Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Rolling motion effect on differential pressure measurement in NEOUL-R flow boiling experiment

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Keywords: Floating nuclear power plant, rolling motion, acceleration effect, differential pressure measurement

1. Introduction

Reliability of thermal-hydraulic parameter measurements is one of the critical factors for both experiments and actual powerplants. In case of floating nuclear power plants and related thermal-hydraulic experiments concerning ocean condition effect on thermal-hydraulic phenomena, the effect of motion condition on the measurements must be clarified to ensure the measured values representing the actual thermal-hydraulic parameters. At Seoul National University, a series of experiments investigating motion driven acceleration effect on thermal-hydraulic phenomena which floating nuclear powerplants can experience are being performed. During the experiments notable effects of the accelerations on the differential pressure measurements were observed, especially with the rolling motion. To discriminate whether the characteristics of measured differential pressure were related to the thermal-hydraulic phenomena inside the test-section or not, qualitative assessment based on each acceleration characteristics was done and quantitative assessments with frequency domain analysis was conducted to confirm the assessment.

2. Experimental facility and procedure

2.1 Experimental facility

To perform experiments under rolling conditions, NEOUL-R motion platform and thermal-hydraulic test loop was utilized as shown schematically in Fig. 1. The motion platform can maintain rolling condition up to maximum rolling angle of 45° and minimum period of 6 s. These motion parameters were determined based on the most probable wave period and maximum rolling angle criterion that ship could withstand suggested by IMO (International Maritime Organization) according to Kim et al. [1] who built the motion platform.

The test loop is a refrigerant (R134a) loop, simulating high pressure water condition based on fluid-to-fluid scaling method developed by Katto [2]. Primary components of the loop can be listed in order as follows, a pump, an accumulator, a pre-heater, a throttling valve, a test-section, and cooling heat exchangers. One notable feature is that the throttling valve was applied to suppress flow fluctuation typically observed in flow boiling or motion condition experiments. Next, multiple different sensors including thermocouples, a flowmeter, pressure transmitters were installed throughout the loop to monitor and record thermal-hydraulic parameters. Also, to measure motion condition specific variables such as instantaneous acceleration for each axis and position of the platform, accelerometer and inclinometer were installed on the motion platform.

The test section consists of heater rod and outer tube forming annulus flow channel geometry which was designed to simulate the rod-centered geometry of the nuclear reactor core. Additionally, in this study heater rod with helical-fin geometry and uniform power profile was utilized, which was previously utilized for investigation of motion condition CHF characteristics by Lee et al. [3]

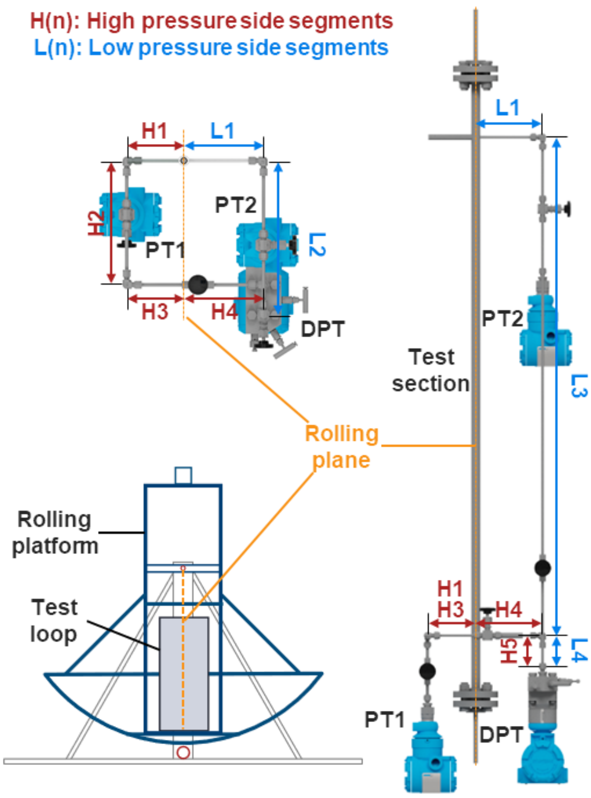

Fig. 1. Overview of rolling platform, test-section, and pressure measurement configurations.

