume % of Nanoparticle in the base fluid. The extensions "nf" and "f" mean Nanofluid and fluid respectively. When there is no Nanoparticle dispersed in the base fluid, φ becomes 0 and thus, we get $\rho=\rho_f$ and $c=c_f$. Therefore, as we can see, although the model was specifically designed keeping in mind the Nanofluids, it is equally valid in case of normal cooling system.

VII. CALCULATION OF EFFICIENCY

The increase in efficiency due to use of Nanofluids can be calculated using the following equation:

$\eta_{increase}\ (\%) = (\frac{\eta_{nf}}{\eta_f} - 1) \times 100$ eq(xi) (4)

VIII. EXPERIMENTAL VERIFICATION

The model was tested with data for both, water based TiO_2 and water based Al_2O_3.

For TiO_2:

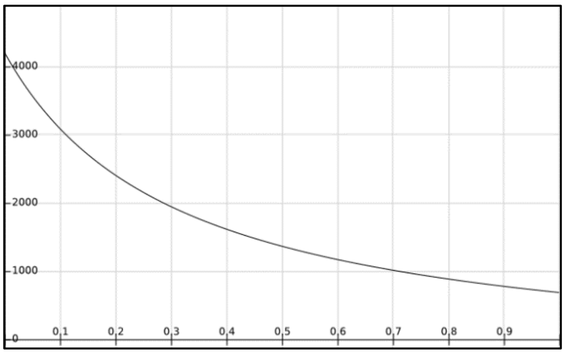

Figure 1. C_{nf} of TiO_2 vs Vol conc

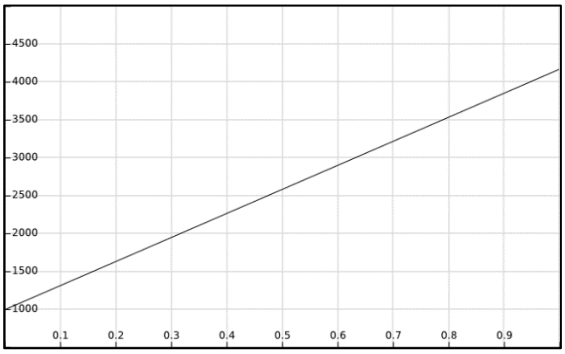

Figure 2. p_{nf} of TiO_2 vs Vol conc

Water based TiO_2 Nanofluid is one of the prime suspects which is expected to increase the efficiency of a liquid cooling system. The Banerjee-Dzubur model was solved for Nanofluid having

- The volume concentration 0.3%,
- The density 4175 kg/m^3,
- The specific heat 692 J/kg,

(The data was taken from experiments conducted by M. Mahendran & Co) where the performance of evacuated tube solar collector using water-based titanium oxide Nanofluid was tested. The model predicts an increase in efficiency of 39.87%.

For Al_2O_3:

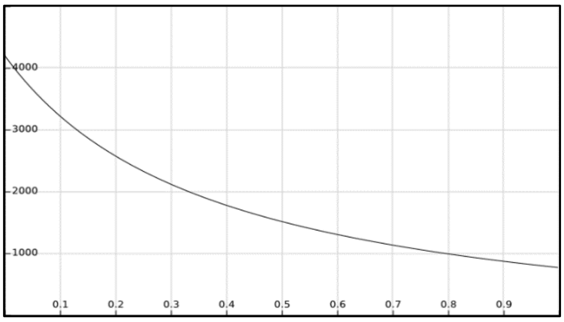

Figure 3. C_{nf} of Al_2O_3 vs Vol conc

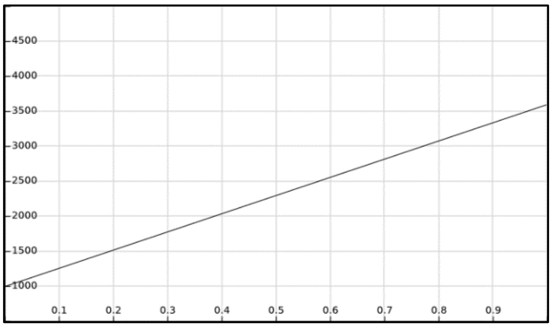

Figure 4. P_{nf} of Al_2O_3 vs Vol conc

Al_2O_3 is another suspected Nanoparticle which can increase the efficiency of a base fluid due to changes in thermal conductivity and specific heat [26][27][28]. In this case, the model was tested with actual data (based on the experiments performed by Roy. G, Nguyen. C. T, Gauthier.C, Galanis. N), where they have used water based Al_2O_3 Nanofluid, having

- the volume concentration 6.8%,
- the density 3600 kg/m^3,
- the specific heat 773 J/kg k,

They experimentally found an increase of 40% in the efficiency. When the Banerjee-Dzubur Model was solved (for laminar flow), the model predicted an increase in efficiency of 36.79% if the correction factor is assumed to be 1. i.e. the predicted value deviated from the experimental value by a margin less than 8% i.e. the correction factor ϒ in this case is 1.087.

IX. CONCLUSION

The Banerjee-Dzubur model fits the experimental data regarding influence of Nanofluids on efficiency very closely. Moreover, it also demonstrates that using Nanofluids like TiO_2 or Al_2O_3 greatly enhances the capability of a liquid cooling system altogether.

X. APPLICATION IN THE FIELD OF DEFENCE

Although the Banerjee-Dzubur model will help extensively in the fields of electronics, this model was developed to serve the defence sector. It was developed to pave the way for incorporation of liquid cooling systems in weapons like rocket launcher. Normally, the personnel using the RF have to take periodic breaks due to overheating. Some incidents even recorded the personnel suffering burns due to extensively using RFs. Banerjee-Dzubur Model shows that in such cases, Nanofluids can make a really big difference. Not just in the comfort but more importantly, reducing the number of periodic breaks required thereby increasing the potency of the weapons like RF that suffers from heating issues.

XI. RESULTS

1. Several Nanofluids can greatly increase the performance of forced convective tubular flow liquid cooling systems.
2. Banerjee-Dzubur model can be used for analyzing this increase in performance with less than 10% error (used to determine the correction factor)

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