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Determination of the Size of a Scale-down CANDU Moderator Test Facility

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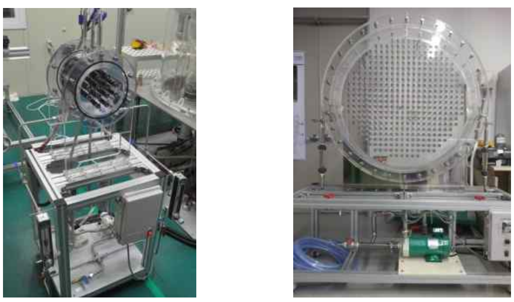
1. Introduction

A series of studies have been performed to derive a set of scaling criteria suitable for reproducing thermal-hydraulic phenomena in a scale-down CANDU moderator tank similar to that in a prototype power plant during steady state operation and accident conditions [1,2].

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

In these studies, the governing equations were initially transformed into dimensionless equations based on the representative characteristic values of the basic design such as the time, tank diameter, inlet fluid velocity, and average temperature rise, and 3 dimensionless numbers, Re, Pr, Ar, were identified as those characterizing the major phenomena of the system. The relevant boundary conditions were then identified in a dimensionless form and compatibility of keeping these 3 dimensionless numbers, the volumetric heat source distribution and the boundary conditions in dimensionless forms the same for both prototype and scale-down tanks were examined, and some of them which are less important are relaxed so as to find a practically implementable set of constrains. The size of the scaled-down moderator tank and the corresponding inlet velocity is then found for the available power supply size. As an example, an analysis was performed for a power supply capacity of 500 kW as compared to 100MW for the prototype.



(a) 1/40 scale (b) 1/8 scale

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

2. Derivation of the dimensionless governing equations and boundary conditions

According to a previous study by Khartabil [1], the dimensionless variables can be defined as below,

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

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

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

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

The following dimensionless governing equations can then be derived.

$$\nabla^* V^* = 0$$

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

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

<u>Boundary Conditions</u>:
- on a fixed solid surface: $V^* = 0$, $q''^* = q_w''^*$
- at an inlet or outlet: Known V^*, T^* or P^*

If the same working fluid is used, Pr can be considered nearly uniform inside the tank. Re and Ar then depend on ΔT, U_i, and D. Therefore, if any combination of ΔT, U_i, and D for which Re, Ar and the dimensionless volumetric heat source, q^* may be kept the same for both facilities, the hydrodynamic similarity inside the moderator tank is maintained. However in practice maintaining both Re and Ar the same for the prototype tank and the scaled down tank turns out to be impossible as the tank dimension for the scaled down tank becomes larger than the prototype tank dimension. Maintaining similarity in Re is not possible because of the need for a reduced tank size. The impact of not maintaining the Reynolds number equivalence is that the relative contributions of the momentum and energy diffusion by molecular motion are not the same between the prototype and scaled-down facility. However, by ensuring a turbulent flow throughout the vessel, the relative contributions of these diffusion processes to the overall balances are negligible. Thus, if Re is sufficiently large to guarantee a turbulent flow throughout the moderator tank for both facilities, it can be justified that the overall similarity for both the prototype and scaled down tanks be reasonably kept [1].

If this argument is true, one then only needs to be concerned how to keep Ar and q^* the same for both the prototype and scaled down tanks.

$$\frac{\Delta T_F}{\Delta T_C} = \left(\frac{U_{i,F}}{U_{i,C}}\right)^2 \left(\frac{D_C}{D_F}\right) \frac{\beta_C}{\beta_F} \tag{1}$$

However $\Delta T_F/\Delta T_C$ 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 the heat source distribution similarity condition or dimensionless volumetric heat source as claimed by Khartabil[2],

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

Integration of these dimensionless volumetric heat source over the whole dimensionless tank volume of each facility is necessary for the closure of the equations.

$$\iiint_{V_c^*} q_c^*\, dV_c^* = \iiint_{V_c} \frac{q_c(x,y,z,t)D_c}{(\rho_{ref}\, C_p U_i \Delta T)_c} \frac{dx}{D_c}\frac{dy}{D_c}\frac{dz}{D_c}$$

$$= \frac{1}{(\rho_{ref}\, C_p U_i \Delta T)_c D_c^2} \iiint q_c(x,y,z,t)\, dxdydz$$

$$= \frac{Q_c}{(\rho_{ref}\, C_p U_i \Delta T)_c D_c^2}$$

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

$$\frac{Q_C}{(\rho_{ref}\, C_p U_i \Delta T)_C {D_c}^2} = \frac{Q_F}{(\rho_{ref}\, C_p U_i \Delta T)_F {D_F}^2} \tag{2}$$

Thus if Eq. (2) is inserted into Eq. (1), one can obtain

$$\frac{Q_C}{Q_F} = \frac{D_c}{D_F}\left(\frac{U_{i,C}}{U_{i,F}}\right)^3 \tag{3}$$

From this equation, one can determine the ratio of the inlet average velocity once the heat load ratio and geometry scale are fixed. This inlet average velocity ratio in turn is determined ($\frac{\Delta T_F}{\Delta T_C}$) from Eq. (1). If ΔT_F and D_F are acceptable from the view points of coolant temperature measurement accuracy and space available for the instruments installation and probe accessibility, one can fix this combination of Q, D and ΔT.

3. Application of derived criteria to a scale-down tank

The heat load to the moderator tank of a CANDU-6 reactor during a full power steady state is 100 MW, and the tank diameter is 7.6 m, the inlet mass flow rate is 1019 kg/s, and the temperature difference between inlet and outlet of tank is 23.3 ^{o}C. The power supply of the scaled-down moderator tank is 500 kW, and the diameter is fixed to be 1.9 m and the length is 1.5 m, which is 1/4 of the prototype tank. If these values are inserted into Eq. (3), one obtains

$$\left(\frac{U_{i,C}}{U_{i,F}}\right) = 3.684$$

As the inlet mass flow rate of the scale-down tank,

$$m_{i,F} = \left(\frac{U_{i,F}}{U_{i,C}}\right)\left(\frac{A_{fi,F}}{A_{fi,C}}\right) m_{i,C}$$

$$= (1019\text{kg/s}) / (3.684\times16) = 17.287 \text{ kg/s}$$

The average moderator temperature difference ratio can be found from Eq. (1)

$$\frac{\Delta T_F}{\Delta T_C} = \left(\frac{U_{i,F}}{U_{i,C}}\right)^2 \left(\frac{D_C}{D_F}\right) \frac{\boldsymbol{\beta}_C}{\boldsymbol{\beta}_F}$$

$$= (1/3.684)^2 \times (4) \times (1) = 0.295$$

4. Summary and Conclusions

To design a small test facility for the moderator flow circulation and local subcooling inside the CANDU-6 moderator, a scaling study was performed 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.

ACKNOWLEDGMENTS

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Nomenclature

V : fluid velocity vector (m/s)
ρ : moderator density (kg/m^3)
U_i : moderator velocity at the inlet nozzle (m/s)
D : diameter of the moderator tank (m)
β : thermal expansion coefficient
$q(x,y,z,t)$: heat generation rate per unit volume of the moderator (W/m^3)
q" : heat flux (W/m^2)
Ar : Archimedes number
Q : total heat generation or supply rate (W)

Subscript

ref : reference condition
C : CANDU-6
F : Scaled-down facility

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