EXPERIMENTAL DETERMINATION OF THE FRICTION FACTORS IN TWO PHASE FLOW THROUGH A POROUS MEDIUM

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ABSTRACT

In a severe accident, the decay heat from the fuel located in the calandria may boil the water circulated through the end shields of a CANDU (Canada Deuterium Uranium) reactor, causing a two phase flow of water and steam. This two phase mixture may interfere with heat transport if a thin film of steam forms on the inside surface of the end shields. As water and steam run through the end shields, frictional energy loss results in a pressure gradient. The pressure gradient is directly related to the velocity of the fluid, which can be inferred from the permeability of the end shield. Therefore, this project serves to determine the friction factors that cause pressure drop in the end shields of a CANDU Reactor and aims to examine the safety mechanism of existing end shields. The results of this project corroborated the Gibilaro equation for one phase flow and implied the lack of proper handling of important friction factors in equations for two phase flow. Therefore, further studies on two phase flow through porous medium are needed.

Dans un accident grave, la chaleur de désintégration du combustible situé dans la calandre peut faire bouillir l’eau circulant à travers les boucliers d’extrémité d’un réacteur CANDU, provoquant un flux à deux phases d’eau et de vapeur. Ce mélange à deux phases peut interférer avec le transport de la chaleur si un film mince de forme de vapeur sur la surface intérieure des boucliers d’extrémités. Comme l’eau et la vapeur parcours à travers les boucliers d’extrémités, les pertes frictionnelles d’énergie résultante dans des gradients de pression. Le gradient de pression est directement lié à la vitesse du fluide, qui peut être déduit de la perméabilité du bouclier d’extrémité. Par conséquent, ce projet sert à déterminer les facteurs de friction qui provoquent la chute de pression dans les boucliers d’extrémité d’un réacteur CANDU et vise à examiner le mécanisme des boucliers d’extrémités existants. Les résultats de ce projet ont corroboré l’équation Gibilaro pour un flux de phase et impliquent le manque de traitement approprié des facteurs de friction importants dans les équations pour l’écoulement diphasique. Par conséquent, de nouvelles études sur l’écoulement diphasique à travers des milieux poreux sont nécessaires.

INTRODUCTION

In a CANDU Reactor, end shields are protective structures located at both ends of the calandria (reactor core). They serve to absorb radiation emitted from the core and protect the fueling machine and personnel. End shields are made of steel plates and are packed with little steel balls inside, through which water is circulated as a coolant.

In a severe accident scenario, the core may collapse into a molten mixture called corium due to varying reasons such as a loss of coolant accident (LOCA) or control rod failure. Under such circumstances, the circulation of cooling water through the end shields may be interrupted and the extreme heat emitted from the core may cause the water to boil, creating a two phase mixture of water and steam.

As a two phase mixture flows through a porous medium, frictional energy loss lowers the pressure. The pressure drop over distance is called pressure gradient, denoted as \( \frac{\Delta P}{\Delta L} \) (Pa/m). Measuring and analyzing pressure gradient is an important part of this project because it is directly related to the velocity of the fluids, which determines the permeability of the porous medium.

In a severe accident, when heat is added to the end shields, steam bubbles absorb the heat and carry it away. However, as the difference between the heating surface temperature and the water saturation temperature increases, the heat flux will rise as an increasing number of bubbles are formed. Soon, the heat exchange rate will reach a threshold called the
critical heat flux (CHF), at which the rate of bubbles forming will equal that of bubbles leaving the surface. This phenomenon occurs when bubbles coalesce and form a thin film of steam around the inner surface of the end shield, insulating the heating surface from the cooling water. Film boiling does not allow efficient heat transfer due to the low thermal conductivity of steam. Once critical heat flux is passed, the heat flux plummets rapidly, and components such as the calandria tube sheet may begin to melt.

It is found that a higher pressure drop spells a higher average velocity of the fluid, and thus increases the rate of bubbles leaving the surface. This means that more heat will be absorbed before it reaches critical heat flux, decreasing the potential for reaching film boiling. Therefore, it is important to characterize the correlation between the pressure gradient and the average velocity of the fluids through a porous medium.

