DEVELOPMENT OF ONE DIMENSIONAL PINET CODE AND ANALYSIS OF HEAT REMOVAL IN OSCILLATING SODIUM COLUMN

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Abstract

While testing materials in research reactors, heat is generated from neutron/gamma heating in the test chamber. It is required to remove this heat to maintain the specimen at a required temperature and maintain the integrity of the supporting structures. For this purpose, a cooling arrangement with an oscillating sodium column cooled by circulating helium has been proposed considering safety and space constraints. The arrangement has been modeled using general-purpose in-house system dynamics code PINET. Simulations were carried out for a reference case, and then parametric studies with different parameters were carried out to understand their influences on heat removal rate. For the reference case with a helium inlet temperature of 313 K and flow rate of 40 CMH (at Standard Temperature and Pressure (STP) conditions - 0 °C and 1 atm), the average specimen chamber temperature was predicted as ~445 K, and its range of variation was predicted as 1.1 K. The total heat to be removed by cooling helium was ~1.7 kW. Parametric studies were carried out with different helium inlet temperatures and mass flow rates, and the change in chamber temperature with changes in these parameters was estimated.

1. INTRODUCTION

One of the objectives of nuclear research reactors is material testing in a neutron environment. The test materials are placed in a specially designed test chamber. Heat is generated in the chamber due to neutron/gamma heating. Cooling the chamber is essential to maintain lower temperatures. The space available for cooling arrangements is usually limited. Liquid sodium is preferred as a coolant because of its good heat transfer characteristics. However, handling liquid sodium outside the reactor is difficult as it reacts violently with air and water and will be radioactive. Hence, a cooling arrangement with an oscillating sodium column cooled by helium is proposed. Extensive research has been carried out on modeling pulsating heat pipes (PHPs) [1], [2]. In the present study, thermal-hydraulic analysis of a specimen chamber with a compact cooling arrangement has been carried out. Unlike pulsating heat pipes, the legs contain two phases of two different components – sodium and argon separated by an interface. And the instantaneous interface position between sodium and argon in the legs is known from the externally applied excitations. The model was developed using general-purpose in-house system dynamics code PINET [3]. The code has been validated against various thermal fluid phenomena like pressure transients, conjugate heat transfer, and natural circulation in loops.

The schematic of the cooling scheme considered in the study is shown in Fig. 1, along with the reference dimensions. The specimen chamber at the bottom is connected to two limbs/legs half-filled with liquid sodium. Argon cover gas is present above sodium to prevent its contact with air. The sodium level in the limbs is varied continuously with the help of an oscillator. Outer tubes are provided around the limbs and form the annular cooling jackets through which helium is passed to remove the heat from sodium in the limbs. The material of the tubes is stainless steel. A similar cooling arrangement has been proposed for testing materials in the Fast Breeder Test Reactor (FBTR) and Jules Horowitz Reactor (JHR). RISHI (Research facility for Irradiation studies in Sodium at HIgh temperature) loop has been set up in IGCAR, Kalpakkam, to test the functionality of the arrangement.

2. MODELING DETAILS

The schematic of the model built in PINET code is shown in Fig. 2. The model developed is for the case of testing the loop in the FBTR pool. The tube walls are modeled with heat slab components, the helium conduits with pipe elements, sodium columns with pipe elements (with interface), and the specimen chamber with a node. After a convergence study on important parameters, all pipe components are divided into five axial meshes.

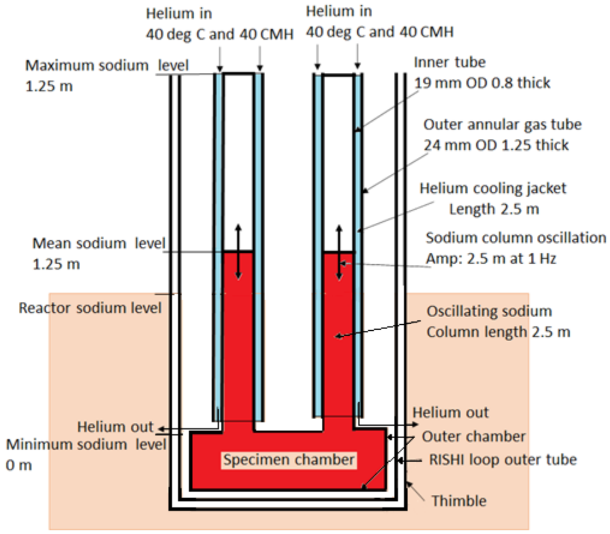
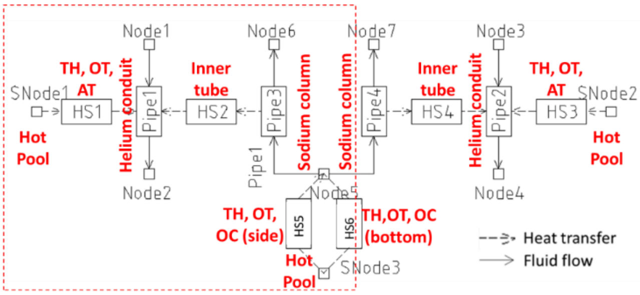


FIG. 1. Schematic of the cooling scheme for the specimen chamber.



Legend:
TH – Thimble,
OT – RISHI loop outer tube,
AT – Annular Gas Tube,
OC – Outer Chamber,
HS – Heat Slab,
Node – Fluid Node,
SNode – Solid Node

FIG. 2. Schematic of the model.

