Experiments of Two-phase Flow Dynamics of Marine Reactor Behavior under Heaving Motion

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Two-phase flow dynamics of a marine propulsion reactor—of the steam generator in particular—subjected to heaving acceleration were studied on a small-scale rig simulating the primary and secondary circuits of those of N. S. Mutsu. To impart the heaving acceleration, the rig was mounted on a suspended platform oscillated in vertical direction by hydraulic device. Heaving acceleration applied to this rig proved the responding variations of circulating flow, of evaporator steam void fraction and of downcomer water level to be proportional in amplitude to that of the acceleration. The circulating flow was found to pulsate with phase lag behind the heaving acceleration indicative of a second order lag function. Constriction of flow channel downstream of the evaporator—producing resistance against flow amounting to 1.15 times that of the entire loop—proved to amplify significantly the responding pulsations of circulating flow. The pulsations were conversely appreciably diminished by the insertion of a second channel constriction upstream of evaporator—producing 2.7 times loop resistance. When devoid of heaving acceleration, with insertion of flow constriction downstream of evaporator, circulating flow was indicated to be controlled by density wave oscillation, whereas upon application of heaving acceleration, the flow came to be controlled by the external acceleration.

KEYWORDS: two-phase flow, U-type steam generator, heaving, ship motion, marine reactor, density wave oscillation, flow kinetics, pulsations

I. INTRODUCTION

A characteristic environmental condition particular to the functioning of marine reactor systems is their being subjected to bodily acceleration applied by hull rolling, pitching and heaving. These environmental factors affect the reactor plant’s operating conditions independently of internal factors such as the rates of steam flow and of water feed. This circumstance calls for proper grasp of the effects brought by ship motion on the hydraulic behavior of reactor components such as the steam generator.

Ship motion will affect the operating variables, e.g. of the steam generator secondary circuit such as the water level and exit flow rate (single-phase) of the downcomer, and the void fraction and exit flow rate (two-phase) of the evaporator. The manner in which these variables are affected will differ in terms of time lag between external disturbance and functioning response according to the effective volume available in the system component and to the time taken for fluid transit through the component. It moreover remains to be determined whether the relation between disturbance and response is linear or nonlinear. What is more, the disturbance—i.e. ship motion—itself is not strictly regular. All the above observations point toward the necessity of remedying the current lack of a valid mathematical model to serve in estimating reactor component response to ship motion.

Studies in the above connection have covered the effect of heaving on critical heat flux(1)-(3) and of heaving or rolling on the natural circulation flow(4)-(6), but to the present authors’ knowledge, no study has related ship motions to the hydrodynamic behavior of a nuclear reactor component such as steam generator.

The present study was undertaken in connection with the design work on the nuclear ship Mutsu: Experiments were conducted using a small rig simulating the primary and secondary circuits of N. S. Mutsu to examine basic relevant phenomena, and to evaluate the design calculations. The results were used for planning the experiments to be effected on N. S. Mutsu during cruises, and for evaluating the results of such experiments.

The experimental cruises undertaken by N. S. Mutsu during 1991 under various sea and weather conditions served to gain valuable data concerning the effects brought by hull motion on the ship’s reactor plant(7). Among the different modes of hull motion affecting the various reactor operating variables, the most prominent effect was brought by heaving on the steam generator water level. Hence, the relation between heaving and the steam generator dynamics was taken up as primary sub-
ject in the present study. The effects on changing the evaporator channel diameter and of locally constricting the flow channel were also examined.

The steam generator of N. S. Mutsu is configured as schematized in Fig. 1. The water level is detected by mean of the pressure difference transducer $\Delta P$ measuring the deviation of pressure at a set position in the liquid phase of the steam generator from a reference pressure keyed to the vapor phase in the steam generator dome. The signals emitted by the transducer are screened through a low-pass filter to eliminate spurious pressure ripples. In experiments during cruise, oscillations of the screened pressure—indicating the water level $L_D$—were related to the records of ship motion, in particular, heaving.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental rig was arranged as schematized in Fig. 2, simulating the recirculation form of N. S. Mutsu's steam generator: It consisted of primary loop (with electric heater, pressurizer, circulating pump and pipe connections), and secondary loop (with evaporator, separator, downcomer, pipe connection) together with steam disposal and return feed system.

