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Technical note

Twofold application of nanofluids as the primary coolant and reactivity controller in a PWR reactor: Case study VVER-1000 in normal operation

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ABSTRACT

The use of nanofluid as a dual heat transfer enhancer and excess reactivity controller in a typical pressurized power reactor (PWR) is the focus of this study. Presently, boric acid is the dominant method for reactivity control in PWRs and Chemical & Volume Control System (CVCS) controls the boric acid concentration during reactor operation. In this study, we have replaced the coolant fluid of the first loop with a nanofluid which act as coolant, neutron moderator and neutron absorber. A full core of VVER-1000 as a typical PWR system is modeled with coupled neutronics and fluid dynamic codes. Among five nanofluids investigated, 2% volume fraction silver oxide is found to satisfy both neutronics and thermohydraulics safety margins of VVER-1000 nuclear reactor.

1. Introduction

Numerous studies have investigated heat transfer enhancement by replacing base fluid with a nanofluid. Circulation of nanoparticle/water (nanofluid) in the primary cooling loop of a light water reactor have shown to increase in heat removal from the core. Improvement in Critical Heat Flux (CHF) as well as Departure from Nucleate Boiling Ratio (DNBR) are achievable as the result of the base fluid replacement with nanofluid (Buongiorno et al., 2009). Nanofluids have also shown to be promising (Buongiorno and Truong, 2005) as a safety enhancement in the event of a loss of coolant accident (LOCA) (Buongiorno et al., 2009).

Although neutronic properties of nanofluids and achieving criticality in the presence of nanoparticles have been studied (Hadad et al., 2010, 2013; Nazififard et al., 2012; Safarzadeh et al., 2014).

In this study, coupled neutronic/thermohydraulic behavior of a nanofluid as the primary coolant of a VVER-1000 reactor and with dual responsibility of heat transfer enhancement and excess reactivity controller is investigated. For the neutronic modeling, the base water/boric-acid fluid is replaced with a nanofluid and the criticality is investigated by adjusting nanofluid volume fraction. Thermohydraulic study which concerns with heat transfer enhancement, is investigated by modeling an average channel of the reactor core with nanofluid specified from neutronic study. The neutronics and thermohydraulic are iterated to achieve convergence on temperature and power distribution along the channel.

2. Material and methods

Among variety of nanofluids available for our objectives, we considered the following factors to narrow down to a short list:

a. Thermal neutron absorption cross section,
b. Thermophysical properties including heat capacity, conductive heat transfer coefficient, viscosity, friction factor,

we use two models to solve the problem, first, VVER-1000 core is modeled with MCNP5 code for the neutronic calculation, and then a fuel assembly is modeled with a computational fluid dynamic code (CFD) for the thermohydraulic calculation (Nazififard et al., 2012; Liu and Ferng, 2010). Fig. 1 illustrates the flowchart that shows how the coupling of neutronic/thermal-hydraulic codes has been carried out.

2.1. Fuel Assemblies (FAs) modeling

The core is modeled with 8 different FAs where the enrichments ranging from 1.6 to 4.02 wt percent. Each FA may contain any of 6 types fuel rods (FR). Based on combination of FRs in an assembly, 8 types of FA are defined (Hadad and Ayobian, 2006; Hadad and Porhemmat et al., 2015; Hadad et al., 2009).

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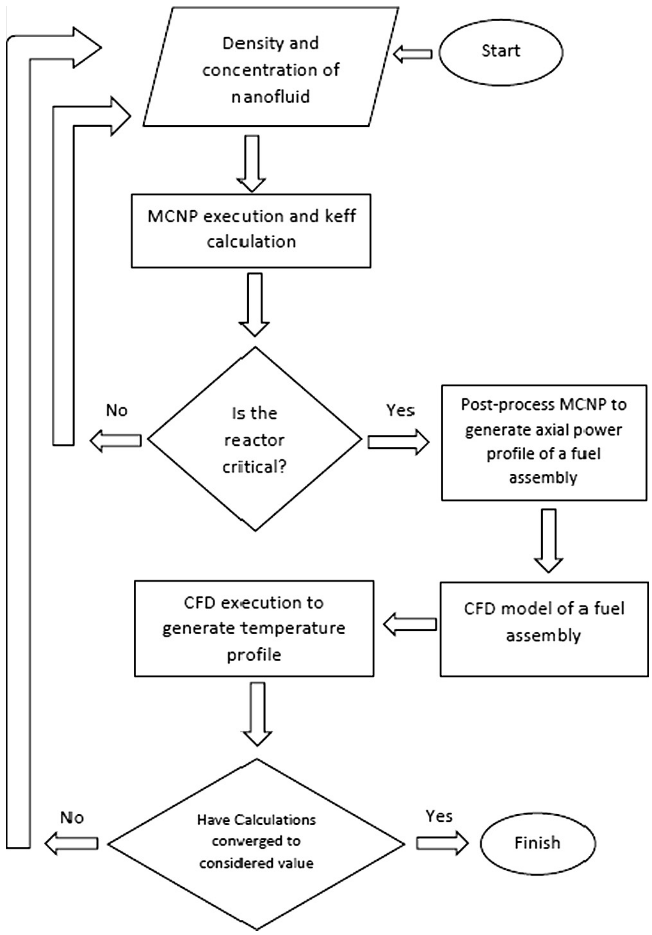

