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Computational Fluid Dynamic Analysis of Alumina Nanofluid Coolant for a Typical PWRs

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1. Introduction

An innovative newly way of enhancing the heat transfer capability of fluids is to suspend nano-size particles in the fluid which improve the thermal conductivity of fluid. Nanofluid is a suspension of nanoparticles in base fluid. Nanofluids have attracted enormous interest from researchers due to their potential for high rate of heat exchange incurring either little or no penalty in pressure drop. Surveys such as that conducted by Williams et al. [1] have shown that that circulation of water-based nanofluid in the primary cooling loop of PWR will improve the heat removal from the core. However, using nanofluids as working fluids has a number of limitations because any change in the reactor core materials affects the criticality and hence the effective multiplication factor. Previous studies of the application of nanofluids to LWR predicted that among nanofluids at low volume concentrations, both the alumina and zirconia nanoparticles are basically transparent to neutrons, and their contribution to coolant activation is minimal and can be used in LWRs.

The scope of the present paper is to add a further contribution to nanofluids turbulent convection in a subchannel of a typical Small Modular Reactor (SMR) core. Developing turbulent forced convection flow of Al_2O_3/Water nanofluid in a subchannel is numerically investigated. The finite volume method is employed to solve the problem and two phase mixture model is considered. A three dimensional steady state is considered, with uniform heat flux on the fuel rods wall. The study is carried out for water with spherical alumina nanoparticles with a diameter of 38 nm.

2. The CFD methodology

For the purpose of numerical analysis, geometry and boundary conditions were extracted from a typical SMR.

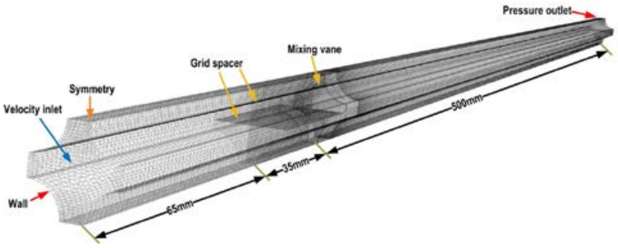

Fig. 1 Computational domain meshes.

The CFD analysis was performed using the commercial CFD code ANSYS FLUENT 12.1. The computational domain consists of a subchannel with length *L* of 600 mm (65 mm upstream and 500 mm downstream of the top of grid spacer) as depicted in Fig. 1. The fuel rod diameter *D* is 9.5 mm, and the pitch-to-diameter ratio *P/D* is 1.32 (Fig. 2).

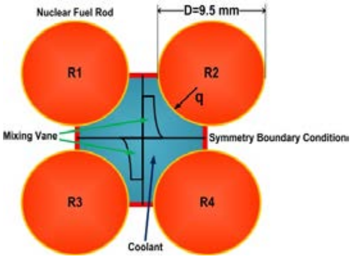

Fig. 2 Cross section at the grid spacer location.

At the channel inlet, profiles of uniform axial velocity 6.79 m/s (similar with Karotous et al [2] experiments), temperature 570°K prevail. A constant 250 KW/m^2 heat flux is specified for the fuel wall heat flux. Operating pressure was 15 MPa. In the absence of experimental data available correlation were used to calculate the thermophysical properties. Classical formulas for a two-phase mixture are used to compute the density. Pak and Cho [3] presented an accurate expression for determining the density of nanofluids as;

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_P \tag{1}$$

A couple of expressions are proposed for determining the specific heat of nanofluids [4] as

$$C_{nf} = ((1-\varphi)C_f + \varphi C_p) \tag{2}$$

$$C_{nf} = ((1-\varphi)\rho_f C_f + \varphi\rho_P C_p)/\rho_{nf} \tag{3}$$

Eq. (3) is theoretically more consistent since the specific heat is a mass specific quantity whose effect depends on the density of the components of a mixture [4].

$$\mu_{nf} = (123\varphi^2 + 7.3\varphi + 1)\mu_{bf} \tag{4}$$

$$K_{nf} = (4.97\varphi^2 + 2.72\,\varphi + 1)K_{bf} \tag{5}$$

The nanofluid viscosity is an important parameter for practical applications since it directly affects the pressure drop in forced convection. Eq. (4) is purely experimental, and turns out to be more apt than the classical models, such as Einstein or Brinkman, which drastically underestimate the nanofluid viscosity [4]. Eq. (5), based on a classical model, nonetheless yields good estimation of the thermal conductivity in the present case. In order to validation of CFD model, ANSYS FLUENT simulation results are compared to Laser Doppler Velocimetry (LVD) measurements performed by Karoutas et al. [2].

