EXPERIMENTAL AND THEORETICAL STUDY ON NATURAL CIRCULATION CAPACITY UNDER ROLLING MOTION CONDITION

Sichao Tan
Harbin Engineering University College of Power and Nuclear Engineering, Harbin, 150001, P.R. China
Phone: 13091441949
e-mail: tansichao@yahoo.com.cn

Pu-zhen Gao
Harbin Engineering University College of Power and Nuclear Engineering, Harbin, 150001, P.R. China
Phone: 0451-82569655
e-mail: gaopuzhen@sina.com

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ABSTRACT
Effect of rolling motion on natural circulation capacity was studied experimentally and theoretically. Experiments were conducted under the conditions of rolling and unrolling motions. The experimental results show that natural circulation capacity decreases under rolling motion condition. A mathematic model was developed to calculate the natural circulation capacity under rolling motion condition, considering the characteristics of natural circulation, the model was modified. The calculated results agree with experimental data well. Effect of rolling motion on natural circulation was analyzed through calculation and the following conclusions were obtained: (1) The increase of flow resistance coefficient is the main reason that the natural circulation capacity decreases under rolling motion condition; (2) Non-uniform distribution of fluid mass in the pipe has also influence on natural circulation capacity.

1. INTRODUCTION
Natural circulation has extensive application in the nuclear power engineering and other fields [1]. In-depth study of the natural circulation has been carried out in order to cool and depressurize the reactor primary coolant system after accident. The nuclear-power ships are often rocked by ocean waves, which will introduce an additional acceleration to the marine reactors [2]. The additional inertia makes primary coolant system flow fluctuate periodically and destroys the system’s stability [3-4]. Natural circulation capacity is also influenced by ocean conditions.

Effect of rolling is the most complicated of the ocean conditions compared with heaving and incline. Effect of rolling motion on natural circulation capacity was studied experimentally and theoretically in this paper.

2. TEST APPARATUS AND PHENOMENA
2.1 Test loop
The test loop was shown in Fig.1. It was composed of pressurizer, coolant pump, cooler, test tube and preheater. The working fluid was water.

The fluid was heated to the required inlet temperature in the preheater, then it entered the test tube and was heated continually, and then it flew into the cooler to be cooled, after a cycle the fluid came back to the preheater.

Fig.1 Schematic experimental loop
1 pressurizer; 2 electromagnetic flowmeter; 3 preheater; 4 test tube; 5 condenser; 6 downcomer; T temperatures measured; P pressures measured

2.2 Rolling plate
The rolling plate was a 2m×2.5m rectangular plane with vertical axis in the middle. The rolling axis
was the O-O axis, as shown in Fig.2. The plate was horizontal and the test tube was vertical in the normal case. The rolling plate was driven by a crank and rocker mechanism, as shown in Fig. 3. Different rolling amplitude could be obtained through changing the length of rocker and linkage. The rolling plate could be controlled to roll with certain period by changing the frequency of the electromotor, just as the ship in the ocean. The rolling motion was simulated as the sine wave. The rolling angle could be approximated by:

$$\theta = \theta_m \sin(2\pi / t_0)$$  \hspace{1cm} (1)

where $\theta$ was the rolling angle, rad, as shown in Fig. 3; $\theta_m$ the rolling amplitude, rad; $t_0$ the rolling period, s; $t$ time, s.

The experimental parameters ranges: inlet subcooling, $10 \sim 60 \degree$C; amplitude of rolling, $10 \degree, 15 \degree, 20 \degree$; period of rolling, $7.5s, 10s, 12.5s$; pressure, $0.1 \sim 0.4$ MPa.

From Fig.4 and Fig.5, such conclusion can be reached that natural circulation capacity decreases under rolling motion.

2.3 Phenomena

Natural circulation capacity is defined as volume flow under same thermal parameters. If the volume flow is large, outlet temperature of heat tube is low and the system is safe.

To compare with unrolling case, the relative natural circulation capacity (RNCC) is defined as the rate of average volume flow in rolling case and volume flow in unrolling case.

Effect of rolling amplitude on RNCC is shown as Fig.4, and the RNCC decreases when rolling amplitude increases. Effect of rolling period on RNCC is shown as Fig.5, and the RNCC increases as rolling period increases.