The purpose of this project was to determine the friction factors that cause pressure drop in the end shields of a CANDU Reactor and to provide useful pressure drop data. The investigation contributed to the understanding of the process of heat dissipation in a severe accident scenario and the influence of different friction factors on heat transfer inside an end shield. The project also provided data that examined the safety mechanism of existing end shields and offered insights into future end shield designs.

EXPERIMENTAL MATERIALS AND METHODS

2.1 Apparatus

The experiments used air instead of steam due to reasons of safety and cost-effectiveness. The basic components of the setup were: an acrylic tube test section, a water reservoir, and a 2.00 hp pump, which provides a flow of water of up to 110 liters per minute. The instrumentation consisted of a magnetic flow meter, and two air rotameters. Deionized water was used for the magnetic flow meter to measure the water flow rate. The test section, a 1-meter long acrylic tube, was placed on an inlet header with a perforated grid plate put in-between to prevent balls from falling. There were two main loops in the system: a water loop and an air loop. The test section was encompassed by the water loop and the air loop was joined perpendicularly to the water loop 60 cm below the test section. One of or both air and water could be run vertically upwards through the test section. A total of 5 pressure transducers were used: 4 of them, located 20 centimeters apart, measured the pressure along the test section while the other one measured the inlet pressure of air.

2.2 Experimental Methods

In one phase flow, only water or air flow is initiated while in two phase flow, combinations of water and air with different velocities are run through the test section. As water and air flow in, their flow rates are measured by a flow meter and a rotameter, respectively. Data is collected and analyzed using a Data Acquisition System in LabVIEW. After each run, two fast acting valves are shut off, isolating the test section, in order to measure the ratio of water to air in the tube. The data collected was then imported into an Excel worksheet, averaged, and used to calculate different parameters in a premade template. A theoretical and an experimental pressure gradient are calculated, respectively and then graphed against the same parameter and compared. The formulae used to calculate the theoretical pressure gradient are shown in Table 1 and Table 2.

RESULTS

The results of this project are divided into two stages: one phase flow and two phase flow.

3.1 One phase flow

For one phase flow, the Gibilaro correlation is used to calculate the theoretical pressure gradient. In one phase flow data analysis, the pressure gradient is plotted against the average velocity of the fluid. The air correlation between pressure gradient and average velocity using 4" and 2" diameter tubes are shown below (Figures 1, 2).

The pressure gradient grows at an increasing rate as the average velocity of air goes up. The experimental data tightly fits the equation, which is a solid line. In addition, the pressure gradient is much higher in the 2" diameter tube than in the 4" tube. As the maximum flow rate of air is fixed, a smaller cross sectional area enables it to have higher maximum velocity, and thus a higher pressure gradient.

The one phase water data and the Gibilaro correlation (Figures 3, 4) reconcile well at low velocity. However, it becomes constantly lower than the equation when
FIGURES AND TABLES

File for Experimental Determination of Friction Factors in Two Phase Flow Through a Porous Medium

Figure 1: Air pressure gradient in 4” tube

Figure 2: Air pressure gradient in 2” tube

Figure 3: Water pressure gradient in 4” tube

Figure 4: Water pressure gradient in 2” tube

Figure 5: Larkin’s correlation

Figure 6: Dhir’s correlation
velocity passes 0.15m/s. This is primarily caused by the fact that the water flow meter could not accurately measure any flow rate above 39 liters per minute.

3.2 Two phase flow

For two phase flow, three different equations are used to calculate the theoretical pressure gradient, Larkins’ (Figure 5), Dhir’s (Figure 6) and Turpin’s (Figure 7) equations. The two phase flow data is plotted against different parameters, based on the equations. Different air flow rates are also marked differently when a distinction between them is noticed.