3. Result and Discussion

Figure 3 compares the pressure loss along the axial length of the subchannel obtained by ANSYS FLUENT 12.1 with Karoutas et al [2] and In el al. [5] CFD simulations for pure water to validate the computational model. Heat transfer calculations were made for different volume concentration of nanofluid by applying a constant temperature (T = 570 K) to the inlet of the channel and a constant heat flux to fuel walls (q = 250 kW/m^2) across the subchannel. Results showed enhancement on the heat transfer using nanofluid in comparison to the base fluid (Fig. 4). This behavior can be partially explained with the improved thermophysical properties of the nanofluid such as thermal conductivity. Contours of velocity magnitude in some particular x-y planes along the subchannel are given in Fig. 5.

Although the nanofluids have great potential for enhancing heat transfer, research work on the concept, enhancement mechanism, and application of the nanofluids in nuclear reactors and power plants is still in its infancy. The current investigation was limited by the absence of experimental data for nanofluid. A complete understanding of heat transfer performance of the nanofluids is prerequisite to their practical application to a commercial nuclear reactor. It is recommended that further research be undertaken in the neutronic and metallurgical analysis of nanofluids for apt nanoparticle and its optimum concentration in the base fluid.

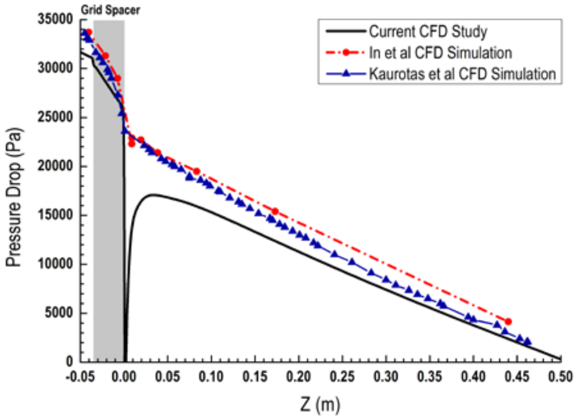

Fig. 3 Pressure loss along the subchannel for pure water [Pa].

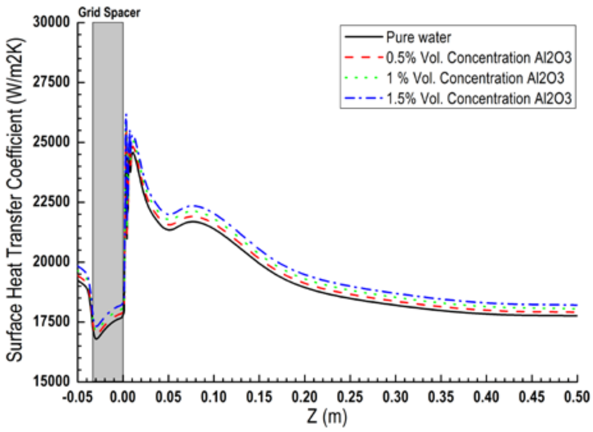

Fig. 4 Average wall heat transfer coefficient [W/m^{2}K]

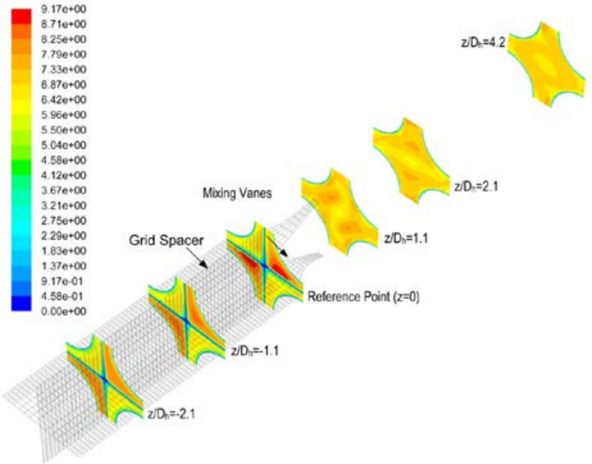

Fig. 5 Contours of velocity magnitude [m/s].

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