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NUMERICAL INVESTIGATIONS ON FUEL CELL COOLING BY INTRODUCING WATER-ALUMINUM OXIDE NANOFLUID

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Abstract— ***The present study pertains to a fuel cell which is encapsulated in a horizontal duct open at both the ends. The nanofluid as coolant is permitted to pass through the annular region between the fuel cell and duct. Water based nanofluid, namely Water-Al_2O_3 is taken as coolant in the present investigations. The numerical simulations are carried out to obtain the heat transfer behaviour of encapsulated fuel cell by maintaining its temperature within the safe limit. For that, a 2D numerical model is being developed. The continuity, momentum and energy equations are solved to predict the thermal behaviour. The simulations are accomplished to predict the temperature fields and temperature contours. The trends of results are along the expected lines. The model parameters taken are fuel cell heat flux of 10 W/cm^2 and nanofluid velocity of 9 m/s at duct inlet. The Water-Al_2O_3 is observed as the nanofluid really suitable for fuel cell application without any sort of thermal issues.***

Keywords— Numerical, Fuel Cell, Cooling, Simulation, Water-Al_2O_3, Nanofluid.

I. INTRODUCTION

Fuel cells are marvelously used to power fuel cell vehicles and are also utilized for primary and backup power for housing, manufacturing and business shops. Xuan and Roetzel [1] established concepts of heat transfer correlations concerning about nanofluids. S. Litster and McLean [2] described about the functioning of various proton exchange membrane (PEM) fuel cell electrodes.Min et al. [3] performed the parametric studies of proton exchange membrane fuel cell (PEMFC) numerically. Xuan et al. [4] reviewed about the contaminations in PEM type hydrogen fuel cells. Chaitanya et al. [5] investigated about the effects of anisotropic heat conduction in PEM type fuel cells. Nguyen et al. [6] used Al_2O_3 water nanofluid to enhance heat transfer in an electronic liquid cooling system. Sangseok and Dohoy [7] described about the various approaches for thermal management of proton exchange membrane fuel cell systems. Jong-Woo and Song-Yul [8] investigated about the coolant control in PEM fuel cell systems.Zhang and Kandlikar [9] performed critical reviews of cooling techniques in PEM fuel cell stacks. Mohamed and Atan [10] analyzed about the excessive heating on thermal and electrical resistance of a polymer electrolyte membrane fuel cell. Keshavarz et al. [11] executed numerical studies on the influences of nanofluids on mini-channel heat sink.

From the aforesaid text, to the best of author' knowledge, it is well understood that there is not a single detail computational study relating to the effects of water based nanofluid (namely Water-Al_2O_3) on heat transfer behaviour of fuel cells. With this perspective, the present paper demonstrates numerical investigations with the stated nanofluid on thermal characteristics of fuel cells. And also, the numerical model includes additional key factors like inertia, viscosity and gravity effects apart from the usual issues concerning the present physical problem. However, the stated model ignores both compressibility and viscous heat dissipation effects. The model is very well demonstrated for the detailed numerical investigations on the influences of the already stated nanofluid (as this significantly affect the cooling characteristics) by taking fuel cell heat flux and duct inlet nanofluid velocity as the important model parameters. Finally, the predictions of the model relating to stated nanofluid is along the lines of expectations as well.

II. DESCRIPTION OF PHYSICAL PROBLEM

The graphical sketch of an illustrative fuel cell to be inserted in a duct is shown in the figure 1. The corresponding physical model as illustrated in figure 2, describes about the overall heat transfer from the fuel cell which is encapsulated in a horizontal duct open at both the ends. The coolant considered in the present investigations is water based nanofluid named as Water-Al_2O_3. A 2D model is considered to save computation/simulation time by ignoring end effects in the transverse direction. The model includes the viscosity along with the gravity effect as well.

The fluid flow is considered to be laminar and incompressible. The no slip boundary condition is specified at the walls. The velocity inlet boundary condition is set at the entry to the duct from where water based nanofluid is allowed to pass through. A pressure outlet boundary condition is specified at the exit of the duct. The ambient condition is taken at the entry to the duct. For cooling of the fuel cell surface, a convective boundary condition in the form of heat flux is introduced to simulate the overall temperature variation inside the duct due to heat transfer. The thermo-physical properties of current nanoparticles alongside the other system parameters, are described in table 1.

