Numerical Modeling on Heat Transfer Behavior of Fuel Cell by Using AlN, Cu And TiC water Based Nanofluids

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Abstract- *It is greatly necessary to conduct thermal investigations of fuel cell for its smooth and efficient functioning. The current research involves a fuel cell which is encapsulated in a horizontal duct open at both the ends. The nanofluid as coolant is allowed to pass through the annular region between the fuel cell and duct. Three different water based nanofluids, namely Water-AlN, Water-Cu and Water-TiC, are considered as coolants in the present investigations. The numerical studies are carried out to obtain the heat transfer behavior of encapsulated fuel cell for 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 behavior. The simulations are performed to predict the temperature fields and temperature contours. The trends of results are along the expected lines. Simulation results predicted with three different water based nanofluids are analyzed and compared for realizing the relative importance of the stated nanofluids. Model parameters considered are fuel cell heat flux of 10 W/cm2 and nanofluid velocity of 9 m/s at duct inlet. The Water-Cu is observed as the nanofluid delivering the ultimate fuel cell workout without any sort of thermal devastation.*

Keywords- Fuel Cell, Cooling, Simulation, Nanofluids, Water-AlN, Water-Cu, Water-TiC.

I. INTRODUCTION

The generation electricity takes place by fuel cells through the electrochemical reactions. Here, the chemical energy stored in the fuel gets transformed to electrical energy. Mostly hydrogen is used as fuel and the ambient air acts like an oxidant. However, in few cases methanol is also used as fuel and pure oxygen as oxidant. Fuel cells require a fuel source and will perform for infinite period of time if inflows of fuel are maintained. As the power generation takes place without burning of fossil fuels (or any other energy sources), fuel cells produce very less pollution since the byproduct involved in fuel cell is only heat and water.For the said reason it comes under green energy technology. The maintenance of fuel cell is simple since there are very few moving parts in the system as compared to any other energy sources. Fuel cells do not use normal fuels for instance oil or gas and can then lessen pecuniary hankering on oil generating realms.

Usually, the batteries need solid reactants for instance lead, cadmium or other metal. Once these reactants are depleted, they must be discarded or recharged. Batteries can be regenerated either with electricity or by replacing the electrodes. Fuel cells maintain their popularity as efficient power generators.Considering their high energy conversion efficiency, zero emission potential, low noise and potential use of renewable fuels, the fuel cells are considered as future devices for mobiles, stationary and portable power applications. Researchers across the globe are still working for its implementation to some of the space programs and produce power for probes, satellites and space capsules. Fuel cells also have been used in various other applications due to its tremendous success. Fuel cells are effectively deployed to power fuel cell vehicles and are also utilized to provide electric power for domestic, manufacturing and business houses.

II. LITERATURE REVIEW

Xuan and Roetzel [1] introduced ideas of thermal correlations about various 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. Xuanet al. [4] reviewed about the contaminations in PEM type hydrogen fuel cells. Chaitanyaet 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.Houchanget al. [12] examined about the functional behaviors of air-cooled proton exchange membrane fuel cell lots at ambient circumstances.

III. OBJECTIVES OF PRESENT RESEARCH WORK

From the already stated research works, to the best of author' understanding, it is very apparent that there is not a single complete computational research concerning to the impacts of water based nanofluids (namely Water-AlN, Water-Cu and Water-TiC) on thermal performance of fuel cells. With this perspective, the present paper demonstrates numerical investigations with the stated nanofluids 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 nanofluids (as they significantly affect the cooling characteristics) by taking fuel cell heat flux and duct inlet nanofluid velocity as the important model parameters. Finally, the model results relating to the several nanofluids are along the expected lines as well.

IV. DESCRIPTION OF PHYSICAL PROBLEM

The illustrative sketch of a distinctive fuel cell to be inserted in a duct is portrayed in the figure 1. The associated physical model as demonstrated 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 coolants considered in the present investigations are three different water based nanofluids named as Water-AlN, Water-Cu and Water-TiC. 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 nanofluids are 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 several nanoparticles accompanied by the concerned system variables, are mentioned in table 1.

