Natural Circulation Flows in the PULSTAR Reactor

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INTRODUCTION

Natural circulation is observed adjacent to heated surfaces as a result of density changes incurred during the heating and cooling process. Natural circulation is extremely important in the mitigation of reactor accidents involving loss of forced cooling. To initiate natural circulation, four requirements must be met:

1. There exists a heat source available to the flowing fluid.
2. There exists a comparable heat sink.
3. The thermal center of the heat sink be higher than the thermal center of the source.
4. There exists a complete flow path.

Natural circulation may be demonstrated in the PULSTAR by operating the reactor in the absence of forced cooling. In this mode, the reactor core acts as the heat source and the pool as the heat sink. The objective of this laboratory is to study the behavior of the PULSTAR during operation under natural circulation conditions.

THEORY

The natural circulation mass flow rate for a uniformly heated channel in a pool (subject to certain assumptions) has been shown to be given by

\[
\dot{m} \approx \sqrt[3]{\rho \kappa^2 \beta^2 g \left( q' H^2 + \sum_j k_j \right)} \left[ 1 + \frac{fH}{D_e} + \sum_j k_j \right]^{-1} \tag{1}
\]

If the channel of interest is the PULSTAR core, then under the uniform axial heat flux assumption,

\[
\dot{Q} = q' H \tag{2}
\]

where \( \dot{Q} \) is the reactor thermal output and Equation (1) becomes

\[
\dot{m} \approx \sqrt[3]{\rho \kappa^2 \beta^2 g \frac{\dot{Q} H}{C_p} \left[ 1 + \frac{fH}{D_e} + \sum_j k_j \right]} \tag{3}
\]

If it is assumed that all parameters in Equation (3) are constant, this implies the natural circulation mass flow rate in the reactor goes as the cube root of the power, i.e.

\[
\dot{m} \propto \dot{Q}^{1/3} \tag{4}
\]

In reality, the friction factor and the local loss coefficients can be functions of velocity, particularly at lower flow rates. We can rewrite Equation 3 as

\[
\dot{m}^3 \left[ 1 + f \frac{H}{D_e} + \sum_j k_j \right] \propto \dot{Q} \tag{5}
\]

or assuming the local losses can be represented in terms of an equivalent length to diameter ratio.
\[ m^3 f \sum_j \left( \frac{L_j}{D_e} \right)_j \propto \dot{Q} \]  

(6)

The friction factor is frequently represented in the form

\[ f = a \text{Re}^{-b} \]  

(7)

where \( b = 1 \) if the flow is laminar, 0 if the flow is fully turbulent, and 0.2 or 0.25 if the flow is turbulent and the flow channel corresponds to smooth pipes. Since the Reynolds number is proportional to mass flow rate, Equation 6 may be rewritten as

\[ m^{3-b} \propto \dot{Q} \]  

(8)

or

\[ \dot{m} \propto \dot{Q}^{\frac{1}{3-b}} \]  

(9)

Core mass flow rate under natural circulation is not a directly measurable quantity on the PULSTAR. However, the temperature rise across the core may be easily obtained by insertion of a thermocouple wand into one of the core cooling channels. We may relate the mass flow rate and temperature rise across the core by

\[ \dot{m}C_p\Delta T = \dot{Q} \]  

(10)

such that the temperature rise is related to the power by

\[ \Delta T = \frac{\dot{Q}}{\dot{m}C_p} \propto \frac{\dot{Q}}{\dot{Q}^{\frac{1}{3-b}}} \]  

(11)

\[ \Delta T \propto \dot{Q}^{\frac{2-b}{3-b}} \]  

(12)

EXPERIMENTAL PROCEDURE

Thermocouples are mounted on both ends of aluminum wands which are placed in core coolant channels. The length of the wand is such that the thermocouples provide a reasonable estimate of the average coolant inlet and outlet temperatures from a fuel bundle. The reactor will be operated at 100 kW with the reactor coolant pump on. To initiate natural circulation, the reactor coolant pump will be stopped and the students will observe visually, and through the thermocouple readings, flow reversal and the onset of natural circulation. Core averaged \( \Delta T \) is to be measured as a function of power while operating under steady state natural circulation.

ANALYSIS

From the measured \( \Delta T \) and power, fit your data to an equation of the form

\[ \Delta T = K_0 \dot{Q}^{\frac{2-b}{3-b}} \]  

for \( b = 0, 0.2, 0.25, \) and 1 and to the more general form.
\[ \Delta T = K_1 \dot{Q}^n \]

Compare your fits to the model predictions. From the measured powers and temperatures, compute the core averaged mass flow rate and corresponding Reynolds Numbers. The Reynolds Numbers can be used to infer whether the flow is actually laminar or turbulent.