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Hydrodynamics around a shroud tube assembly of a fast breeder reactor

Ankit Kumar Gautam, Pradipta Kumar Panigrahi*, Sunil Kumar

Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India

ABSTRACT

Control plug assembly of a liquid sodium cooled fast breeder reactor is partially submerged inside the liquid sodium coolant pool, free surface of which is blanketed with cover gas, mainly Argon to provide a non-reactive environment. It receives high velocity coolant flow from the fuel subassembly which travels through annular gap inside Control Safety Rod Driving Mechanism (CSRDM) assembly leading to swelling of free surface and gas entrainment inside the coolant pool. Entrained gas bubbles travel through different submerged components of the reactor and induces numerous complications including reactor power fluctuation, cavitation in inlet pumps and heat transfer inhibition in heat exchangers. Study of hydrodynamics around the shroud tube is crucial to examine cover gas entrainment inside the pool. The present study reports an experimental study on a 1:9 scale down model of CSRDM shroud tube assembly based on Froude number similarity. Eccentricity of the control rod inside the shroud tube is also an important parameter as temperature gradient along the CSRDM assembly leads to longitudinal thermal stress causing displacement of control rod from its center position in the shroud tube. Flow behavior around shroud tube, hump formation at the axial exit of shroud tube, air entrainment inside coolant pool have been reported for various parameters viz. inlet flow rate (q_i), free surface height (h_f) and eccentricity of central rod (e). Dye visualization, Schlieren visualization, Bulk visualization have been carried out and digital image processing techniques have been adopted for quantification of hump parameters and entrained air fraction inside the coolant pool.

The axial flow from the exit of the shroud tube impinges on the free surface like a wall jet. At low Froude number, the impinging jet flow travels radially outward on the interface like a wall jet boundary layer. The shear of the free surface flow drags the jet like flow from the pores upward leading to mixing between the vortices inside the shear layer and the free vortices from the pores of the shroud tube. At high Froude number, the impinging jet like flow penetrates through the interface leading to hump formation. The downward motion of the hump reduces the radial free surface flow and blankets the radial flow from the pores of the shroud tube. The eccentricity of the central rod leads to asymmetric axial flow from the shroud tube and thus the resulting hump becomes asymmetric due to impingement of asymmetric jet. Therefore, the impingement angle of the downward hump motion becomes different at both sides of the shroud tube with asymmetric flow field and bubble formation process inside the liquid pool. However, the synchronization between the hump unsteadiness and the surface wave motion leads to mixing of air bubbles inside the liquid pool. Average entrained air fraction increases with increase in inlet flow rate and decreases with increase in free surface height.

1. Introduction

The Prototype Fast Breeder Reactor (PFBR) uses liquid sodium as its coolant flowing at maximum temperature of nearly 547 °C. Control Plug (CP) assembly is a crucial component of the reactor which houses several critical subcomponents such as Control Safety Rod Driving Mechanisms (CSRDMs), Diverse Safety Rod Driving Mechanisms (DSRDMs), thermo-wells, Failed Fuel Localization Modules (FFLMs), Neutron detector. These components perform numerous functions including reactor power control, temperature monitoring inside core, power measurement and failed fuel identification. For further details on CP assembly design and sub-components refer Prakash et al. (2012). These components are subjected to cross flow and are prone to Flow Induced Vibration (FIV) due to slender geometry. To guard them from such risks various support components such as core cover plate, upper stay plate, lower stay plate and lattice plate are installed. CP shell and porous CSRDM shroud tubes have perforations that facilitates coolant flow received from fuel subassembly.

CP assembly is partially submerged into liquid sodium pool and is located right above the reactor core top. The CSRDM and DSRDMs,

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* Corresponding author.
E-mail address: panig@iitk.ac.in (P.K. Panigrahi).

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Nomenclature

q_i	inlet flow rate (lpm)
h_f	free surface height (mm)
e	eccentricity of central rod (mm)
L	length of shroud tube (mm)
r	inner radius of shroud tube (mm)
n	total number of perforations
d	perforation diameter (mm)
R	number of rows
Fr	froude number $(U/\sqrt{g(h_f+L)})$
U	characteristic velocity (m/s)
O	total number of pixels in horizontal direction
P	total number of pixels in vertical direction
N	total number of image frames
C	number of holes in a row
D	inner diameter of shroud tube (mm)
P_c	circular pitch of perforations (mm)
P_v	vertical pitch of perforations (mm)
C_p	pressure recovery coefficient
I_{rms}	intensity rms value
I_{avg}	intensity average value
x	radial distance from shroud tube's center (mm)
r_o	outer radius of shroud tube (mm)
ε_{vol}	air bubble fraction
h_{max}	maximum hump height (mm)
w_{max}	maximum hump width (mm)
α	submergence angle (Degree)
α_T	thermal diffusivity (m^2/s)
ϕ	porosity
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
CSRDM	Control Safety Rod Driving Mechanism
PFBR	Prototype Fast Breeder Reactor
FIV	Flow Induced Vibration
CP	Control Plug
DSRDM	Diverse Safety Rod Driving Mechanism
FFLM	Failed Fuel Localization Module
ARDM	Absorber Rod Driving Mechanism
NFR	Nominal Flow Rate
RPM	Revolutions Per Minute
lpm	liters per minute
CFD	Computational Fluid Dynamics
RGB	Red Blue Green