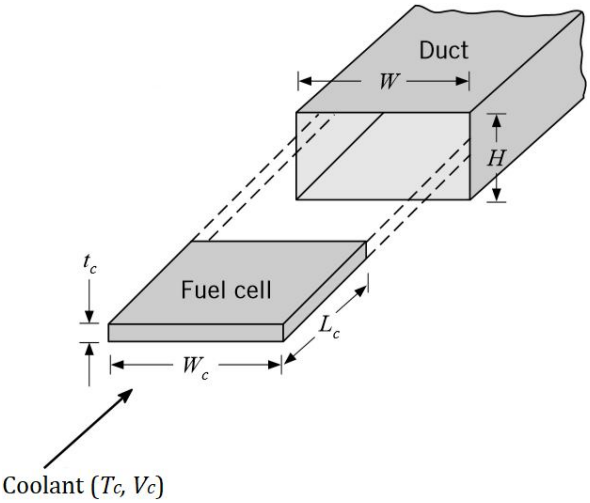

Figure 1. Schematic of fuel cell to be kept in a rectangular duct

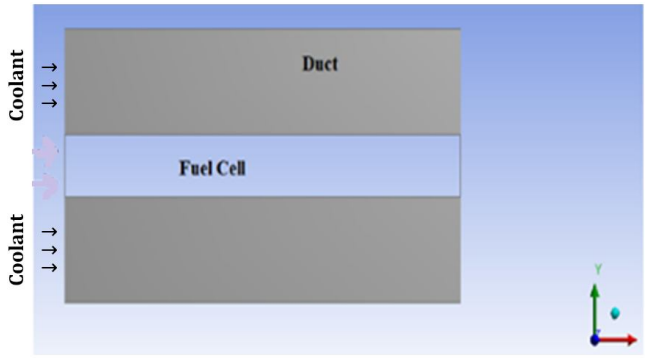

Figure 2. 2D computational domain with coolant flow in duct

Table 1Thermophysical properties of nanoparticles and model data

Nanoparticle Properties	**AlN**	**Cu**	**TiC**
Density, ρ (Kg/m^3)	3260	8940	4930
Specific heat, C_P (J/kg-K)	740	385	711
Thermal conductivity, k (W/m-K)	285	401	330
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		

V. MATHEMATICAL FORMULATION

The talked about physical problem is expressed as a set of governing transport equations which are solved by the

present computational procedures involving both modeling and simulation. The related continuity, momentum and energy equations in 2D for a fully developed hydrodynamic and thermal flow situations are described in equations from (1) to (4), respectively. The compressibility and the viscous heat dissipation effects are not taken into considerations for the current physical circumstances.

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

VI. NUMERICAL PROCEDURES

A. Numerical scheme and solution algorithm

The said governing transport equations are expressed in generalized form as mentioned underneath.

$$\frac{\partial}{\partial t}(\rho\varphi)+\nabla.(\rho\,\mathbf{u}\,\varphi)=\nabla.(\Gamma\nabla u)+S \quad (5)$$

The transformed governing transport equations are discretized with the second order upwind scheme using a pressure based finite volume method with the SIMPLER algorithm, where Γ represents a transport property (k or μ), ϕ denotes any conserved variable and S is a source term.

In the beginning, both the continuity and momentum equations are solved all together to find 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 (but not separately) on account of interdependency between the related parameters.