2.2 Experimental procedure

The experiment was subjected to assess the motion driven acceleration effect on single and two-phase condition thermal-hydraulic phenomena. Therefore, to observe the acceleration effect without other interferences such as flow fluctuation, the following procedure was applied. First, to reduce and maintain the flow fluctuation within negligible range (< 1% of flow rate), throttling was applied at the inlet of the test-section with the valve mentioned in previous section. Next, the power applied to the heater rod was increased stepwise from zero to CHF detection point. At each step data was recorded for 60 seconds with 10 Hz sampling frequency, when all parameters reached quasi-steady state. Discrimination of quasi-steady state has been done by checking the range of heater rod wall temperature fluctuation stays within certain range.

3. Results and analysis

3.1 Experimental results and discussion

The differential pressure measurement under rolling condition showed periodic fluctuation as shown in Fig.2 (a).

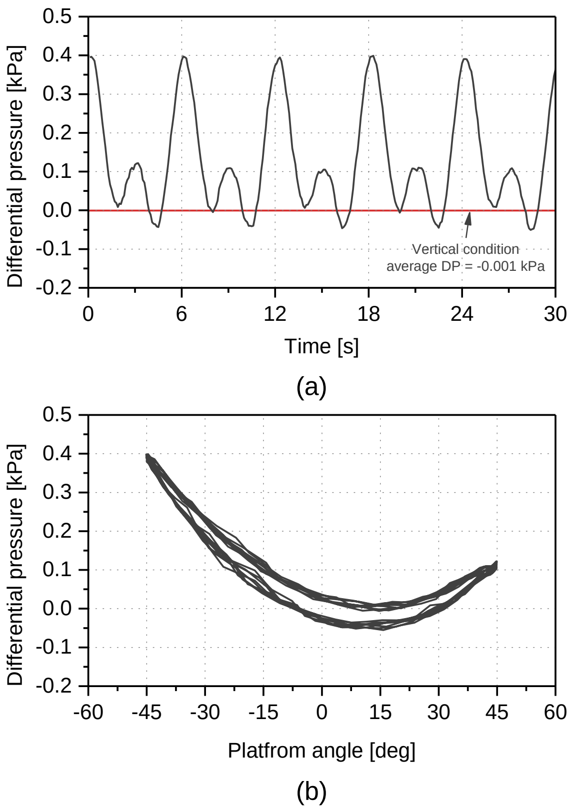

Fig. 2 Differential pressure measurements vs. time (a) and vs. platform angle (b) under rolling condition with max. platform angle of 45° and 6 s period. (Condition: pressure = 2.5 MPa, mass flux = 529 kg/m²s, inlet subcooling = 37 K, heater power input = 0 kW)

The fluctuation itself is a natural phenomenon considering the head pressure drop is proportional to the acceleration which periodically varies under rolling condition. However, two notable characteristics can be found with the differential pressure data plotted with the instantaneous platform angle as shown in Fig. 2 (b). One is the asymmetric peak at each end of the rolling angle and the other is hysteresis-like deviation at the center region of the platform angle range. Considering the test-section is mounted at the middle of the rolling platform and aligned perpendicularly to the rolling axis, vertical acceleration is applied symmetrically independent to the sign of the platform angle, and corresponding symmetric fluctuation can be expected. Therefore, these asymmetric characteristics can be treated as results of unexpected motion effects and needs to be discriminated whether the measurement is due to test-section pressure drop asymmetricity or not.

To clarify the asymmetric characteristics of differential pressure measurement, qualitative assessment was done by comparing accelerations applied to fluid under rolling conditions. Accelerations can be separated into two groups which are gravitational and fictitious accelerations due to rotational motion. The 3 kinds of fictitious accelerations: centrifugal, Euler, and Coriolis acceleration can be calculated with Eq. (1), (2), and (3), where $\vec{\omega}$, $\vec{r}$, and $\vec{v}$ denoting angular velocity, position respect to the rotational axis, and fluid velocity respectively.

$$\vec{a}_{centrifugal} = \vec{\omega} \times (\vec{\omega} \times \vec{r}) \quad (1)$$