Fig. 1. Flowchart of neutronic/thermal-hydraulic codes coupling.

2.2. Core modeling

During the first cycle, core consists of 163 FAs arranged in a hexagonal lattice. Since the fluid temperature is not constant through the core, we divided the core height into 10 isothermal regions. The nanofluid density variation with temperature is evaluated from the following relationship (Xue and Xu, 2005).

$$\rho_{nf}(t) = (1-\phi)\rho_{bf}(t) + \phi\rho_p(t) \quad (1)$$

where $\rho_{nf}(t)$, $\rho_{bf}(t)$ and $\rho_p(t)$ are temperature dependent densities of nanofluid, water and nanoparticle respectively, and ϕ is nanoparticle volume fraction in the nanofluid.

2.3. Thermohydraulic modeling

A single fuel assembly (FA) to numerically represent nanofluid circulation in the reactor core is modeled (Hadad et al., 2015). Due to symmetric arrangement of fuel pins in a FA, geometric modeling of only 7 fuel pins is sufficient. Fuel pins have 9.1 mm OD and 12.75 mm pitch arranged in a triangular array having a height of 3550 mm along which the heat flux entrance to the fluid flow. Using flow cross section and the hydraulic diameter, Reynolds number is found to be greater than 2500, which implies the dominancy of the turbulent flow.

2.4. Single-phase model

This model, which is widely used in previous studies considers the nanofluid as a homogeneous fluid with effective properties and uses the differential equations that express conservation of mass, momentum, and energy:

$$\nabla \cdot (\vec{V}) = 0 \quad (2)$$

$$\nabla(\rho\vec{V}\vec{V}) = -\nabla P + \nabla \cdot (\mu_t \nabla \vec{V}) + \rho g \quad (3)$$

$$\nabla \cdot (\rho\vec{V}H) = -\nabla \cdot q'' - \tau_t : \nabla\vec{V} \quad (4)$$

That V is velocity (m/s), ρ is density (kg/m^3), P is pressure (N/m^2), H is enthalpy (joul/kg), q'' is heat flux (W/m^2) and μ_t is fluid dynamic viscosity (kg/m.s).

2.5. Boundary conditions

At the fuel assembly inlet, profiles of uniform axial velocity, u_0 = 5.6 m/s for water and temperature, T_0 = 564 °K, are assumed. At the fuel assembly exit section, the fully developed conditions are assumed. Surface heat flux from fuel rod surface is assumed to be constant in each of the 10 segments along its 3550 mm height. During reactor operation, pressure is stabilized at 15.5 MPa and pool boiling is not credible.

3. Result and discussion

Table 1 illustrates Volume fractions of each nanofluid that for this, core can be critical.

Due to high critical volume percentage of alumina and zirconia nanofluids (50% and 40%), they are not considered as practical nanofluids for this study's objectives.

3.1. Multiplication factor

Fig. 2 shows that Keff decreases with nanofluid volume fraction increase. However, there is distinct response for different types of nanofluids. Variations of Keff value vs. volume fraction is plotted for 5 types of nanofluids plus the water/boric acid which is the base fluid. Since selecting the nanofluid with the lowest concentration which could make the core critical is our objective, water/silver and water/silver oxides are the best candidates.

3.2. Scattering cross sections

In Fig. 3 variations of nanofluids scattering cross sections for different volume fractions are presented.

3.3. Moderator temperature coefficient of reactivity

Moderator reactivity value for water/silver oxide is illustrated in Fig. 4. In this figure "R^2" is the correlation coefficient and the line slope represents the reactivity coefficient.

Moderator reactivity coefficients of other nanofluids and water/boric acid are presented in Table 2.

Table 1
Critical volume percentage of nanoparticles.

Nanofluid	Critical volume percentage
Alumina	50
Zirconia	40
Silver	1.2
Silver oxide	2.0
Copper oxide	13