Heaving motion was imparted to the experimental rig by suspending it on a hydraulic device arranged as shown in Fig. 3.

The conditions applied in the rig experiment are specified in Table 1, together with the corresponding design conditions adopted for the actual ship. Practical agreement is seen between experimental and design conditions.
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on such essential thermohydraulic parameters as mass and heat fluxes, steam quality and void fraction. The void fraction in steam generator is of particular significance in this instance of two phase natural circulation. Also important for considering the effect of heaving motion on the circulating flow is the relation between the period $\tau_h$ of heaving acceleration and time $t_t$ taken by the fluid to pass through the evaporator. It is seen in Table 1 that the ratio $t_t/\tau_h$ was not far from unity in experiments both on rig and on actual ship. This coincidence is the composite result of the flow driving force being influenced concurrently by heaving acceleration and by the inertia of flowing fluid in pulsating flow.

To examine the effect of changing the flow channel area of the evaporator (one of the experimental parameters), alternative forms of evaporator shell were used in the rig experiment. Two forms-designated Types A and B—respectively presented effective channel diameters of 40 and 100 mm. A third shell-Type R or reference—of 90 mm effective channel diameter, was arranged with electric heater incorporated within the evaporator.

In rig experiment, measurements were made (a) on the primary loop, to determine (a-1) temperatures—$T$ in Fig. 2—(using sheathed chromel-alumel thermocouple), (a-2) flow rate—$W_H$—(using orifice flowmeter), (a-3) pressurizer pressure—$P_p$—(using diaphragm type pressure transducers), and (a-4) pressurizer water level—$L_p$—(using diaphragm type differential pressure transducers), and (b) on the secondary loop, to determine (b-1) circulating flow rate upstream of evaporator—$W_C$—and flow rates of (b-2) feedwater—$W_F$—(using electromagnetic flowmeter), and of (b-3) steam flow—$W_S$—(using vortex shedding flowmeter), (b-4) pressure—$P_S$—and (b-5) differential pressure—$D_{P_1}$, $D_{P_2}$—(using diaphragm type differential pressure transducers), from which were derived (b-6) the water level of downcomer $L_{DC}$, and (b-7) the steam void fraction of the evaporator.

The measured pressurizer and downcomer water levels and steam void fraction of evaporator were corrected to eliminate the effect of heaving acceleration. Approximate measuring instrument sensitivities were $1^\circ C$ for temperature, and 1% of full range for flow rate (500 kg/h full range), 0.5 MPa for pressure, and 600 mm Aq full range for differential pressure and 500 mm full range.

Before applying the heaving motion to the rig, a run of experiment was started by letting the pressures, temperatures and flow rates in both primary and secondary loops attain steady state. The rig was then set to heave, and thereafter the heater power was automatically controlled to maintain constant coolant temperature at heater exit. Throughout a run, the feedwater and steam flow control valves were maintained at constant opening.

### III. RESULTS AND DISCUSSIONS

#### 1. Stationary State Flow

Data obtained on the steam generator in stationary state prior to heaving application are given below using the symbols indicated in Fig. 4. "Re-circulation ratio"
$R$ is the inverse of steam quality at the evaporator exit, calculated using the expression.

\[ R = (W_S + W_R)/W_S = W_C / W_S, \tag{1} \]

where $W_C$: Rate of circulating flow in steam generator (= the evaporator entrance flow rate)

$W_S$: Steam flow rate

$W_R$: Recirculating flow rate.