$$\vec{a}_{Euler} = \frac{d}{dt}\vec{\omega} \times \vec{r} \quad (2)$$

$$\vec{a}_{Coriolis} = 2\vec{\omega} \times \vec{v} \quad (3)$$

Next, front and top view of the test-section, pressure transmitters, and impulse line configuration with rolling plane were shown in Fig. 1. Assuming homogeneous fluid filled in test-section and impulse lines, the axial and lateral component of gravitational accelerations do not cause asymmetricity regardless of the platform angle. This is due to the gravitational head characteristics which is only determined with elevation. For example, when platform angle altered, head pressure drop of impulse line segments L1 and H1 are compensated by H4 and H3 respectively. In the case of fictious accelerations, Euler and Coriolis acceleration are both lateral directional accelerations having directional dependency. The difference between gravitational acceleration and Euler acceleration is that the Euler acceleration varies proportional to axial distance as shown in Eq. (2) causing head pressure drop of segment H4 to become larger than L1, which can lead to the asymmetric differential pressure measurements. On the other hand, since Coriolis acceleration is proportional to the fluid velocity and angular velocity, it only affects moving fluid inside the test-section. The small head proportional to the test-section diameter caused by Coriolis acceleration acts on both pressure taps and becomes maximum at 0° platform angle, where angular velocity is highest. Also, Coriolis acceleration has vector corresponding to the angular speed, causing differential pressure measurement to have hysteresis-like characteristics which is observed with the actual measurements.

3.2 Frequency domain analysis

To decompose the acceleration effects on differential pressure measurements and assess them quantitatively, analysis on frequency domain was done utilizing FFT method for domain transformation. The decomposition of differential measurement signal is possible regarding dependency on direction of the motion resulting frequency difference. Within a period of the rolling motion, the centrifugal acceleration fluctuates twice since it is proportional to the square of the angular velocity i.e., independent of the direction of the motion. On the other hand, Euler and Coriolis acceleration fluctuates once like rolling motion itself due to directional dependency. Therefore, differential pressure fluctuation driven by centrifugal and vertical component of the gravitational acceleration will have frequency equal to the two times of the motion frequency and those driven by directional dependent acceleration will have frequency equal to the motion frequency. As a result, two peaks on the expected frequencies are observed as shown in Fig. 3, where x-axis indicates ratio between the differential pressure frequency and rolling frequency, y-axis indicating thermal equilibrium quality at outlet representing heat input of the heater rod, and the color scale shows the amplitude of fluctuation at each coordinate. In Fig. 4. decomposed signals for each frequency peak are plotted against time and platform angle with the raw signal. Additionally, due to distortion of the decomposed signal at the beginning and end region, caused by discreate Fourier transform characteristics, 12 to 42 s result is shown out of 60 s data.

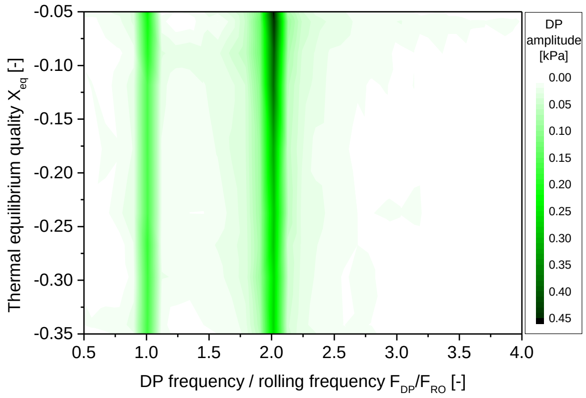

Fig. 3. Differential pressure measurement power spectrum under rolling condition with max. platform angle of 45° and 6 s period. (Condition: Pressure = 2.5 MPa, mass flux = 1410 kg/m²s, inlet subcooling = 23 K)

It can be clearly seen that the differential pressure measurement is mixture of signals with two frequencies at Fig. 3. Also, in the previous section, asymmetricity can be caused by Euler and Coriolis acceleration driven head was suggested. Considering the frequency ratio equal to unity represents intensity of asymmetricity which seems independent to the density change inside the test-section represented by the outlet quality. This supports suggestions made, since the density of fluid in impulse line is not directly affected by the condition of fluid inside the test-section.