4.2. Choice of grid size, time step and convergence criteria

A broad and thorough grid-independence test is accomplished to introduce an appropriate spatial discretization, and the levels of iteration convergence criteria to be utilized. As an outcome of this test, we have used 50 × 20 uniform grids for the final simulation. Corresponding time step taken in the simulation is 0.0001 seconds. Though we checked with smaller grids of 30 and 40 in numbers for 20 mm height of the computational domain, it is observed that a finer grid system does not alter the results significantly. In other words, the statistical data reveals that the finer grids have minor effect in the simulation results which is quite obvious from the definition of grid-independence test. Furthermore, the smaller grid connects to to more computational time comprising more constancy in results of several contours/fields.

Convergence in inner iterations is confirmed merely while the condition $\left|\frac{\varphi-\varphi_{old}}{\varphi_{max}}\right| \le 10^{-4}$ is fulfilled at once for all parameters, where φstands 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 $\varphi_{max}$is the maximum value of the parameter at the present iteration level in the intact field.

VII. RESULTS AND DISCUSSION

The numerical simulations are done to examine the impacts of three different water based nanofluids (such as Water-AlN, Water-Cu and Water-TiC) on cooling behaviors 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 with the fuel cell is considered to be 10 W/cm^2 and the velocity of nanofluid at the duct inlet is taken to be 9 m/s.

A. CASE STUDY WITH WATER-ALUMINUM NITRIDE NANOFLUID AS COOLANT

With the talked about model conditions, with the aim of examining the impact of Water-AlNnanofluid on the heat transfer characteristics of the fuel cell, the numerical simulations are accomplished, by considering the thermophysical properties of the said nanofluid.

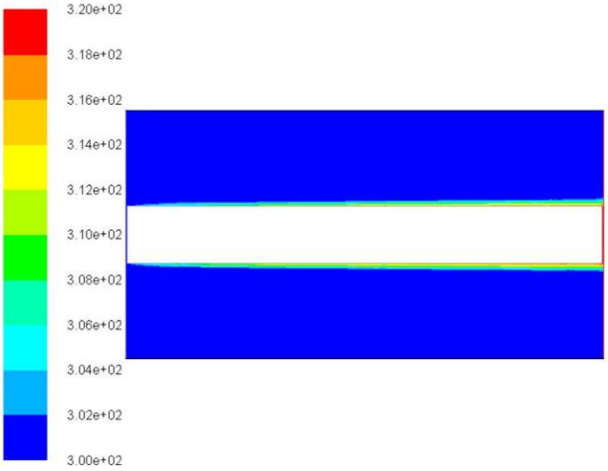

Figure 3. Temperature field with Water-AlNnanofluid as coolant.

Figure 3 demonstrates the simulated results of the temperature field (alongside the colored scale bar showing the temperature values in terms of K) as observed at the present model conditions by taking Water-AlNnanofluid as coolant. The surface temperature of fuel cell is found to be 320 K, which is far above the ambient and may trigger thermal failure of the fuel cell. As expected, the temperature of the Water-AlNnanofluid is maximum near the vicinity of fuel cell. And also, the temperature of the Water-AlNnanofluid 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 associated temperature contour is also illustrated in figure 4. The trends of results are along the expected lines as well.

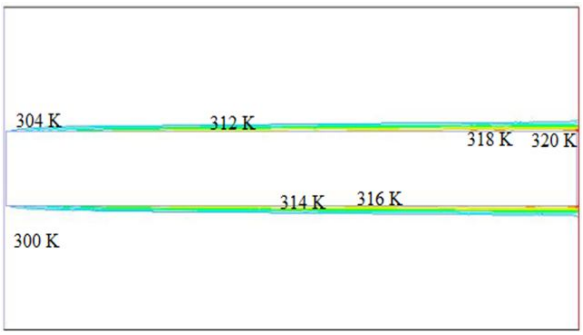

Figure 4. Temperature contour with Water-AlNnanofluid as coolant.

B. CASE STUDY WITH WATER-COPPER NANOFLUID AS COOLANT

With the talked about model conditions, with the intention of observing the effect of Water-Cu nanofluid on the heat transfer characteristics of the fuel cell, the numerical simulations are done, by taking into account the thermophysical properties of the said nanofluid.

