



Design and criticality analysis of colloidal slurry nuclear reactors



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ARTICLE INFO

Article history:

Received 23 June 2017

Received in revised form 28 August 2017

Accepted 1 September 2017

Keywords:

Colloidal slurry

Critical reactor

MCNP model

ABSTRACT

A novel nuclear reactor concept is presented in this paper which can sustain the controlled fission reaction and has an innovative mechanism of reactivity control. The concept of this reactor is based on the stability of colloidal suspensions. These suspensions consist of colloidal fuel particles suspended in a moderator with a controllable separation distance. The packing factor of the colloidal suspension can be controlled by slightly modifying the ionic concentration of the suspension medium, effectively controlling the criticality of the reactor. Based on local average separation distance between particles, thermalization of neutrons can be varied and can be used to manipulate neutron multiplication factor k_{∞} . Numerical calculations are performed with the help of MCNP software to obtain optimal configuration of critical assemblies. For the numerical case studies presented in this paper, uranium dioxide (UO_2) fuel particles with size $\geq 10 \mu\text{m}$ in different liquid solvents are considered. The fuel particles are simulated as hard spheres packed in Bravais lattice structures within the solvent medium. Simulations involve neutron interactions of a uniform colloidal suspension of spherical fuel elements of diameters 5 cm–0.001 cm. The homogeneous fuel equivalence was found to occur for particles sized below 0.010 cm diameter. Criticality curves are generated for fuel particle configurations with varying particle density, confirming fuel configurations can be controlled by only modifying particle packing factor. Additional criticality curves are generated for various cylindrical geometries of fuel suspension vessels with modular form factors. Triethylene glycol is substituted as a moderator and suspension fluid with higher boiling point as compared to water. The type of moderator or solvent does not have any significant impact on criticality performance.

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1. Introduction

Nearly all nuclear power reactors currently operating around the world are heterogeneous thermal reactors i.e. the reactor core consists of lumped regions of fuel surrounded by moderator. There are several advantages of heterogeneous assembly of fuel-moderator over homogeneous mixture, but one of the most significant advantage is the improvement in multiplication factor by increasing the resonance escape probability of neutrons emitted after fission reaction (Lamarsh, 1966). The critical condition of the reactor must be controlled by some means other than changing the properties of the fuel or the geometry of the reactor, normally by introducing neutron absorbing control rods into the core. The dependence on neutron absorption as the principal control scheme reduces the actual burnup of the fuel. The inclusion of mechanical control elements increases the minimum size of the reactor and also requires excess reactivity. Similarly, the heat transfer process becomes complex as reactor coolant is circulated other indirect

heat exchange loops. Therefore some of desirable features of a homogeneous reactor such as simplified control system and heat transfer system (Lane, 1958; Bajorek et al., 2010) are no longer available in these heterogeneous reactors.

In this paper a novel reactor concept consisting of a colloidal slurry of fuel particles in a neutron moderating solvent is presented and analyzed. Such a reactor would be able to adjust the pitch distance between its fuel elements (fuel particles) during operation, eliminating the need for an absorbing control medium. The effective neutron multiplication factor (k_{eff}) of the colloidal suspension can instead be adjusted by influencing the electrostatic and van der Waal forces present between suspended fuel particles in a colloidal suspension. A conventional example of this physics is seen in day to day life if one adds vinegar into milk resulting into cottage cheese suspension. Apart from innovative control mechanism, this design offers to retain the advantages of both heterogeneous and homogeneous reactors. The goal of this paper is not to present any merits of this new conceptual reactor design but to present this idea and relevant criticality calculations in a generalized manner.

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1.1. Fundamentals of colloidal slurry

A stable colloidal suspension consists of solid particles with characteristic size $\leq 10 \mu\text{m}$ uniformly dispersed in a solvent. The stability of these suspensions is dictated by the forces between the suspended particles which dictate the separation distance and movement of the suspended particles. These forces or potentials are sensitive to the particle material, solvent characteristics (ie ionic concentration) charge distribution on the particle's surface, and separation distance (pitch) (Bindra and Jones, 2009). In a colloidal suspension, electrostatic forces provide repulsive potential between particles, which have similar surface charges. Van der Waals forces are attractive, but are purely dependent on dipole interactions of adjacent molecules. The stabilization of any colloidal suspension is heavily dependent on the balance of these potentials, composition of the suspension fluid, as well as the surface chemistry of the colloid particles. Importantly, the forces that contribute to particle spacing can be manipulated by chemically altering the pH level of the moderating fluid.

In this conceptual design of colloidal slurry reactor, the reactor fuel consists of a suspension of uranium dioxide particles in a solvent medium, ideally a polar liquid. Generally, it is much easier to control colloidal stability with ionic or polar solvents. Classical examples of colloidal suspensions use water as the solvent but in order to obtain power generation with practical thermodynamic efficiency of secondary cycles, high temperature (up to 300–400 °C) solvents with low vapor pressure such as ionic liquids or molten salts can provide feasible solutions. Therefore, the possible system design can be obtained with high temperature ionic liquid such as $\text{C}_4\text{MIM}:\text{TF}_2\text{N}$ (1-Methyl-3-propylimidazolium bis(trifluoromethylsulfonyl) imide) as solvent, moderator, and primary heat transfer system. This medium would serve as both a moderator and as a charge transmitting electrolyte. In case of aqueous or polar solvents the governing interaction potentials are described by classical DLVO (Derjaguin, Landau, Verwey, and Overbeek) theory. According to DLVO theory, the van der Waals and electrostatic potentials govern the interactions between suspended particles.

