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Two simple correlations for the inception of density-wave oscillations in long sodium-heated steam generator tubes

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Abstract—Two phenomenological correlations have been established to predict the inception conditions of density-wave oscillations (DWO) in sodium-heated steam generator tubes longer than about 13.9 m. These have been verified with 363 data obtained for the following ranges of conditions. Geometry: straight, helically coiled and serpentine tubes and those comprising a vertical and a horizontal tube; tube length: 13.9–68.1 m; ID: 7.9–24.2 mm; pressure: 5.3–19.1 MPa; outlet steam quality: 1.10–2.38; sodium inlet temperature: 341–648°C; inlet subcooling: 3–168°C; sodium- to water/steam-side mass flow ratio: 8.8–19.9. They predict the power at the inception of DWO from these data accurate to about 4.5% for 98% of the time. The RMS error is about 2%. The correlations include stable conditions for the 2039 test runs carried out to produce the foregoing 363 data.

INTRODUCTION

SUFFICIENT evidence has been presented in the literature that the main type of dynamic instability of interest to the design of steam generators is that caused by the propagation of density waves. This type of instability is generally referred to as density-wave oscillations (DWO) or less frequently, mass flow-void feedback, time-delay or parallel channel instability. The present study deals with the determination of the inception conditions of DWO (ICDWO) in sodium-heated steam generator tubes (SHSGTs). These conditions are, per definition, the steady-state operation conditions (i.e. power, mass velocity, inlet subcooling, pressure and etc.) in a SHSGT just before DWO appear in the tube.

DWO are due to multiple regenerative feedback between the flow rate, the vapour generation rate and the pressure drop, and are low-frequency flow oscillations, the period of which is of the same order of magnitude as the total transit time of a fluid particle in the steam generator. DWO have been extensively studied during the last two decades. For a detailed literature survey on the subject, the reader is referred to [1]. In the following, only the literature data found pertinent to the present study are briefly mentioned.

Experimental studies for the determination of the ICDWO in the tubes of large capacity sodium-heated steam generators have been reported in refs. [2–4] and those in small test units comprising a single tube equipped with a by-pass pipe or a few parallel tubes in refs. [5–9]. The results obtained in these studies for the ICDWO have been correlated using either a stability model [4, 9, 10] or the methods of dimensional analysis [4, 6, 7, 11]. The former is, in general, a simultaneous solution of one-dimensional non-steady-state, linearized or non-linearized continuity, momentum and energy conservation equations with appropriate boundary conditions and subsidiary equations. These subsidiary equations are relations for the properties of water and steam, empirical correlations for void fraction, heat transfer and pressure drop for different flow regimes in a steam generator tube, and a correlation for the thermal non-equilibrium condition in subcooled nucleate flow boiling. Almost all the stability models given in the literature have been worked out in computer programs.

Although in the absence of final experimental data about stability, the use of a stability model may be justified, it is, in principle, an inadequate method to predict the period and the ICDWO, as demonstrated, for instance, in refs. [12, 13]. This may be due to the following reasons:

- —The conservation equations used in the stability models presented in the literature are derived on the assumption that an elementary volume is infinitesimally small and that the two phases are completely mixed in this volume [12]. This assumption applies to a continuous fluid. However, a two-phase flow medium is not homogeneous but heterogeneous, at least, for slug-plug and annular flow.
- —Almost all the heat transfer, void fraction and pressure drop correlations used in the models have not been developed or even verified for non-steady-state conditions.
- —In most models, a slip ratio is used. This again is controversial to the assumption used for the derivation of the conservation equations.
- —Most models are based on linearized conservation equations. The conservation equations are highly non-linear; therefore such stability models, by definition, are less suitable for predicting the period of the limit cycle oscillations.