The measured stationary data on the circulating flow rate $W_C$ and re-circulation ratio $R$ are as indicated in Fig. 5, plotted against heat input $Q$. It is known that, with single-phase natural circulation, the flow is proportional to the cube root of the heat input. Assuming a similar relation to hold also with two-phase system, curves representing $W_C \propto Q^{1/3}$ are drawn in Fig. 5, which are seen to well fit the measured plots for both Type A and Type R steam generators. The run with Type B steam generator (not plotted in Fig. 5) proved to produce fluctuating unsteady flow, for some reason yet to be determined. Steady flow was ensured in the Type R steam generator by the heaters arranged uniformly within the steam generator.

The plots of circulating flow rate are at a lower level in the case of Type R than of Type A. This can be ascribed to the larger channel cross section of the Type R inducing a lower driving force per unit cross sectional area for equal heat input, and a resulting smaller void fraction, both concurring to overbalance the inverse trend induced by the lower fluid resistance accountable to the same factor of larger channel cross section.

The re-circulation ratio $R$ is seen to have lowered with rising heat input $Q$. At $Q = 40 \text{kW}$, $R$ came to acquire a value almost equal to the design rated condition of $R = 5$ adopted for the actual ship.

2. Response to Heaving—Generalities

Indicated in Fig. 6 are responses to heaving obtained on Type A steam generator at 38 kW heat input, in respect of representative operating variables. Also shown for comparison—in broken lines—are corresponding data from runs performed devoid of heaving.

Heaving motion was applied in the wave form shown in the upper diagram (a) of the figure of \pm 0.2 g amplitude with approx. 0.2 Hz frequency (5 s period)—and was initiated about 1 minute after start of run.

The resulting responses are indicated in the lower diagrams (b) to (g) of Fig. 6, which represent the variations in time during the period between 20 and 220 s after start of run. It is seen that heaving little affected the primary loop variables of pressurizer pressure $P_p$ in Fig. 2—and water level $L_p$ (diagram (b)), and of the temperatures at heater entrance $T_1$ and exit—TIC 1— (diagram (c)). The secondary loop variables, on the other hand, are seen to have been sensitively affected by heaving: The evaporator temperatures have oscillated with heaving in the upstream region $T_3$, $T_4$—(diagram (d))—although they have tended to approach constant saturation temperature further downstream $T_7$, $T_8$, $T_9$—(ditto:). Oscillations are seen reflecting the heaving motion on all the remaining diagrams (e), (f) and (g) covering the secondary loop variables: Diagram (e) records the steam void fraction at evaporator exit—(o)—and the pressure difference $\Delta P_1$—between two levels on the upper part of evaporator; diagram (f)
Fig. 6  Typical responses to heaving shown by representative operating variables—Type A steam generator at 38 kW heat input under heaving to 0.2 g at 0.5 Hz frequency
is for the circulating flow rate—$W_C$; it is seen phased roughly in synchrony with the heaving cycles; poorer synchrony is seen with diagram (g) for the downcomer water level—$L_{DC}$. The mechanism of this lag of phase seen of the downcomer water level will be discussed in detail in the ensuring section 3.

The records from other runs at different heater input rates and heaving conditions proved to present response behavior qualitatively similar to that from the run described above.

The variations of circulating flow rate $W_C$ and of downcomer water level $L_{DC}$ are plotted in Fig. 7, in mean values of the undulation amplitudes during a sampling period of approximately 100 s, indicated in percentages of the mean values of the relevant variables—$W_C$, $L_{DC}$—during the same period. The lines drawn in the diagrams represent least squares fitting: In diagram (a), the straight solid and curved broken lines represent fitting respectively to 1st power (linear) and to 1/2 power (square root) of acceleration $G$. The quality of fit is much the same between the two.