The mass, momentum, and energy conservation equation for fluids is given by equations (1), (2), and (3), respectively. The energy equation in the walls (solid) is given by equation (4).

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho V A)}{\partial x} = d''' \tag{1}$$

$$\frac{\partial(\rho V)}{\partial t} + \frac{\partial(\rho V^2 A)}{A\partial x} + \frac{\partial p}{\partial x} + \rho g \cos\theta + f\frac{\rho V|V|}{2D} = S_x \tag{2}$$

$$\frac{\partial\left(C(\rho h_0 - p)\right)}{\partial t} + \frac{\partial(C\rho V A h_0)}{A\partial x} = q''' \tag{3}$$

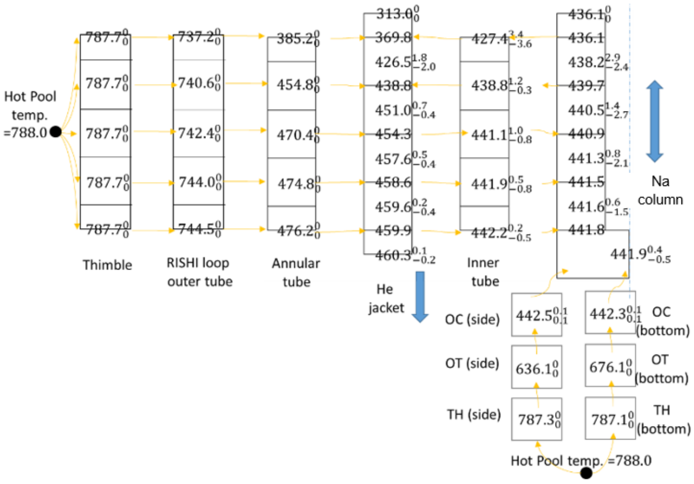
$$C_p\frac{\partial(\rho T)}{\partial t} = \frac{1}{A}\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right) + \frac{1}{A}\frac{\partial}{\partial y}\left(kA\frac{\partial T}{\partial y}\right) + q''' \tag{4}$$

Where t is time, x is displacement in the flow direction, ρ is density, p is pressure, T is temperature, h_0 is total enthalpy, V is velocity, k is thermal conductivity, C_p is specific heat, d''' is mass source, q''' is energy source, S_x is momentum source, f is friction factor, D is diameter, A is area of cross-section, θ is angle of inclination of pipe, g is the acceleration due to gravity, C is the volume fraction of liquid.

The thermal capacities of the specimen chamber and the gas phase are not considered. The walls in contact with gas were treated adiabatic. Time steps are chosen for the simulation so that all the volumes are either empty, half-filled, or fully filled at each instant. The Dittus-Boelter correlation [4] models heat transfer between helium and structures, while the Seban-Shimazaki [5] correlation models that between sodium and structures in the turbulent regime (Re > 5000). In the laminar regime (Re < 2300), Nusselt number values of 5.384 and 4.364 are used in annular and circular channels, respectively [6]. It is linearly interpolated in the transition regime. Two sources of heat addition to the arrangement are considered –heat transfer from the surrounding through the specimen chamber and heat transfer from the surrounding in the helium jacket region. Heat flux on the outer surface of the thimble and the specimen chamber is due to contact with hot pool sodium at 515 °C. The sodium column oscillates with an amplitude of 2.5 m at 1 Hz. For the reference case, helium inlet pressure, temperature, and mass flow rate are 2 bar, 313 K, and 40 CMH (per limb at STP conditions), respectively.

3. RESULTS AND DISCUSSION

The temperature distribution in the domain for the reference case is shown in Fig. 3. In general, all temperatures will be oscillating. In the notation T_{-a}^{b}, T represents cycle averaged temperature, and the instantaneous temperature varies from T-a to T+b. The average temperature of the specimen chamber is ~441.9 K (168.1 °C). The average net heat added to the domain is ~1.56 kW per limb (~1.26 kW from the helium jacket and ~0.3 kW from the chamber region). It equals the heat removed by helium (thereby ensuring heat balance). The peak-to-peak amplitude of chamber temperature oscillation is ~0.9 K.



(The arrows indicate the direction of heat transfer)

FIG. 3. Temperature (K) distribution in the domain (reference case).

For a helium inlet temperature of 303 K and 323 K, the specimen chamber temperature was obtained as $433.9_{-0.5}^{0.4}$ K and $449.9_{-0.5}^{0.4}$ K respectively (with reference flow rate). For a helium flow rate of 80 % and 120 % nominal, the specimen chamber temperature was obtained as $472.0_{-0.5}^{0.4}$ K and $423.5_{-0.5}^{0.4}$ K respectively (with reference Helium inlet temperature). Thus, chamber temperature increases with an increase in helium inlet temperature and decreases with an increase in helium flow rate. Also, it is observed that the range of chamber temperature oscillation in all the cases is less than 1 K.

4. SUMMARY

One dimensional analysis of the specimen chamber of the RISHI loop in FBTR has been carried out using the PINET code. For the reference case with a helium inlet temperature of 313 K and flow rate of 80 CMH (40 CMH per limb) under STP conditions, the average specimen chamber temperature is predicted as ~442 K. Its range of variation is ~1 K. The total heat to be removed by cooling helium is ~3.12 kW (1.56 kW per limb).

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