NOMENCLATURE

A	cross-sectional area [m^2]
a, b	dimensionless constants
c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
c	average specific heat at constant pressure [J kg^{-1} K^{-1}]
D	coil diameter [m]
d	tube diameter [m]
G	mass velocity on water/steam side [kg m^{-2} s^{-1}]
h	enthalpy on water/steam side [J kg^{-1}]
K	inlet throttling coefficient
L	total effective tube length [m]
l	length of a heat transfer region [m]
m_1	number of ICDWO-data
m_2	number of test runs before the ICDWO-run
n	number of tubes in a test unit
P	pressure [Pa]
r	latent heat of evaporation [J kg^{-1}]
Q	rate of heat transfer [W]
q	heat flux [W m^{-2}]
T	temperature on sodium side [°C]
t	temperature on water/steam side [°C]
Δt	inlet subcooling [°C]
U	overall coefficient of heat transfer [W m^{-2} K^{-1}]
v	specific volume [m^3 kg^{-1}]
W	mass flow [kg s^{-1}]
X	thermodynamic steam quality
y	axial coordinate [m]; $y = 0$ at the beginning of superheated steam region.

Subscripts

a	refers to a large capacity unit
b	refers to boiling region
c	refers to critical point for water
i	refers to inlet condition
l	refers to water at the state of saturation
j	refers to the beginning of superheated steam region
n	refers to sodium side
o	refers to outlet condition
p	refers to preheat region
s	refers to superheated steam region
v	refers to steam at the state of saturation
w	refers to water/steam side.

Considering these shortcomings of stability models, empirical correlations have been reported in refs. [6, 7, 11] to predict the ICDWO for both electrically- and sodium-heated steam generator tubes with a better accuracy. As a general rule, an empirical ICDWO-correlation is only applicable to the range of data from which it has been derived, while a stability model should not possess this deficiency. In two-phase flow, the dimensionless numbers used for the correlation of experimental data are not, in general, derived from the well known three classical methods of dimensional analysis. As shown in ref. [14], the dimensionless numbers which fully characterize the dynamics of two-phase flow are numerous and it is practically impossible to take all of them into account when correlating the data. Therefore, the dimensionless numbers used in the ICDWO-correlations reported in refs. [6, 7, 11] have been selected using experimental evidence. Current sodium-heated steam generators use tubes longer than approx. 13.9 m. At the inception of DWO in such a tube, the results of extensive experiments carried out with different types of SHSGTs (i.e. more than 2400 data) have shown that the ratio of the length of the superheated steam region to the total tube length is of considerable magnitude [6, 7] and that the difference between the temperature on the sodium side and the water/steam side at the water/steam-side outlet is not large [2–9]. The use of these two pieces of empirical evidence simplifies significantly the correlations reported in [6, 7, 11], and yields two simple correlations for the prediction of the ICDWO in SHSGTs longer than approx. 13.9 m. Both correlations seem convincing and they are accurate. The aim of this paper is to present the derivations of these correlations, the results of a new insight gleaned from the earlier data [7]. The reason why they do not predict well the ICDWO in SHSGTs shorter than 13.9 m will be explained.

EXPERIMENTAL DATA

The data reported in refs. [2–9] for nine test units (TUs) have been considered. The operating conditions of the data and the geometries of the TUs have been summarized in Table 1. All the test units were counter-flow sodium-heated steam generators. In each unit, the flow orientation was upward on the water/steam side and downward on the sodium side. The ICDWO were the operating conditions measured for the last stable test run before DWO occurred in a TU. For practically all the tests reported in refs. [2–9], DWO were generated either by increasing the sodium-side inlet temperature [3, 5–7] or by decreasing the water/steam-side mass flow [2–4], and the remaining operating conditions were not adjusted.

TU1 was a single tube consisting of a vertical and a V-shaped horizontal tube. TU2 was similar to TU1. TU3 was a helically coiled tube. A constant pressure drop was maintained in each tube by means of a by-pass pipe. For 59% of the ICDWO-data obtained with TU3, the inlet throttling coefficient was not large since this was due to flow meters installed at the inlet of the unit and $K = 15$–27.

