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Investigation of heat transfer from a totally blocked fuel subassembly of fast breeder reactor with 7 and 19 pin bundles

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ABSTRACT

Liquid metal cooled fast breeder reactor is emerging as an important future power source. It uses sodium as the primary coolant, due to its favourable neutronic properties, high boiling point and large heat transfer coefficient. It is essential to continuously monitor adequacy of fuel pin/fuel subassembly cooling, so that sodium does not reach its boiling point. Sodium boiling within the fuel subassembly leads to large coolant flow reduction (as the density ratio of sodium liquid to sodium vapour is very high), under-cooling of fuel pins and hence damage to fuel subassembly. Development of partial flow blockage in the fuel pin bundle is possible due to the compact nature of fuel pin arrangement within the fuel subassembly, with small hydraulic diameter (typically, ~3 mm), despite the elaborate design provisions and coolant chemistry control. In the safety analysis, a total flow blockage is usually considered as an upper bound of all the partial blockages. The present work investigates the power level at which liquid sodium reaches its boiling point for different sizes of fuel subassembly. A porous body model has been developed based on local pressure-drop correlations for the axial/cross flow through fuel pin bundles. The model considers the total flow blockage situation in the fuel subassembly wherein the fuel pins and sodium (within the blocked subassembly) are considered as heat generating orthotropic porous medium. The proposed porous body model has been compared with a Computational Fluid Dynamics (CFD) model describing the same blockage condition. The commercial CFD code ANSYS FLUENT 15.0 has been used for the computational purpose. It has been found that the trapped liquid sodium coolant inside the blocked subassembly reaches its boiling point (1153 K at atmospheric pressure) at lower power input per pin in a 19 pin bundle model than that in a 7 pin bundle. This is traced mainly due to the fact that as the number of pins in the subassembly increases, the surface area of the hexcan wall (which is the ultimate heat sink) increases leading to enhanced heat dissipation in large size subassemblies. However, as the number of pins increases, the internal resistance for radial heat transfer increases, leading to increased sodium temperature inside the subassembly. These two competing effects determine the peak sodium temperature in the subassembly. Since the later effect is dominant, the permissible heat generation per pin decreases as the number of fuel pins in the bundle increases.

1. Introduction

Fast breeder reactor (FBR) is emerging as an eminent source of power due to large breeding capacity, high burn up and strong potential to transmute heavy isotopes. Primary system of a pool type FBR, wherein the reactor core is submerged in a large sodium pool is depicted in Fig. 1 (Velusamy et al., 2010). The choice of liquid sodium as coolant in FBR is due to its suitable thermal hydraulic and neutronic properties to remove dense heat generated from the compact FBR core (typical hydraulic diameter ~3 mm). It is necessary to have a satisfactory reactor design to ensure safety during normal and off normal operations. One such off normal operation is total blockage of a fuel subassembly. A typical medium sized FBR contains ~217 fuel pins per subassembly along with 487 flow sub channels (Chetal et al., 2006). Each of these fuel pins is wound with helical wires to guard the pins against flow induced vibration, ensure adequate space for coolant flow between adjacent pins and induce transverse flow for better coolant mixing. The tiny sub channels of FBR fuel subassemblies enhance the possibility of blockages. The blockage formation in fuel pin bundles could be initiated by various possible ways such as loading of blocked subassembly, passing of foreign particles such as weld spatter present in primary circuit through core via coolant, clogging by broken spacer