1.2. Interaction potentials

Intermolecular forces occur by virtue of two or more molecules attracting each other even though they are neutrally charged on average, which are commonly referred to as van der Waals forces. These attractive forces arise from a cooperative oscillation of electron clouds on a collection of molecules at close range. In its general form, energy of interaction (U) due to these intermolecular forces between two volumes V_1 and V_2

$$U = \oint_{V_1} \oint_{V_2} dV \frac{A}{r^6} \quad (1)$$

where A is the Hamaker constant, and r is the separation distance. Quantification of van der Waals potential, using classical relations, between spherical particles of radius r_h separated from a large planar surface by distance x in a medium, is resolved to,

$$U_{vdw} = -\frac{A}{6} \left[\log \frac{x(x+4r_h)}{(x+2r_h)^2} + \frac{2r_h^2}{x(x+4r_h)} + \frac{2r_h^2}{(x+2r_h)^2} \right] \quad (2)$$

The Hamaker constant, $A = \frac{\sqrt{A_h} - \sqrt{A_w}}{\sqrt{A_s} - \sqrt{A_w}}$, can be computed from the individual literature values for the particles, substrate and solvent denoted by subscripts h , s , and w , respectively.

In a stable colloidal suspension of similarly polarized (monovalent) particles, the ionic concentration of the medium provides a repulsive electrostatic force on the surface of colloidal particles. The electrostatic interactions can be approximated with average

surface charge on each particle; ionic layers are formed on the surface with number density gradually decreasing into the bulk (Hidalgo-Álvarez et al., 1996). In order to find the net potential of this arrangement Guoy-Chapman gave a double layer model. This double layer (Stern layer) potential is associated with the electrophoretic mobility, and is better known as zeta potential. The Guoy-Chapman model is linked to the basic principles of electrostatics, with the Poisson equation

$$\nabla^2 \psi = -\frac{2ze n_0}{\epsilon} \sinh(ze\psi/kT) \quad (3)$$

where, k is the Boltzmann constant, T is the temperature of medium, e charge of an electron, z atomic number, ϵ is the dielectric constant of water or solvent, ψ is surface potential and n_0 is the ionic concentration in solution. The surface charge concentration can be approximated with experimentally measured zeta-potential and then electrostatic potential between particle and substrate can be computed as

$$U_{el} = \pi \epsilon r_h [(\psi_h + \psi_s)^2 \log(1 + e^{-\kappa x}) + (\psi_h - \psi_s)^2 \log(1 - e^{-\kappa x})] \quad (4)$$

where κ is the inverse Debye length, x is the separation distance, r_h is the particle radius, ψ_h is the surface potential of particle and ψ_s is the surface potential of substrate. The total interaction potential between hematite particle and alumina substrate is shown in Fig. 1 The peptization of any colloidal suspension is heavily dependent on the balance of these potentials, composition of the suspension fluid, as well as any coatings on the surface of the colloid particles. The extent of this force is often described in terms of the Debye length, which quantifies a charge carrier's net electrostatic effect in solution (Kirby, 2010). The Debye length (often denoted as λ_D) for a specific colloidal suspension can be calculated as follows:

$$\kappa = \lambda_D^{-1} = \frac{z^2 e^2 n_0}{\epsilon k T} \quad (5)$$

The Debye length is inversely proportional to the square-root of the ionic concentration in the electrolyte. Fig. 2 shows the strong relationship between the debye length and the concentration of Co-ions and Counterions. Net result of changing charge concentration in the solvent leads to direct influence on particle separation distance.

Additionally, it is possible to graft polymer combs to the surfaces of colloid particles or vessel side walls to improve stability (called steric stabilization) and prevent sedimentation and aggregation of fuel particles. These polymer threads increase the

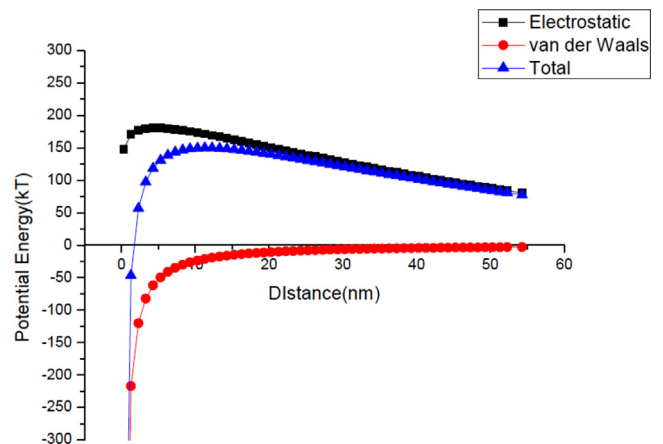


Fig. 1. Interaction potentials between adjacent particles as a function of separation distance due to electrostatic forces, van der Waals forces, and the net force (Jones, 2002).

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