Table 1. Ranges of operating conditions and geometries for the ICDWO-data

	TU1	TU2	TU3	TU4	TU5	TU6	TU7	TU8	TU9
L (m)	19.25	15.10	40.13	43	39.65	18.64	13.88	25.4	68.1
d (mm)	13.12	7.86	18	17	9.4	12.6	11.4	19	24.2
D/d	—	—	83	47	—	—	—	42–63	32–53
n	1	1	1	2	3	139	139	75	33
K	55–383	713	15–665	≈ 0	≈ 0	0	0	≈ 0	≈ 0
Q (MW)	0.22	0.22	0.71	1	1	30	17	40	40
P (MPa)	7.6–19	14.1	6–19.1	9.9	16.7	5.3–17	16–17.3	6.8–13.1	5.9–9.9
G (kg m^{-2} s^{-1})	439–1020	353	187–768	—	—	—	—	—	—
X	1.37–2.20	1.40	1.15–2.38	1.44–1.46	1.85	1.10–1.59	1.51–1.62	1.23–1.45	1.21–1.36
T_i (°C)	447–568	405	341–648	507	527	351–452	445–470	405–451	378–445
$T_i - t_o$ (°C)	4–7	39	0–2	21–31	17	4–41	5–35	3–29	3–6
Δt (°C)	23–166	78	3–168	104	128	24–111	87–94	61–152	51–97
W_n/W_w	8.8–19.9	11.4	8.6–29.5	—	—	—	—	—	—
m_2	880	—	1054	—	—	105	—	—	—
m_1	160	1	146	2	1	33	8	6	6
Ref.	6, 7	5, 7	6, 7	8	9	2, 7	3	4	4

TU4 comprised two parallel helically coiled tubes and TU5 three parallel serpentine tubes.

TU6–TU9 were large capacity shell-and-tube-type sodium-heated steam generators. TU6 and TU7 were manufactured with straight vertical tubes and TU8 and TU9 with helically coiled tubes. In order to detect DWO, some selected tubes in each of them were specially instrumented. In the present study, the ICDWO measured in these tubes were considered. A large capacity sodium-heated steam generator consists of many tubes and the operating conditions in each tube of the steam generator are different from its average operating conditions with the exception of the sodium-side and the water/steam-side inlet temperature and the water/steam-side inlet and outlet pressure. For the tests reported in ref. [4] for TU8 and TU9, the steam outlet temperature was not measured in the specially instrumented tubes. However, for the tests carried out in each of these units, the average steam outlet temperature of the unit did not significantly deviate from the sodium-side inlet temperature (see Table 1). Therefore, the outlet steam temperature in these tubes was assumed to be identical to the average steam outlet temperature of the unit. Experimental evidence, however, indicates that the former was higher than the latter [2, 15]. This assumption is on the conservative side for the results obtained in the present study.

The properties of water and steam have been evaluated from the data given in ref. [16] and those of sodium from the correlations in ref. [17]. A thermodynamic equilibrium between water and steam in the superheated steam region of a SHSGT has been assumed.

DERIVATION OF FIRST CORRELATION

For this purpose, the results of the tests carried out in TU1 and TU3 have been used [6, 7]. These results are briefly mentioned below.

In both TU1 and TU3, DWO started when the length of the superheated steam region was between about 70 and 80% of the total tube length. Thus these units operated in a once-through mode at the inception of DWO.

In all the tests at the inception of DWO, the difference between the sodium-side and water/steam-side temperature decreased approximately exponentially along the superheated steam region, as illustrated in Fig. 1 for the few tests carried out in TU1. This is due to the behaviour of the specific heat of steam in the vicinity of the saturation temperature at high pressures, that is, this specific heat decreases exponentially as a function of temperature. The power developed along the superheated steam region is also given in Fig. 1, which shows that in the last 50% of this region, hardly any heat was transferred to the water/steam side.

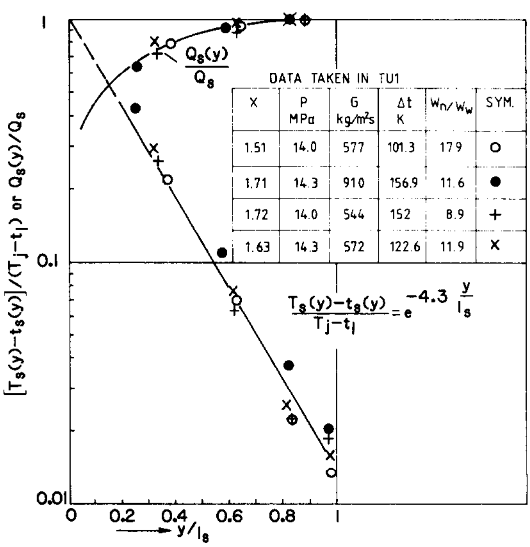

FIG. 1. Profiles of the dimensionless temperature difference between the sodium and water/steam side and the dimensionless power along the superheated steam region [6, 7].