Flow in natural circulation depends on the two factors of driving force $\rho GH$ ($\rho$: density of water, $G$: acceleration, $H$: height) and flow resistance $kW^2$ ($k$: coefficient, $W$: flow rate). Driving force is directly related to heaving acceleration, but the effect of heaving on flow rate is circumstantial in the case of two-phase natural circulation: If the driving force is dominant compared with the effect of heaving acceleration, such as in the case of flow delivered from a pump, the flow rate would respond linearly to acceleration\(^{(3)}\). If on the other hand, acceleration imparts a relatively powerful influence, such that $\rho GH \approx kW^2_C$, the flow rate $W_C \propto G^{1/2}$ in approximation. The plots of Fig. 7(a) can be considered to lie somewhere in-between the two cases of $W_C \propto G$ and $W_C \propto G^{1/2}$.

The water level $L_{DC}$ is influenced both by flows into and out of the evaporator. The plots of Fig. 7(b) have been fitted by straight line, which also proved to well fit the plots obtained on the actual ship during experimental voyages\(^{(7)}\). Detailed discussion on this aspect will be given in the following section.

3. Frequency Response to Oscillating Acceleration

Frequency analysis applying the Blackman-Turkey method\(^{(10)}\) was performed on the data from run with Type A steam generator at 38 kW heat input with heaving to 0.2 g at 0.5 Hz.

Analyzed results are presented in Fig. 8, giving the power spectra of key operating variables: The diagrams (b)—for heater entrance temperature (T-1 of Fig. 2)—and (f)—for steam generator pressure ($P_s$)—are characterized by a single peak at zero frequency, indicating no dependence on frequency, i.e. no influence of heaving.

Conversely, peaks coinciding with the heaving frequency—indicative of sensitivity to heaving acceleration—are seen in the diagrams representing vertical acceleration (diagram (a)), steam generator flow rate $W_C$ (diagram (c)), evaporator steam void fraction $\alpha$ (diagram (d)), and downcomer water level $L_{DC}$ (diagram (e)). Minor peaks at 2.5 Hz, and further minute occasional peaks are also seen on these spectra. These subsidiary peaks could be ascribed to boiling noise, inferring from the more prominent incidence of the additional peaks in diagrams (d) for steam void fraction in evaporator compared with what appears in the other diagrams (a), (c), and (e).

To further verify the relationship with heaving presented by the spectra in the above diagrams (a), (c), (d) and (e), coherence curves were derived, as shown in Fig. 9. Coherence though reduced to a much lower degree—is seen to have extended to frequencies higher than indicated by the spectra of Fig. 8.

Response functions are presented in Fig. 10, where R.S.C. signifies the range in which significant coherence was noted. For circulating flow rate (diagram (a)), the gain $\Delta W_C/\Delta G$, and phase lag ($\tau_{W_C} - \tau_G$) have both lowered with rising frequency, with the phase lag approaching $\pi$ radian (180°) toward higher frequencies, which is indicative of a second-order lag function.

Steam void fraction (diagram (b)) is seen to have somewhat raised its gain $\Delta \alpha/\Delta G$ within the range of significant coherence, whereas in the same range the phase lag ($\tau_{\alpha} - \tau_G$) has conversely lowered. For this variable in particular, the range of significant coherence has been limited to a narrow band below 1 Hz, on account of the already-noted involvement of extraneous noise.

Fig. 7 Percentage mean amplitudes of circulating flow rate and downcomer water level undulations during 100 s period
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Downcomer water level in reference to acceleration (diagram (c)-1) has lowered its gain \( \Delta L/\Delta G \) with increasing frequency, whereas its phase lag \( \tau_L - \tau_G \) has remained roughly on the same level. Within the range of significant coherence, both the curves for gain and for phase lag in diagram (d) of downcomer water level in reference to steam generator flow rate present tendencies similar to the corresponding curves of diagram (c) in reference to acceleration. At 0.5 Hz frequency, the phase lag of downcomer water level in reference to acceleration (diagram (c)-2) \( \tau_L - \tau_G = -3.5 \text{ radian} \) is roughly equal to the sum of phase lags of the water level in reference to flow rate (diagram (d)-2) and of flow rate in reference to acceleration (diagram (a)-2) \( \tau_a - \tau_{WC} \).