collectively known as Absorber Rod Driving Mechanisms (ARDMs) receive about 15.2% (Banerjee et al., 2005) of the total coolant flow emerging from the core. The annular gap between control rod and shroud tube allows coolant entry in axial direction and facilitates exit through perforations of the shroud tube and opening at the top. Argon, an inert gas, covers the free surface to provide non-reactive environment. Liquid sodium emerging out of axial exit and perforations leads to high turbulence, high free surface velocity and free surface swelling resulting in cover gas entrainment. The entrained gas bubbles poses various risks including uneven power distribution inside reactor, cavitation in pumps and inhibition of heat transfer in heat-exchangers. The CSRDM control rod with one end submerged in hot coolant pool at ~547 °C and other end attached to reactor vessel top maintained at ~120 °C undergoes longitudinal thermal stress along its length. As a result, control rod deflects away from its center position in the shroud tube developing eccentricity causing uneven flow and temperature distribution in the coolant pool.

Gas entrainment in the coolant pool occurs due to several factors i.e. formation of vortex dimple at free surface, temperature dependent dissolution of cover gas in sodium, sloshing and breaking of surface waves causing shearing of free surface and entrapment of bubbles (Winterton, 1972; Satpathy et al., 2013; Patwardhan et al., 2012; Madarame and Chiba, 1990; Eguchi et al., 1994).

Several studies have been carried out on CP design and fluid flow characterization around the CP assembly. Natesan et al. (2011) performed three dimensional computational study on single isolated shroud tube and integrated assembly of control plug for different perforation configurations of shroud tube and CP shell. Various other design modifications including jet breakers and baffle plate have been studied for achieving lower maximum free surface velocity. Computational and experimental study by Velusamy et al. (2010) and Banerjee et al. (2013) proposed introduction of baffle plate attached to reactor vessel for controlling free surface velocity within acceptable limits to avoid risk of gas entrainment. Tenchine (2010) highlighted various sources of gas entrainment in the primary sodium pool of an FBR and the challenges in their computational prediction. Experimental study by Banerjee et al. (2013) on a 1/4 scale down model of PFBR using water as simulant revealed that at 60% of nominal flow rate value, gas entrainment occurs and for values lower than 50% of nominal flow rate (NFR), the free surface is calm with negligible vortex formation. Several studies (Padmakumar et al., 2007; Ryan and Julyk, 1977; Prakash et al., 2012) observed that for flow rate condition of 20% to 110% of nominal value there is low FIV risks and no risk of fluid elastic instability.

Flow inside and outside a porous cylinder can be assumed as analogous to the flow around control rod and shroud tube assembly. Therefore, fundamental understanding of flow through a porous cylinder with and without free surface is expected to facilitate the basic understanding of flow around CP assembly. Somasundaran and Mysels (1975) presented analytical results of flow and pressure distribution and effective resistance for a porous cylindrical system for varied pressure boundary conditions. Tas and Bryant (1986) proposed an analytical model for a distribution manifold with uniform discharge and observed substantial agreement with the experimental data. Singh and Rao (2009) provided an analytical solution to model perforated tubes using mass and momentum balance equations. Foust and Rockwell (2007) carried out an experimental investigation on generic catheter tip that exhibits multiple interacting jets during injection process. They observed that flow structures associated with individual jet and interaction between adjacent jets are strong function of jet velocity and hole diameter. Chen and Sparrow (2009) experimentally investigated three different exit port geometries and concluded that the flow efflux from different exit port is dependent on individual resistances to fluid flow. A similar experimental study by Lee et al. (2012) reported the exit flow distribution and discharge angle characteristics of multi perforated tubes.

Various computational results have been reported for entire fluid domain of liquid pool with limited supporting experimental data by Satpathy et al. (2013), Natesan et al. (2011) and Velusamy et al. (2010). Experimental results on detailed flow characterization of perforated tubes submerged inside fluid pool in vertical setting are not available in literature. The effect of eccentricity of control rod, free surface height from shroud tube's top and porosity of the cylinder on flow field around an analogous porous cylinder is not available in literature. Therefore, the present study is directed towards experimental study of flow behavior around a 1:9 scale model of CSRDM shroud tube assembly as a function of inlet flow rate (q_i), free surface height (h_f) and eccentricity of Control rod (e) inside the shroud tube. Dye visualization has been carried out to report the nature of flow from the perforations of the shroud tube. Schlieren visualization has been carried out to show the nature of flow near the air–water interface and average radial flow from

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