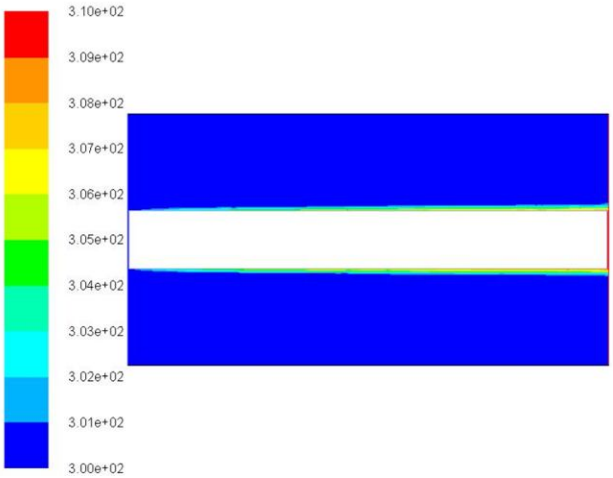

Figure 5. Temperature field with Water-Cu nanofluid as coolant.

Figure 5 elucidates the simulated results of the temperature field (accompanied by the colored scale bar exhibiting the temperature values in terms of K) as found at the stated model conditions by taking into consideration Water-Cu nanofluid as coolant. The surface temperature of fuel cell is found to be 310 K, which is very close to the ambient and also within the safe limit of temperature as desired in order to avoid the thermal failure of the fuel cell. As expected, the temperature of the Water-Cu nanofluid is maximum near the vicinity of fuel cell. And also, the temperature of the Water-Cu 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 related temperature contour is also illustrated in figure 6. The trends of results are also along the lines expectations.

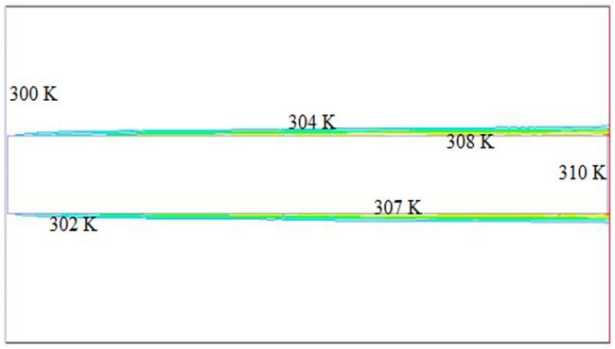

Figure 6. Temperature contour with Water-Cu nanofluid as coolant.

C. CASE STUDY WITH WATER-TITANIUM CARBIDE NANOFLUID AS COOLANT

With the present model conditions, with the purpose of studying the effect of Water-TiCnanofluid on the heat

transfer characteristics of the fuel cell, the numerical simulations are conducted, by introducing the thermophysical properties of the talked about nanofluid.

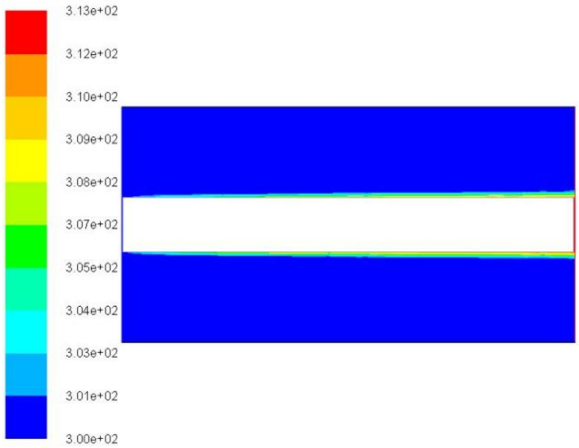

Figure 7. Temperature field with Water-TiCnanofluid as coolant.