The phase lag between steam void fraction and heaving acceleration \( \tau_a - \tau_G \) (diagram (b)-2) incorporates a combination of the phase lags between circulating flow rate and acceleration \( \tau_{WC} - \tau_G \) (diagram (a)-2) and some degree of that between void fraction and flow rate \( \tau_a - \tau_{WC} \).

The effect of heaving on the steam generator secondary circuit can be explained by the mechanism described in what follows.

Referring back to Fig. 4, the balance of forces acting in natural circulation flow whether with or without heaving acceleration can be represented by the following relations:

\[
\tau_{WC} - \tau_G - \tau_L - \tau_G = -3.3 - 0.2 \text{ radian}.
\]

Fig. 8 Power spectra of key operating variables—Type A steam generator at 38 kW heat input under heaving to 0.2 g at 0.5 Hz frequency

Fig. 9 Coherence with between operating variables indicated by power spectra of Fig. 8 to respond to heaving acceleration
For circulation flow $W_C$:

$$(g + AG)(\rho_{DC} - \rho_{EF})H_{EP} + (P_{DC} - P_{EF})$$

$$- \Delta P_{kW_2} = I_C dW_C/dt.$$  \hspace{1cm} (2)

For evaporator exit flow $W_E$:

$$(g + AG)(-\rho_S H_S - \rho_{EF} H_{EP}) + (P_{EF} - P_S)$$

$$- \Delta P_{kW_2} = I_E dW_E/dt,$$  \hspace{1cm} (3)

where symbols other than defined in Fig. 4 are:

- $g$: Acceleration of gravity
- $\Delta G$: Added acceleration of heaving
- $H_S$, $H_{EP}$: Height of fluid filling separator and evaporator, respectively
- $\Delta P_{kW_2}$, $\Delta P_{kW_2}$: Resistance against circulating flow $W_C$ and against evaporator exit flow $W_E$
- $I_C$, $I_E$: Inertias of flows $W_C$ and $W_E$

$t$: Time.

The superposition of heaving acceleration $\Delta G$ to that of natural gravity affects the terms of Eq. (2) in the following matter. The 1st term is directly affected by the change of acceleration, with no time lag. This change of the 1st term will affect the force causing the circulation flow $W_C$.

The 2nd term of Eq. (2) is influenced by the mass and the energy carried in the fluid contained in the downcomer and evaporator, to vary with a time lag determined by the mass and the heat capacity of the same fluid quantities. The downcomer pressure $P_{DC}$ of the same 2nd term is further influenced by change in the downcomer water level $L_{DC}$, and the consequential nature of this influence adds to the time lag in reference to the original phase of heaving acceleration. Evaporator pressure will further be influenced by the heat transferred from the primary circuit, but the effect of this
factor can be considered to be small.

The 3rd term of Eq. (2)—for resistance against flow—varies with the rate of circulating flow.

Of the foregoing factors influencing the time lag of the response to heaving acceleration shown by the circulating flow $W_C$ as expressed by Eq. (2), the predominant influence is exerted on the 1st term, which is directly affected by the causal heaving acceleration, with no time lag.

In Eq. (3) for the evaporator exit flow $W_E$, the application of heaving acceleration will add directly to the 1st term. The 2nd term of Eq. (3) is influenced similarly to that of Eq. (2) with a time lag. This 2nd term can be considered to constitute the predominant force underlying the evaporator exit flow $W_E$. This value $W_E$ will be influenced by the heaving acceleration through the medium of change in evaporator pressure, and will appear with a time lag.

Consequently, the direct and immediate effect of heaving acceleration on the flows $W_C$ into and $W_E$ out of the evaporator will be in opposite direction, being governed by the 1st terms respectively of Eq. (2)—positive and Eq. (3)—negative.

If the flow is single phase, $W_C = W_E$ at all times so that Eqs. (2) and (3) will be integrated into a single equation, although the individual values of their component variables will vary cyclically. With two-phase flow, on the other hand, the balance of flow rates will cyclically vacillate, reflecting the differently-phased changes in the pressure and hence also in the density of the flowing fluid.