3. MATHEMATIC MODEL

For natural circulation, the thermal driving head (gravity head) was equal to the friction pressure drop and local pressure drop, just as Eq.2.

$$\Delta p_{\text{driven}} = \Delta p_g + \Delta p_{\text{friction}}$$ \hspace{1cm} (2)

In rolling case the additional pressure drop should be considered (Eq.3) and the additional pressure drop can be calculated with the correlations in Ref.[5].

$$\Delta p_g' = \Delta p_g + \Delta p_{\text{add}}$$ \hspace{1cm} (3)

The gravity head in rolling case vary with rolling, just as

$$\Delta p_g = \Delta \rho g h_v \cos \theta + \Delta \rho g h_h \sin \theta$$ \hspace{1cm} (4)
Heat transfer under rolling motion can be calculated with the correlations in Ref.[5].
To simplify the calculation, supposing the outlet temperature of heated tube is invariable in rolling case, because experimental data show that outlet temperature of heated tube lagged a little. The temperature difference between inlet and outlet of heated tube, fluctuated amplitude of outlet temperature and outlet density are shown as Tab.1. So the variety of outlet temperature can be ignored.

<table>
<thead>
<tr>
<th>$T_{out} - T_0$</th>
<th>$\Delta T_{out}$</th>
<th>$\rho_{out} - \rho_0$</th>
<th>$\Delta \rho_{out}$</th>
<th>$T_{out} - T_0$</th>
<th>$\Delta T_{out}$</th>
<th>$\rho_{out} - \rho_0$</th>
<th>$\Delta \rho_{out}$</th>
</tr>
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<tbody>
<tr>
<td>55.2</td>
<td>2.1</td>
<td>27.1</td>
<td>1.30</td>
<td>56.1</td>
<td>3.0</td>
<td>28.5</td>
<td>1.88</td>
</tr>
<tr>
<td>57.1</td>
<td>2.5</td>
<td>30.3</td>
<td>1.62</td>
<td>57.7</td>
<td>3.5</td>
<td>31.4</td>
<td>2.29</td>
</tr>
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<td>57.5</td>
<td>1.2</td>
<td>31.1</td>
<td>0.77</td>
<td>58.7</td>
<td>3.6</td>
<td>33.6</td>
<td>2.43</td>
</tr>
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<td>40.5</td>
<td>1.47</td>
<td>55.8</td>
<td>2.4</td>
<td>28.1</td>
<td>1.50</td>
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<td>65.9</td>
<td>2.5</td>
<td>28.2</td>
<td>1.72</td>
<td>54.5</td>
<td>3.2</td>
<td>26.1</td>
<td>1.92</td>
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</table>

The friction coefficient used in calculation under rolling motion is same as that in stable flow, the flow under rolling motion is variation, so the friction coefficient in rolling case must be different with that in stable flow.
To avoid the effect of friction coefficient variety, relative flow rate is introduced. Relative flow rate is defined as the rate of average flow rate in rolling case and flow rate in unrolling case with same thermal conditions.
Dividing Eq.3 by natural circulation driving head in upright case, we get

$$\frac{\Delta p_g'}{\Delta p_g} = \frac{\Delta p_f'}{\Delta p_g} + \frac{\Delta p_{add}}{\Delta p_g} \quad (5)$$

$$\frac{\Delta p_f'}{\Delta p_g} = \frac{C_0 v^2}{C_0 v^2} = C^* \left( \frac{v'}{v} \right)^2 \quad (6)$$

Therefore, as the upright natural circulation driving head, the driving head and additional pressure drop in rolling case are known, the relative flow rate under rolling motion can be obtained.

4. RESULT AND DISCUSSION
The calculated results show that average flow rate of natural circulation in rolling case is same with that in unrolling case. Considering the experimental data, average flow rate in rolling motion is lower than that in unrolling case; the friction coefficient should be modified. For a flow fluctuation, three parameters are important which include the maximal flow rate, the least flow rate and average flow rate. Considering three parameters, corrected coefficient is chose and an empirical correlation to modified flow friction coefficient under rolling motion is obtained (Fig.6 and Eq.7).

$$C_R = 1 + \left( -0.085 + 0.5355 f^{-*2} \right) \theta^* \quad (7)$$

$\theta^*$ was relative rolling amplitude, $f^{-*}$ was relative rolling frequency.