Figure 7 illuminates the simulated results of the temperature field (in conjunction with the colored scale bar demonstrating the temperature values in terms of K) as acquired at the talked about model conditions by including Water-TiCnanofluid as coolant. The surface temperature of fuel cell is found to be 313 K, which is also somewhat close to the ambient and within the safe limit of temperature as desired in order to avoid the thermal failure of the fuel cell.. As expected, the temperature of the Water-TiCnanofluid is maximum near the vicinity of fuel cell. And also, the temperature of the Water-TiCnanofluid 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 concerned temperature contour is also depicted in figure 8. The trends of results are along the expected lines as well.

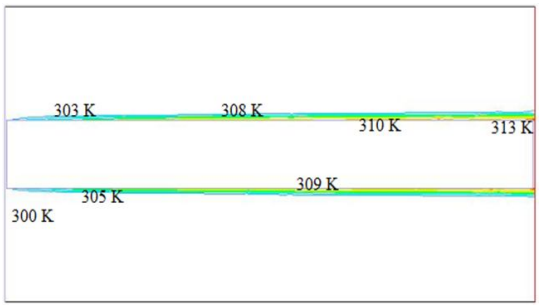

Figure 8. Temperature contour with Water-TiCnanofluid as coolant.

D. COMPARISON OF TEMPERATURES OF FUEL CELLS OBTAINED WITH VARIOUS NANOFLUIDS AS COOLANTS

Table 2 embodies the numerically predicted temperatures of the fuel cells as gotten with the practice of three different water based nanofluids (specifically, Water-AlN, Water-Cu and Water-TiC) as coolants. It is observed that the numerical predictions/results are comparable with each other. As expected, the variations in the numerically predicted temperatures of the fuel cells are witnessed very clearly with the use of the stated water based nanofluids as coolants. This is on account of the variations in the thermal conductivities of the related nanoparticles as declared in table 1.

Table 2. Comparison of numerically predicted temperatures of fuel cells with variousnanofluids as coolants.

Name of Nanofluid	Numerically Predicted Temperature of Fuel Cell(K)
Water-AlN	320
Water-Cu	310
Water-TiC	313

Similarly, figure 9 also demonstrates the plot expressing the variations in the fuel cells temperatures with three different water based stated nanofluids as coolants. It is very evident that the trends of the variations in the numerically predicted results are along the lines of expectations.

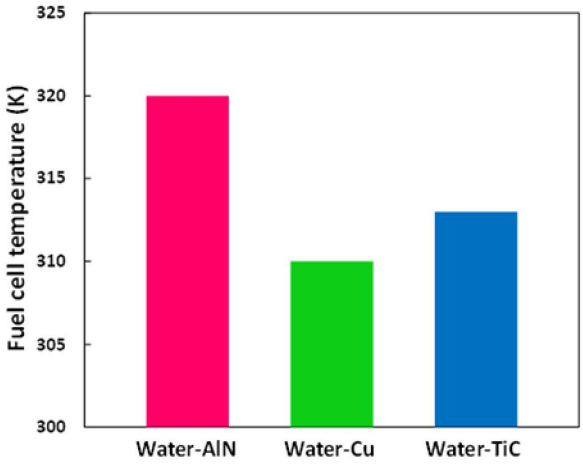

Figure 9. Variations in fuel cells temperatures with different water based nanofluids as coolants.

VIII.CONCLUSION

A computational model with regard to the fuel cell is established to obtain the heat transfer characteristics with three different water based nanofluids, specifically Water-AlN, Water-Cu and Water-TiC as coolants. 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 they 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. The predictions of the model pertaining to the different nanofluids are along the expected lines. 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, the numerically predicted results with three different water based nanofluids are really very much comparable to each other. However, it is observed that the Water-Cu nanofluid renders appropriately effective cooling behavior without any such thermal failure and is the optimum one as the fuel cell temperature is far below the safe limit. Thus, the present model in conjunction with the nanofluid can be applied right away in manufacturing shops to improve heat transfer and for thermal management of fuel cells.

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