The mass balance of fluid in the downcomer can be expressed by

$$A_D \cdot dL_{DC}/dt = W_R - W_C. \quad (4)$$

The downcomer water level $L_{DC}$ will thus depend on the balance between incoming and outgoing flow rates $W_R$ and $W_C$, so that the pulsation of flow rates accompanying the heaving motion will consequently also oscillate $L_{DC}$.

As already mentioned, the balance between $W_R$ and $W_C$ will vacillate cyclically. In experiment, the resulting oscillation of the downcomer water level $L_{DC}$ proved to occur in a phase lagging far behind those of flow and of the void fraction in evaporator. This large phase lag can be ascribed to the complex relations between causal factors and resulting effects subsisting through parallel paths—some of which are direct, involving little time lag, and others which are consequential, with delayed effect.

4. Specific Gain of Flow Rate and Heat Transfer Coefficient

We shall call “specific gain of circulating flow rate” the ratio $(\Delta W_C/W_{C0})/(\Delta G/G_0)$ of pulsatory circulating flow rate to that in steady state devoid of heaving acceleration, expressed as gain on the corresponding value of heaving acceleration. This specific gain proved to vary with heaving frequency as indicated in Fig. 11 in the case of Types A and B steam generators in the range of significant coherence between 0.2 and 1.0 Hz.

The Type A steam generator is seen to have tended to raise its specific gain with increasing heat input, indicating small dependence on heaving frequency. The Type B steam generator has produced fluctuating unsteady data, as noted earlier, but within the range of heat input covered, the general level of specific gain is seen to be much the same between the two types of steam generator.

The heat transfer coefficient of the evaporator tube wall on the secondary side was derived for the Type A steam generator, applying the conventional formula

$$Q_{SG} = U A \theta_m$$

$$1/U = 1/h_o + d_i/(2l) \ln(d_o/d_i) + d_i/d_o(1/h_{SG}), \quad (5)$$

where $Q_{SG}$: Heat input

$A$: Heat transfer area

$U$: Logarithmic mean temperature

$h_o, h_{SG}$: Time-averaged heat transfer coefficients of evaporator primary and secondary sides, respectively, averaged over entire tube length

$d_i, d_o$: Inside, outside diameters, respectively, of heat transfer tube.

The measured time-averaged values of heat transfer coefficients $h_{SG}$ of secondary side, determined experimentally, are plotted in Fig. 12 against heat flux $q$, for both cases with and without application of heaving acceleration. The plots for the two cases are seen to converge in the region toward higher heat flux.

The mode of heat transfer prevailing in the evaporator can be considered to have been single-phase convection in the upstream region within a certain distance from entrance, which distance would diminish with increasing heat flux. Drawn over the plots in Fig. 12 are straight lines representing the formulas given by Stephan-Abdelsalam(11) and Kutateladge(12) for nucleate boiling heat transfer, both of which converge and coincide with the present measured plots toward higher heat flux. The deviation at lower heat fluxes, can thus be ascribed to increasing portion of single-phase convection in this range.

The enhancement of heat transfer with application of heaving acceleration in the range of lower heat flux can
be attributed to mixing action produced in the evaporator by the acceleration.

5. Effects of Constricting Flow Into and Out of Steam Generator

The resistance against flow into and out of the steam generator is an important design parameter that affects the response of water level to heaving acceleration as well as to changes in steam flow.

The element of steam generator that produces the most significant resistance is the swirler vane of steam generator (see Fig. 1), represented by the symbol $K_2$ in Fig. 4. This resistance was introduced in the experimental rig by inserting an orifice ($O$ in Fig. 2) that constricted the flow area to $1/7$. Constriction of the flow entering the evaporator ($K_1$ in Fig. 4) was provided by throttling the valve $V$ in Fig. 2. The resulting added flow resistance amounted to 1.15 times that of the entire loop with the orifice $O$, and 2.7 times the same with the throttled valve $V$.