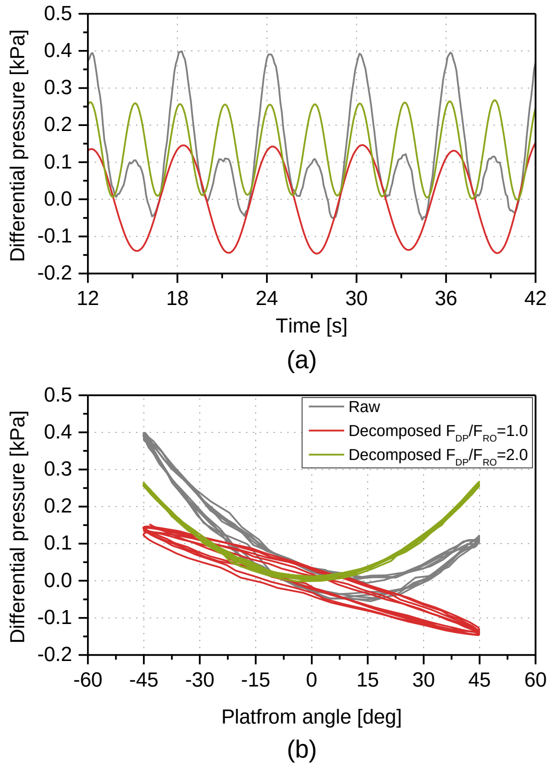

Fig. 4 Differential pressure measurements vs. time (a) and vs. platform angle (b) with decomposed signals for each frequency peak. (Condition: Pressure = 2.5 MPa, mass flux = 529 kg/m²s, inlet subcooling = 37 K)

Considering the asymmetricity is driven by both Euler acceleration and Coriolis acceleration effect, to further assess, separation of the asymmetry peak utilizing phase characteristics of each acceleration. Usually mixture of signals with single frequency and arbitrary phases cannot be decomposed however, in case of the Euler and Coriolis acceleration, they intrinsically have phase difference of $\pi/2$ letting the decomposition possible by utilizing trigonometric identity of the sinusoidal wave. The simplified form of the decomposing equation used are shown in Eq. (4) and (5), where R_F, A, and θ denotes frequency ratio, amplitude, and phase angle.

$$A_{Euler} = \sqrt{[A(R_F = 1)]^2/[1 + tan(\theta(R_F = 1))]} \quad (4)$$

$$A_{Coriolis} = A_{Euler} \cdot \theta(R_F = 1) \quad (5)$$

After the decomposition, assuming the differential pressure fluctuation amplitude is equal to the head fluctuation driven by the lateral acceleration, the characteristic length was calculated with the estimated density and the maximum acceleration. For Euler acceleration case, the calculated statistical mean was found to be 135 mm with 95% of the data within ± 40 mm range which is similar to the actual length of the impulse line segment of L1 and H4 in Fig. 1 with length of around 130 mm. On the other hand, since Coriolis acceleration only exists within the test-section which has diameter of about 15.8 mm and affects both pressure taps simultaneously doubling the effective length, which is also close to the derived statistical mean length of 33 mm ± 20 mm. As a summary the initial quantitative expectations on cause of asymmetric characteristics were confirmed quantitatively with frequency domain analysis.

4. Conclusions

Differential pressure was measured between inlet and outlet of the test-section with vertical annulus geometry under the rolling conditions. Asymmetric differential pressure was measured during rolling motion experiments, which was unexpected since, rolling motion itself was symmetric and the test-section was aligned with the rolling axis allowing the test-section to receive symmetric acceleration parallel to the test-section. Therefore, other accelerations with directional dependency combined with the test-section and impulse line configuration was assessed. There were two possibilities one is that rolling motion affects flow through the test-section causing asymmetric pressure to drop relative to the platform angle and the other is accelerations with asymmetric characteristics affecting the differential pressure measurements due to test-section and impulse line configurations. A later statement was investigated further by comparing asymmetric fluctuations with the equations representing each acceleration. It was found that Euler and Coriolis acceleration can cause asymmetric signal with current experimental loop configuration. To confirm whether the Euler and Coriolis acceleration actually affecting the differential pressure measurement, analysis within frequency domain was done. As a result, with frequency information, the differential pressure measurement consist of two components with symmetrical and asymmetrical characteristics. Also, the peak with the frequency ratio of one was less affected by internal condition of the test-section supporting Euler acceleration effect on the impulse line segments. Lastly by further decomposing the peak, Euler and Coriolis acceleration affected lengths were calculated and confirmed the similarity with the actual length.

REFERENCES

[1] Katto Y., 1979. “Generalized Correlation of Critical Heat-Flux for the Forced-Convection Boiling in Vertical Uniformly Heated Round Tubes - Supplementary Report”. International Journal of Heat and Mass Transfer, 22(6), 783-794.
[2] G. W. Kim, Experimental investigation of critical heat flux on a single heater rod under inclined and rolling conditions, Ph.D. thesis, Seoul National University, 2021.
[3] C. W. Lee et al., “Experimental investigation of CHF on helical finned heater under the static inclination and rolling conditions”, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 19-20, 2022