Larkins’ correlation has different trends for different air flow rates. The collected data is constantly higher than the equation in low to middle range, and gradually approaches it as x increases. In contrast, the collected pressure gradient is much lower than that calculated by Dhir’s equation. They fit at low water velocity, but deviate substantially when the water velocity went up. The fluctuation of Dhir’s correlation also made it difficult to observe a general trend.

On the other hand, Turpin’s correlation, a graph of friction factor f against z, reconciles better with the experimental data. Regardless of the air flow rates, the data fits well with the equation, despite a slight deviation when z is low. The Turpin’s correlation matches the experimental results obtained in this project much better than all the other correlations considered.

DISCUSSION

The one phase flow data collected for both air and water fit fairly well with literature, even though experimental pressure gradient for water was slightly lower at high flow rates. The data validated the experimental setup and procedure used and provided a solid foundation for two phase flow experiments. It was clearly seen that the pressure gradient augmented at an increasing rate as the average velocity of the liquid increased. Also, tube size did not have a significant effect on the pressure gradient in one phase flow.

For two phase flow, different equations presented significantly distinct results. While Larkins’ and Dhir’s correlation substantially deviated from the experimental data, Turpin’s correlation matched it very well. This is partly caused by the fact that Turpin’s experimental setup, such as ball size, was the most similar to that used in this project. Larkins’ equation was designed to describe two phase flow of many liquids and gases including water and air, whereas Dhir’s experiment used various ball sizes. Because different scientists come up with varying correlation equations, based on their choice of the important factors that can affect two phase flow, the results could be starkly different. Larkins’ and Dhir’s equations were allegedly suitable for a much wider range of conditions, but obviously did not reconcile with the experimental results in this project. This implies that they may have prioritized the wrong friction factors or have excluded some important terms. Thus, more studies regarding two phase flow through a porous medium are necessary.

The correlation between the pressure gradient and the average velocity for air and water in both one phase and two phase flow was experimentally determined and compared to literature. While the Gibilaro equation was experimentally corroborated with two different tube sizes, it was also found that the pressure gradient for both one and two phase flow increased at a faster rate when average velocity increased. The pressure gradient in two phase flow, however, was much more difficult to characterize. Different equations often lead to completely divergent results. This was primarily because the topic of two phase flow through a porous medium involves many
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**Table 1.** Formulae used in the calculation of theoretical pressure gradient

<table>
<thead>
<tr>
<th>One Phase Flow</th>
<th>Formulae</th>
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<tbody>
<tr>
<td>Gibilaro Equation</td>
<td>[ \frac{\Delta P}{L} = \left( \frac{150}{Re} + 0.336 \right) \left( \frac{\mu_{\text{eff}}}{\mu} \right) \times (1 - \varepsilon) \times \varepsilon^{-4.9} ]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Two Phase Flow</th>
<th>Formulae</th>
</tr>
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</table>
| Larkins’ Equation | \[ \frac{\Delta P}{L} = \delta - \varrho_m \times g \]  
\[ x = \left( \frac{\Delta P}{\Delta Z} \right) + \left( \frac{\Delta P}{\Delta Z} \right)^2 \]  
\[ \delta = \left( \frac{\Delta P}{\Delta L} \right) + \left( \frac{\Delta P}{\Delta Z} \right)^2 \times 10^{-150} \times \left( \frac{R}{\mu} \right) \]  
\[ \varrho_m = \varrho_1 \times R_1 + \varrho_2 \times R_2 = \varrho_1 \times R_1 + \varrho_2 \times (1 - R_1) \] |
| Dhir’s Equation | \[ \frac{\Delta P}{L} = \frac{150(1 - \varepsilon)^2}{k'_{ef}^3 d_p} \mu_u + \frac{1.75(1 - \varepsilon)}{\eta_{ef}^3 d_p} \sigma \frac{U_f^2}{2} + \frac{150(1 - \varepsilon)^2}{k'^2 d_p} \mu_{ef} \]  
\[ k'_{ef} = 0.01a_{uc}^{0.5} + 0.02a_{uc} + 0.57a_{uc}^3 + 0.40a_{uc}^5 \]  
\[ \eta_{ef} = 0.01a_{uc}^{0.5} + 0.02a_{uc}^2 + 0.57a_{uc}^3 + 0.40a_{uc}^{2.5} \] |