For various combinations of presence and absence of the foregoing elements that constricted the flow into and/or out of the steam generator, the measured responses to heaving shown by the circulating flow $W_C$ into evaporator of Type A steam generator are indicated in Fig. 13. The widest pulsation of $W_C$ is seen to have occurred with the orifice $O$ inserted but with valve $V$ left unthrottled (diagram (c)), the range of pulsation reaching in this case roughly twice that of the original case with both orifice and valve unapplied (diagram (b)).

The foregoing amplification of $W_C$ pulsation with application of flow constriction downstream of the evaporator sharply diminished flow pulsation (diagram (d)).

The values of specific gain on heaving acceleration are presented in Fig. 14 for circulating flow rate into evaporator—$[\Delta W_C/W_{C0}] / (\Delta G/G_0)$— and for downcomer water level—$[\Delta L_{DC}/L_{DC0}] / (\Delta G/G_0)$]. For downcomer water level, the specific gain has varied widely with frequency of heaving oscillation in the original case of both orifice and valve unapplied, and was at a higher level with application of both orifice and valve constriction compared with the case of orifice alone applied.

Stricter examination of the mechanism behind the foregoing behavior calls for determining whether or not there is involved such instability factors as density and sonic wave oscillations, and geysering. Density wave oscillation is characterized by (a) periodical variation, with period determined by the time taken by the fluid to pass through the boiling channel, and (b) occurring without requiring application of external force (i.e. self-excited oscillation). This form of oscillation will increase its instability with flow constriction applied at channel exit.

The share taken by density wave oscillation in the present instance is verified on the power spectra of Fig. 15, obtained from runs with orifice inserted downstream of evaporator but without valve constriction up-
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Fig. 14 “Specific gains” of circulating flow rate and of downcomer water level compared between combinations of presence/absence of flow constriction upstream/downstream of evaporator—Type A steam generator at 40 kW heat input under heaving to 0.2 g at 0.5 Hz frequency

Fig. 15 Power spectra obtained on operating variables to verify share taken by density wave oscillation in presence and in absence of heaving oscillation—Type A steam generator at 40 kW heat input and eventually under heaving to 0.2 g at 0.5 Hz frequency

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ating variables indicated circulating flow into steam
generator to be governed by a second-order lag func-
tion.

(3) Heaving acceleration can be considered to cause
variation of the secondary circuit operating vari-
ables through a mechanism whereby the acceleration
would first directly affect the flow into and out of the
evaporator, which in turn would bring about oscillation
of the evaporator void fraction and pressure, to
consequently pulsate the rate of flow into the evapo-
rator. The balance between the flow into and out of the
evaporator would further influence the balance
of flow into and out of the downcomer, whose water
level would thereupon oscillate as a consequence of
heaving acceleration.

(4) In stationary state devoid of heaving acceleration,
the flow rate through evaporator was larger in the
 case of an evaporator of smaller than of larger cross
section; this effect of difference in evaporator cross
section on the amplitude of flow rate pulsation dis-
appeared upon application of heaving acceleration.

(5) In the region of low heat flux, the secondary side
heat transfer coefficient of evaporator proved to be
enhanced by application of heaving acceleration.

(6) Within the range of variables covered in the present
experiment, the insertion of flow constriction down-
stream of evaporator—representing that account-
able to the steam separator swirler vane in actual
steam generator—proved to amplify the pulsations
of circulating flow and of the downcomer water
level. Additional flow constriction applied upstream
of evaporator—introduced by throttling a valve—
conversely resulted in sharp diminution of the flow
pulsation.

(7) With insertion of flow constriction downstream of
evaporator, circulating flow was indicated to be con-
trolled by density wave oscillation when devoid of
heaving acceleration, whereas upon application of
heaving acceleration, the flow came to be controlled
by the external acceleration.

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