In all the tests at the inception of DWO, the difference between the sodium-side inlet and water/steam-side outlet temperature was quite small, i.e. up to 7°C. In fact, for all the 363 ICDWO-data mentioned in Table 1, the foregoing temperature difference was equal to or less than 18°C with the exception of 19 data.

By using these experimental evidences, the enthalpy of steam at the outlet of a long SHSGT (say TU1 or TU3) can be predicted at the inception of DWO with the following procedure. Figure 1 implies that the decrease in heat flux along the superheated steam region is approximately exponential, that is,

$$q_s(y)/q_j = q_s(y)/[U_j(T_j - t_l)] = e^{-ay/l_s} \tag{1}$$

since $q_j = U_j(T_j - t_l)$ and, along the superheated steam region, the variation of U should be insignificant as compared with that of $(T_s - t_s)/(T_j - t_l)$. For a given SHSGT and operating conditions, a, U_j, T_j, t_l and l_s are constant. Multiplying the two sides of equation (1) with $\pi d \cdot dy$, this equation has been integrated to obtain the power in the superheated steam region

$$Q_s = -U_j(T_j - t_l)\pi d l_s(e^{-a} - 1)/a. \tag{2}$$

Figure 1 implies that a is of considerable magnitude; in this case e^{-a} becomes small in comparison with 1, and equation (2) reduces to

$$Q_s = U_j(T_j - t_l)\pi d l_s/a. \tag{3}$$

For the superheated steam region, the rate of heat transfer equals

$$Q_s = c_n W_n(T_i - T_j) \tag{4}$$

or

$$Q_s = W_w(h_o - h_v). \tag{5}$$

In equation (4), the use of an average specific heat at constant pressure is justified for practical applications. Solving T_j from equations (4) and (5) and inserting this and Q_s given by equation (5) into equation (3), the latter yields

$$h_o - h_v = \left[\frac{U_j \pi d l_s/(aW_w)}{1 + U_j \pi d l_s/(ac_n W_n)}\right](T_i - t_l). \tag{6}$$

The first term on the RHS of equation (6) is, in fact, identical to an average specific heat for steam, as given by the equation below

$$c_w = \frac{\int_{t_l}^{t_o} c_p \, dt}{(t_o - t_l)} \tag{7}$$

since $T_i \cong t_o$. Equations (6) and (7) imply that the outlet steam enthalpy at the inception of DWO is a function of the water/steam-side pressure and sodium-side inlet temperature regardless of the remaining operating conditions and geometry. Thus it seems sufficient to use three variables, i.e. h_o, P and T_i in order to correlate the ICDWO-data considered. After non-dimensionalizing these variables, the correlation obtained is

$$\frac{h_o}{h_c} = \left(1.74 + 0.24 \ln \frac{T_i - t_l}{t_l}\right)[1.026 + 0.04 \ln (P/P_c)]. \tag{8}$$

If the enthalpy of steam at the exit of a SHSGT exceeds the enthalpy of steam predicted by equation (8), DWO appear in the tube.

The power developed along a SHSGT at the inception of DWO is

$$Q = W_w(h_o - h_i) \tag{9}$$

where h_o is given by equation (8). The results of comparing the 363 data mentioned in Table 1 with equation (9) are shown in Fig. 2. This equation predicts the power at the inception of DWO within 4.5% accuracy for 98% of the time. The RMS error for all the 363 data is 1.5%. An error is based on the measured value and the RMS error is the standard deviation of the errors. One of the reasons of this good accuracy is that the outlet steam enthalpy used in the present study was determined from the measured outlet pressure and temperature on the water/steam side, using a Steam Table [16].