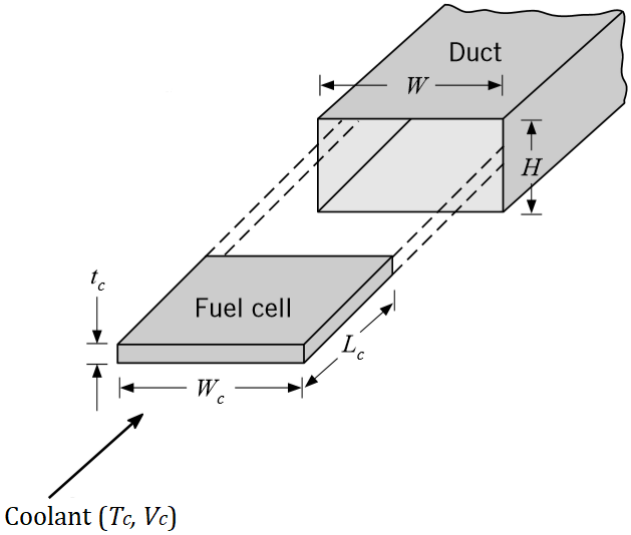

Fig 1. Schematic of fuel cell to be kept in a rectangular duct

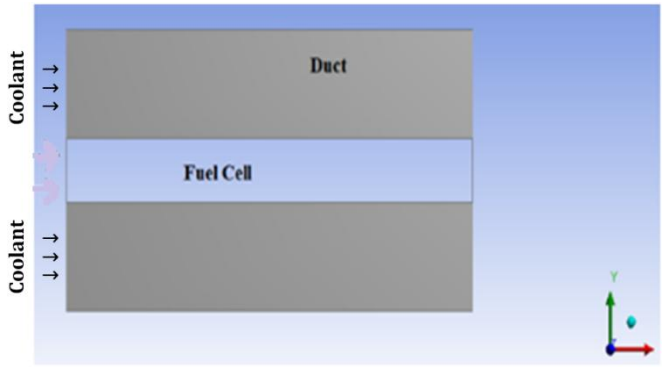

Fig 2. 2D computational domain of physical model with flow of coolant inside the duct

Table 1. Thermophysical properties of nanoparticles and model data

Nanoparticle Properties	**Al_2O_3**
Density,ρ(Kg/m^3)	3970
Specific heat, C_P (J/kg-K)	765
Thermal conductivity, k (W/m-K)	36
Model Data	**Values**
Height of duct (H)	26 mm
Length of fuel cell (L_c)	50 mm
Thickness of fuel cell (t_c)	6 mm
Width of fuel cell (W_c)	50 mm
Width of duct (W)	50 mm
Ambient air temperature	300 K
Fuel cell heat flux	10 W/cm^2
Velocity of coolant at duct inlet	9 m/s

III. MATHEMATICAL FORMULATION AND NUMERICAL PROCEDURES

The continuity, momentum and energy equations in 2D for a fully developed hydrodynamic and thermal flow situation is described in equations from (1) to (4), respectively.

Continuity equation: $$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

X-momentum equation: $$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

Y-momentum equation: $$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial P}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho g \quad (3)$$

Energy equation: $$\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

Initially, both the continuity and momentum equations are solved simultaneously to get the pressure and velocity fields. Then, the energy equation is solved using the stated velocity field to get the corresponding temperature field. In other words, all the said equations are solved together owing to interdependency between the related parameters.

As an outcome of the grid-independence test, 50 × 20 uniform grids have been used for the final simulation. Corresponding time step taken in the simulation is 0.0001 seconds. Convergence in inner iterations is happened while the condition $\left|\frac{\varphi-\varphi_{old}}{\varphi_{max}}\right| \leq 10^{-4}$ is satisfied concurrently for all variables, where φ stands for each variable *u*, *v*, and *T* at a grid point at the current iteration level, φ_{old} represents the corresponding value at the previous iteration level, and φ_{max} is the maximum value of the variable at the present iteration level in the whole domain.

IV. RESULTS AND DISCUSSIONS

Numerical simulations are carried out to study the effects of water based nanofluid (namely Water-Al_2O_3) on cooling characteristics of fuel cell in terms of temperature distributions (i.e. temperature contours/ fields) and surface temperatures of fuel cells. At the outset, the height of the duct is considered to be 26 mm, besides, the thickness and the length of the fuel cell as 6 mm and 50 mm respectively. Furthermore, the heat flux related to the fuel cell is taken as 10 W/cm^2 and the velocity of nanofluid at the duct inlet is selected as 9 m/s.

Water-Al_2O_3 nanofluid as coolant

With the said model conditions, so as to study the influence of Water-Al_2O_3 nanofluid on the thermal behavior of the fuel cell, the numerical simulations are performed, by taking into account the thermophysical properties of the said nanofluid.

Figure 3 demonstrates the simulated results of the temperature field (together with the colored scale bar displaying the temperature values in terms of K) as obtained at the stated model conditions by considering Water-Al_2O_3 nanofluid as coolant. The surface temperature of fuel cell is found to be 350 K (which is less than the safe limit of 356 K temperature as desired in order to avoid the thermal failure of the fuel cell). As expected, the temperature of the Water-Al_2O_3 nanofluid is maximum near the vicinity of fuel cell. And also, the temperature of the Water-Al_2O_3 nanofluid gradually decreases with the increase in the distance from the fuel cell and then it becomes equal to the atmospheric temperature in the far field region. The corresponding temperature contour is also demonstrated in figure 4. In addition, the trends of results are along the lines of expectations. The augment in cooling performance is owing to the thermal conductivity of the stated nanoparticles as described in table 1.