| Turpin’s Equation | \[ \frac{\Delta P}{L} = \frac{2f_{ig} \theta_{ig} U_g^2}{D_f} \]  
\[ f_{ig} = e^{0.9 - 1.12(nZ)^2 + 0.0769(nZ)^2 + 0.0152(nZ)^3} \]  
\[ Z = \frac{Re_1^{1.167}}{Re_1^{1.767}} \]  
\[ D_f = \left( \frac{2}{3} \right) (D_i) \left( \frac{\varepsilon}{1 - \varepsilon} \right) \] |

<table>
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<tr>
<th>Variables</th>
<th>Connotation</th>
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<tbody>
<tr>
<td>Re</td>
<td>Reynolds Number</td>
</tr>
<tr>
<td>D_f</td>
<td>Particle Diameter</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Porosity</td>
</tr>
<tr>
<td>U</td>
<td>Velocity</td>
</tr>
<tr>
<td>( \Delta P )</td>
<td>Pressure Gradient</td>
</tr>
<tr>
<td>( \Delta L )</td>
<td></td>
</tr>
<tr>
<td>( a_{uc} )</td>
<td>Void Fraction</td>
</tr>
<tr>
<td>( f_{ig} )</td>
<td>Friction Factor</td>
</tr>
<tr>
<td>Z</td>
<td>Correlating Factor</td>
</tr>
<tr>
<td>D_f</td>
<td>Equivalent Diameter</td>
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Factors, some of which were still not discovered and undefined. There were so far no widely acknowledged correlation equations that satisfy all the conditions. Thus, more work was needed for the data collected in this project to be used in the examination of the safety mechanism of the existing end shields. However, the results of this project were validated by comparing them to Turpin’s equation, and thus can serve as a reference for future research.

**FUTURE DIRECTIONS**

In a CANDU Reactor, the velocity of the water largely determines whether the steam bubbles will congregate and turn nucleate boiling into film boiling.
During a severe accident, it is often difficult to directly measure the velocity of the water in the end shields. Thus, in order to ensure that the critical heat flux is not reached, it is important for operators to be able to estimate the velocity of the water based on the pressure gradient in the end shield and to infer the speed at which bubbles are escaping. This project measures the pressure gradient of a simulated end shield under different air and water flow rates and provides correlation between the pressure gradient and the average velocity of fluids in both one and two phase flow, which can serve as critical references for the operators. The results of this project facilitate more accurate judgement of the conditions in the end shields in a severe accident scenario.

The application of this project, however, is not limited to nuclear industry. For example, it simulates practical situations in areas such as chemical engineering, where two phase flow through a porous medium is encountered when reactants are mixed with a catalyst. In addition, the results of this project can be used as an important reference for the study of capillary forces, or the intermolecular forces between water and the solid surface. It provides information about the significance of the capillary forces in narrow channels formed by balls of a certain size.

In the future, the permeability of the end shield for steam bubbles under a severe accident scenario can be determined based on these data. The findings can also serve as an important reference for operators to infer the velocities of the fluids in the end shield. In addition, this project, as a simulation of the condition of an end shield, does not involve any heating source. More precise simulation can be done to imitate an end shield in a severe accident scenario, with a wider variety of ball and tube sizes. Also, more work needs to be done on the critical heat flux (e.g. the amount heat needed for water and steam flowing at a certain speed to reach critical heat flux), in order to facilitate the understanding of the conditions to reach CHF.

ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CANDU Reactor</td>
<td>Canadian Deuterium Reactor</td>
</tr>
<tr>
<td>LOCA</td>
<td>Loss of Coolant Accident</td>
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<tr>
<td>CHF</td>
<td>Critical Heat Flux</td>
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KEY WORDS

Two Phase Flow, Porous Medium, End Shields, Fluid Dynamics

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REFERENCE