As stated previously, for practically all the experiments mentioned in Table 1, DWO were generated either by increasing the sodium-side inlet temperature or by decreasing the water/steam-side mass flow, i.e. the enthalpy of the water/steam mixture or steam at the outlet of a TU was steadily increased to generate DWO. This means that in accordance with equation (8) all the test runs carried out during these experiments before the test runs for which the ICDWO were measured were stable. This implies that this equation has, in fact, been verified with more than 2400 data, as could be deduced from Table 1. For some of these test runs, the outlet steam quality was less than 1.

Equation (8) can, in fact, be further simplified. This is shown in the section below.

SECOND CORRELATION

For all the 363 ICDWO-data mentioned in Table 1, the difference between the sodium-side inlet and water/steam-side outlet temperature at the inception of DWO was equal to or lower than 41°C. This difference was equal to or less than 18°C for 344 data and equal to or less than 36°C for 361 data.

With the experiments carried out with TU1 to TU3 and TU6, in all stable test runs (i.e. more than 2379 runs) made before DWO appeared, the difference between the sodium-side inlet and the water/steam-side outlet temperature was equal to or higher than 36°C with the exception of two test runs. For similar tests carried out with TU4, TU5 and TU7 to TU9, this temperature difference was also higher than 36°C, owing to the procedure used to generate DWO during these tests.

Taking the difference between the sodium-side inlet and the water/steam-side outlet temperature at the inception of DWO at 18°C, the error in predicting

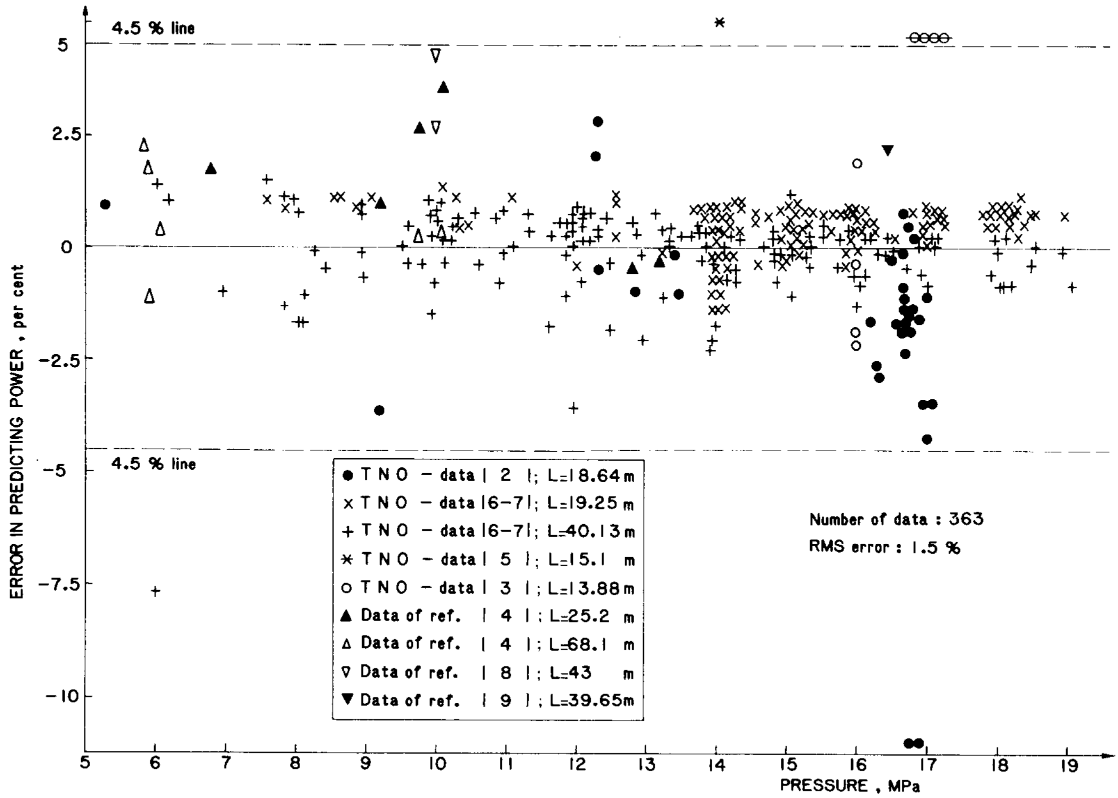

FIG. 2. Correlation of the ICDWO-data.