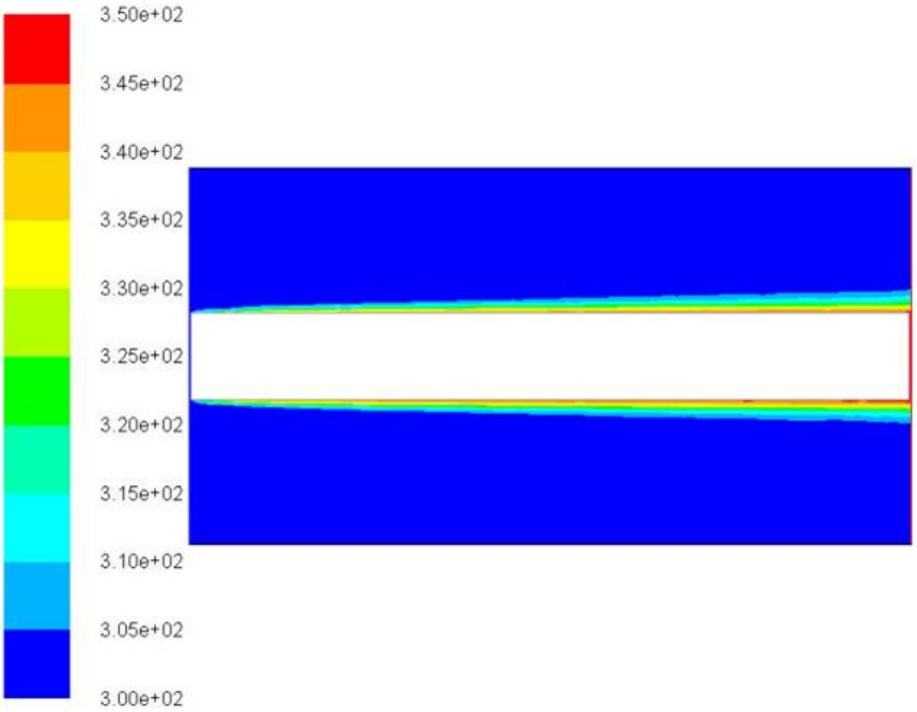

Fig 3. Temperature field with Water-Al_2O_3 nanofluid as coolant.

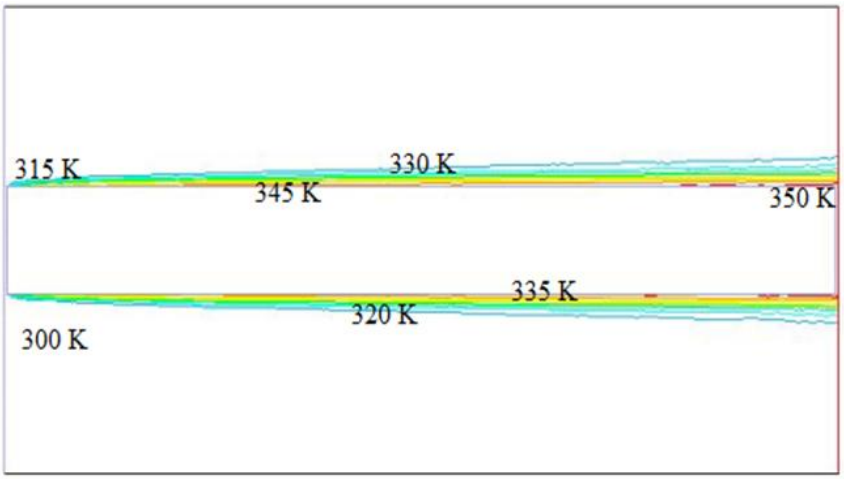

Fig 4. Temperature contour with Water-Al_2O_3 nanofluid as coolant.

V. CONCLUSIONS

A computational model relating to the fuel cell is developed to predict the thermal behaviour with water based nanofluid, namely Water-Al_2O_3, as coolant. The model includes additional key factors like inertia, viscosity and gravity effects apart from the usual issues concerning the present physical problem. However, the stated model ignores both compressibility and viscous heat dissipation effects. The model is very well demonstrated for the detailed numerical investigations on the influences of the already stated nanofluids (as this significantly affect the cooling characteristics) by taking fuel cell heat flux of 10 W/cm^2 and duct inlet nanofluid velocity of 9 m/s as the important model parameters. Direct comparison with other numerical models of fuel cells is not possible because of the absence of such models in the literature. However, the experimental comparison with an in-house experimental setup is planned for the future. With the said model conditions, it is observed that the Water-Al_2O_3 nanofluid renders appropriately effective cooling behaviour without any such thermal failure and is the optimum one as the fuel cell temperature is below the safe limit. Therefore, the said model together with the nanofluid can be used right away in industry to augment heat transfer for better fuel cell performance.

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