Derivation of the Scaling Criteria for a Small Scale CANDU Moderator Test Facility

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1. Introduction

In order to design a small scale facility as shown in Fig.1 for simulating the CANDU moderator circulation phenomena during steady state operating and accident conditions, a study has been performed to derive a set of scaling criteria suitable for reproducing the similar thermal-hydraulic phenomena to that in the prototype power plant.

The major phenomena of the author's interests are the moderator flow circulation and temperature inside the moderator tank during steady state condition and the major accident conditions.

Thus initially a scaling study was performed for the steady state operation condition, and then extended to the LOCA accident conditions.

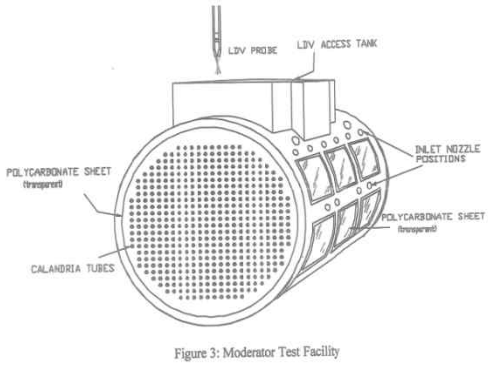

Fig. 1 Illustrated Example of a CANDU-6 Small Scale Moderator Test Facility

2. Steady State Normal Operation Condition

According to the previous study by Khartabil [1], based on the dimensionless variables defined as below,

$$V^* = V/V_i\,,\quad T^* = (T - T_o)/\Delta T\,,\quad P^* = P/(\rho_{ref} V_i^2)$$

$$t^* = tV_i/D\,,\quad \nabla^* = D\nabla,\quad Re = \rho_{ref} V_i D/\mu$$

$$Pr = \mu C_\rho/k\,,\quad Ar = g\beta_{ref}\,\Delta T D\,/\,V_i^2$$

$$q^* = \frac{q(x,y,z,t)D}{\rho_{ref}\,C_\rho V_i \Delta T}.$$

The following dimensionless governing equations can be derived.

$$\nabla^* T^* = 0$$

$$\frac{\vartheta V^*}{\vartheta t^*} + (\nabla^* V^*)V^* = -\nabla^* P^* + \frac{1}{Re}(\nabla^*)^2 V^* - Ar\frac{g}{|g|}T^*$$

$$\frac{\vartheta T^*}{\vartheta T^*} + (V^*\nabla^*)T^* = \frac{1}{RePr}(\nabla^*)^2 T^* + q^*$$

In order to maintain the geometric and dynamic similarity, the dimensionless numbers that appear in these equations as well as the dimensionless boundary conditions need to be kept the same for both the small scale test facility and the prototype reactor. If the geometric similarity can be kept, and the same working fluid is used, the 3 independent variables, D, ΔT, V_i need to be determined for the small scale test facility under the constraints that Re, Pr, Ar numbers are kept the same for both the prototype reactor and small scale test facility. As Pr is already the same, the constraints of keeping the remaining two variables the same can be written as:

$$\frac{V_{F}}{V_{iC}} = \left(\frac{D_c}{D_F}\right)\left(\frac{\rho_C \mu_F}{\rho_F \mu_C}\right),\qquad \frac{\Delta T_F}{\Delta T_C} = \left(\frac{V_F}{V_C}\right)^2\left(\frac{D_C}{D_F}\right)\frac{\beta_C}{\beta_F}$$

If the second condition is inserted into the first condition, ΔT's can be expressed in terms of D's only. But $\Delta T_F/\Delta T_c$ cannot be determined arbitrarily, but needs to be subject to another constraint of the capacity of the power supply,

$$\iiint q_F(x,y,z,t)dV = Q_F$$

and heat source distribution similarity,

$$\frac{q_C(x,y,z,t)D_c}{(\rho_{ref}\,C_p V_i \Delta T)_C} = \frac{q_F(x,y,z,t)D_F}{(\rho_{ref}\,C_p V_i \Delta T)_F}$$

where the capacity of the prototype reactor moderator cooling system,

$$\iiint q_C(x,y,z,t)dV = Q_C$$

is necessary for the closure of the equations.