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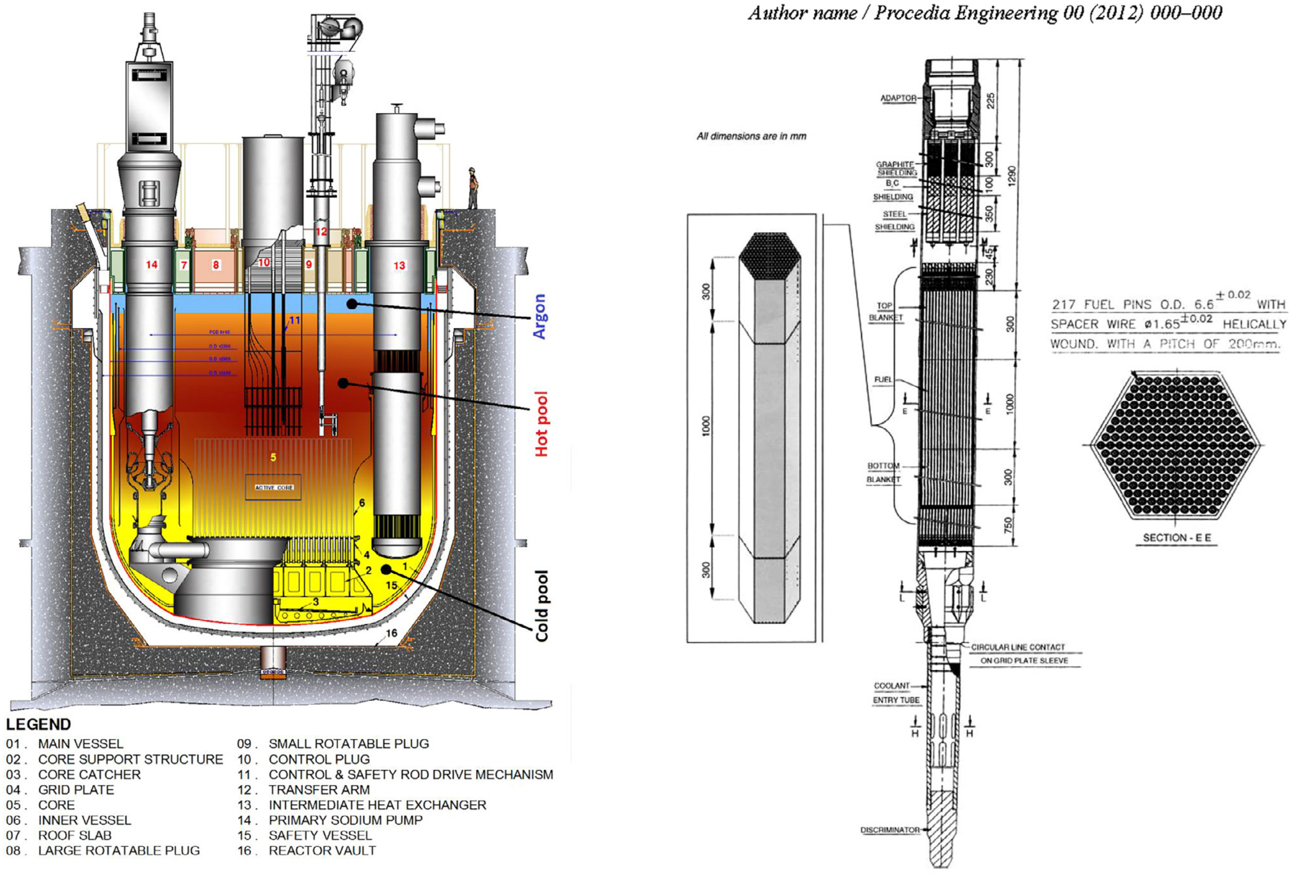
Nomenclature

C_2	pressure drop coefficient of staggered pin bundle (m^{-1})
C_p	specific heat capacity of the porous medium ($Jkg^{-1}K^{-1}$)
d_h	hydraulic diameter (m)
E	Euler number
F	friction factor of laminar flow (dimensionless number)
g	acceleration due to gravity (ms^{-2})
K_1	constant
k	effective thermal conductivity ($Wm^{-1}K^{-1}$)
L	characteristic length (m)
p	pressure (Nm^{-2})
q'''	internal heat generation rate (Wm^{-3})
Re	Reynolds number
T	temperature (K)
T_c	temperature cold wall (K)
u	velocity in x direction (ms^{-1})
v	velocity in y direction (ms^{-1})
w	velocity in z direction (ms^{-1})
x,y,z	coordinates in dimensional form (m)

Greek symbols

ρ	density (kgm^{-3})
β	coefficient of thermal expansion coefficient (K^{-1})
μ	dynamic viscosity of fluid (Nsm^{-2})



(a) (b)

Fig. 1. (a) Primary system of a pool type FBR (b) Prototype fuel subassembly.

wire etc. A heat generating blockage could also be formed due to failed fuel fragments. Irradiation swelling of fuel pins can also lead to flow blockage. These blockages (partial or total) can lead to sodium boiling, clad melting and fuel melting accidents. Although a Computational Fluid Dynamic (CFD) simulation offers a large volume of information regarding thermal hydraulic parameters in a blocked subassembly, such a study is generally time consuming and compute intensive. On the other hand, a porous body based thermal hydraulic model is less compute intensive and less time consuming. Hence, this model is well suited for parametric studies, though it does not provide finer details on thermal hydraulic parameters. Development of such a model and validate it against the CFD model is the main focus of this paper. In this model, the tightly packed fuel lattice of FBR has been considered as a tube bank porous media and a porous model has been developed based on the local pressure drop in the fuel pin bundles due to axial and cross stream flows. Subsequently, an investigation into the maximum power input per fuel pin for which the trapped liquid sodium reaches its boiling point for different sizes of fuel subassembly has been carried out.

2. Literature review

A large volume of research has been reported in open literature dealing with fuel subassembly blockages and core disruptive accident (CDA). The fuel subassembly blockages in FBR can be partial or total. The blockage can also vary according to the blockage geometry (shape and size), position and porosity. Gast and Smidt (1970) discussed the Bethe Tait model (KAERI/AR-546/99) of CDA in detail and explained a