$$\theta^* = \theta_m / 10 \quad (8)$$

$$f^{-*} = 10 / t_0 \quad (9)$$

$$C_R \approx 1 + \left( 1 + c \alpha_m / T^2 \right) \beta_{max} \quad (10)$$

With Eq.10, we can achieve the conclusion that the main parameter influencing flow friction coefficient under rolling motion was the largest angular acceleration $\beta_{max}$.
Modified calculated result results agree with experimental data well, as shown in Tab.2. A vage flow rate and RNCC decrease as flow friction coefficients modified, so increase of flow friction is the main factor to decrease RNCC.
### Tab. 2  Comparison between calculated results and experimental results

<table>
<thead>
<tr>
<th>Rolling amplitude /period</th>
<th>$\bar{V}_c / v_0$</th>
<th>$\bar{V}_c / v_0$</th>
<th>$v_c^+ / v_0$</th>
<th>$v_c^- / v_0$</th>
<th>$v_c^- / v_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20º /12.5s</td>
<td>0.897</td>
<td>0.882</td>
<td>1.315</td>
<td>1.393</td>
<td>0.345</td>
</tr>
<tr>
<td></td>
<td>0.891</td>
<td>0.889</td>
<td>1.306</td>
<td>1.370</td>
<td>0.426</td>
</tr>
<tr>
<td></td>
<td>0.937</td>
<td>0.897</td>
<td>1.298</td>
<td>1.352</td>
<td>0.456</td>
</tr>
<tr>
<td>20º /10s</td>
<td>0.785</td>
<td>0.789</td>
<td>1.280</td>
<td>1.428</td>
<td>0.214</td>
</tr>
<tr>
<td></td>
<td>0.792</td>
<td>0.795</td>
<td>1.262</td>
<td>1.397</td>
<td>0.262</td>
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<tr>
<td></td>
<td>0.838</td>
<td>0.802</td>
<td>1.262</td>
<td>1.371</td>
<td>0.319</td>
</tr>
<tr>
<td></td>
<td>0.856</td>
<td>0.827</td>
<td>1.223</td>
<td>1.275</td>
<td>0.396</td>
</tr>
<tr>
<td>10º /10s</td>
<td>0.884</td>
<td>0.892</td>
<td>1.203</td>
<td>1.201</td>
<td>0.555</td>
</tr>
<tr>
<td></td>
<td>0.908</td>
<td>0.909</td>
<td>1.242</td>
<td>1.186</td>
<td>0.680</td>
</tr>
<tr>
<td></td>
<td>0.918</td>
<td>0.926</td>
<td>1.154</td>
<td>1.176</td>
<td>0.665</td>
</tr>
<tr>
<td>10º /7.5s</td>
<td>0.743</td>
<td>0.786</td>
<td>1.055</td>
<td>1.199</td>
<td>0.388</td>
</tr>
<tr>
<td></td>
<td>0.809</td>
<td>0.798</td>
<td>1.113</td>
<td>1.168</td>
<td>0.495</td>
</tr>
<tr>
<td></td>
<td>0.830</td>
<td>0.810</td>
<td>1.112</td>
<td>1.144</td>
<td>0.576</td>
</tr>
</tbody>
</table>

To analyze effect of rolling motion, flow caused only by rolling motion is calculated, the loop is presumed as the same temperature and no circulation flow before rolling. Calculated results are shown as fig. 7, and the dot line is average flow rate.

![Fig.7 Fluctuation only caused by rolling motion](image.png)

The average flow rate is not zero, because the distribution of fluid mass in the pipe is not symmetrical, or else the average flow rate is zero. In unrolling case, distribution of fluid mass has no effect on natural circulation flow except the available height, and has an important effect on flow in rolling case because of the additional acceleration.

For single phase natural circulation, effects of rolling have two aspects, one side rolling motion makes fluid flow fluctuation which increase flow friction coefficients, another side, additional pressure drop caused by rolling may increase or decrease RNCC, because the direction of additional acceleration varies with time.

5. CONCLUSION

(1) For single phase natural circulation, effects of rolling have two aspects, one side rolling motion makes fluid flow fluctuation which increase flow friction coefficients, another side, additional pressure drop caused by rolling may increase or decrease RNCC, because the direction of additional acceleration varies with time.

(2) Due to non-uniform distribution of fluid mass in the pipe, flow rate is influenced under rolling motion caused by acceleration centripetal.

The ultimate factor of increase of friction coefficient is fluctuation of flow, so the study of friction coefficient under fluctuation should be needed.

ACKNOWLEDGMENT

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REFERENCES


of a Marine Reactor in Rolling Motion and Heat Transfer in the Core,” Nuclear Engineering and Design, 215, pp.69-85.