If both sides of this equation are integrated over the relevant space domains, we obtain another constraint as below:

$$\frac{Q_C D_c}{(\rho_{ref}\,C_p V_i \Delta T)_C} = \frac{Q_F D_F}{(\rho_{ref}\,C_p V_i \Delta T)_F}$$

Therefore in summary provided the geometric similarity is kept, either $\Delta T_F/\Delta T_c$ or equivalently D_c/D_F can be determined by the power supply capacity ratio, Q_c/Q_F.

3. LBLOCA without Offsite Electric Power Condition

The major phenomena of the authors' interests in the small scale experiment of the moderator test facility to be built at KAERI are the moderator thermal-hydraulic conditions relevant to the initiation of the sustained film boiling or dryout of the calandria tube outside surface as a result of the pressure tube and calandria tube (PT/CT) contact incurred by the heated pressure tube ballooning during the blowdown phase of LBLOCA without offsite electric power. As this phenomenon is known to be incurred by the lack subcooling of the moderator adjacent to the relevant calandria tube, it is necessary to measure this parameter locally inside the moderator tank during the simulated LOCA accident condition in the scaled down test facility.

On the other hand, it has been known from the preceding accident analysis [3] that the transient inlet mass flow rate to the moderator tank under this LBLOCA with loss of offsite electric power of CANDU-6 begins to coast down after 15 sec of the accident and 1/4 of the normal flow is recovered by the operation of a pony motor to the main flow pump in 90 sec, and PT/CT ballooning contact is known to occur mostly between 10 ~ 25 sec into the accident, the flow condition of the moderator cooling system is thought to be still in the tail of the forced convection during PT/CT ballooning contact phenomena. Therefore maintaining the dynamic similarity in the moderator cooling loop only needs to focus on the forced convection condition where keeping ΔP across the pump, the friction pressure drop along the loop and the rate of inertial momentum change in a dimensionless manner the same for both scaled down facility and the prototype reactor matters. If the dynamic similarity of the whole loop is met, the dimensionless boundary conditions at the inlet and outlet of the moderator tank can be met automatically as the loops are closed ones, and the loop circulation time in the prototype reactor system (~ 200 sec) is much longer than the period where most of the major phenomena complete. Therefore the scaling analysis of the small scale test facility will be carried out from these points of view in 2012.

4. Summary and Conclusions

In order to design a small test facility for the moderator flow circulation and local subcooling inside the CANDU-6 moderator tank for the normal steady state and major accident conditions including LBLOCA with loss of offsite electric power, a scaling study was performed for the full power normal steady state operating condition and a set of scaling criteria has been derived to determine the tank size, the inlet velocity and the average moderator temperature rise as a function of the available power supply capacity.

As an extension the major considerations for the scaling analysis that is supposed to ensure reproduction of the major local phenomena of the safety concern in the scaled down test facility during LBLOCA with loss of offsite electric power have been proposed, and discussed. As a result, it was found that ensuring the dynamic similarity between the small scale test facility and the prototype CANDU-6 may only need to focus on the forced convection flow condition, not on the natural convection or mixed convection flow conditions in the main cooling loops. As a result of this rationale, the similarity analysis could be much more simplified than the case of including the natural convection flow condition in the scaling analysis.

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Nomenclature

ρ : moderator density
V_i : moderator velocity at the inlet nozzle
D : diameter of the moderator tank
β : thermal expansion coefficient
$q(x, y, z, t)$: heat generation rate per unit volume of the moderator
Ar : Archimedes number
Q : total heat generation or supply rate

Subscript

ref : reference condition
C : CANDU-6
F : Small scale facility

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