power has been calculated from the 363 ICDWO-data mentioned in Table 1, since these data include t_i, T_i and P. This error is between -3.6 and 4.2% with one exception. The RMS error for all the 363 data is 2%. For design purposes, two RMS errors are generally used. This means that the aforesaid temperature difference should be taken equal to 36°C. For this case, all the 2402 test runs mentioned in Table 1 were indeed stable with the exception of two test runs. The error in predicting power from the 363 ICDWO-data is between -7.1 and 1.2% with two exceptions. The above yields a simple correlation to predict the ICDWO: In order to avoid DWO in a SHSGT longer than 13.9 m, the difference between the sodium-side inlet and water/steam-side outlet temperature should be higher than 18°C, i.e.

$$T_i > t_o + 18. \qquad (10)$$

This temperature difference is, in fact, much lower than 18°C for a SHSGT longer than about 40 m (see Table 1).

SHORT SHSGTS

Both correlations have been checked with the 11 ICDWO-data obtained with a so-called short (i.e. 10-m long), vertical SHSGT equipped with a by-pass [5]. They do not fit the data well, i.e. the first correlation predicts the power at the inception of DWO from these data with a deviation varying between 5.8 and 20.1% and the second correlation between 5.6 and 23.4%. The RMS errors are 14.1 and 12.4%, respectively. Although these accuracies are quite acceptable at the present state of art (see, for instance, ref. [9]), the correlations are not recommended for short SHSGTs. The reason for this is explained as follows: in refs. [6, 7], it is demonstrated that DWO in long SHSGTs (i.e. TU1 and TU3) are time-delay oscillations. The length of the superheated steam region and the transit time in this region are of vital importance for the mechanism of DWO. In order to trigger the multiple regenerative feedback mechanism which generates DWO in a long SHSGT, when outlet pressure and inlet throttling are kept constant, the length of the superheated region has to reach a considerable magnitude (as stated before, the ratio of the length of the superheated steam region to the total tube length was between 70 and 80% at the inception of DWO in TU1 and TU2). Thereafter DWO appear and the multiple regenerative feedback mechanism begins to operate. For this mechanism, a dimensionless empirical relation was established using the dimensionless transit times in different heat transfer regions of a once-through steam generator tube in refs. [6, 7]. This relation was verified with 176 ICDWO-data obtained with TU1 and TU2 and it is given by

$$\frac{1+\left[\dfrac{l_s v_p^2}{l_p v_s^2}\right]^{0.5}}{1+\left[\dfrac{l_s v_p^2}{l_p v_s^2}\right]^{0.5}+\left[\dfrac{l_s v_b^2}{l_b v_s^2}\right]^{0.5}} = b(1+K)^{-0.028}(0.855-0.15P/P_c) \qquad (11)$$

where b is 1 for TU1 and 0.92 for TU3. Thus b appears to be a weak function of tube length. For the 10-m long SHSGT, b is about 1.18 and the ratio of the length of the superheated steam region to the total tube length was about 20% at the inception of DWO. At this inception, equation (11) should be fulfilled. Just at the start of superheating at the outlet of a SHSGT, the LHS of this equation is equal to about 1, and decreases when superheating is increased. During the experiments carried out to generate DWO in TU1 and TU2, inlet subcooling and pressure on the water/steam side were kept constant while the sodium-side inlet temperature was gradually increased for most of the tests. This implies that the RHS of equation (11) was constant. On its LHS v_b was also constant if the steam quality along the boiling region varied linearly. The second term both in the numerator and the denominator of this equation need not be considered for the purpose of the present work since they are of a second order of importance. When approaching the ICDWO during these experiments, the length of the superheated steam region gradually increased and the difference between the sodium-side inlet temperature and water/steam-side outlet temperature gradually decreased. Consequently l_b and v_s also decreased. When the degree of superheating is increased, the variation of $l_s/(l_b v_s^2)$ in a long SHSGT is small compared with that in a short SHSGT. It follows from the foregoing that for the fulfilment of equation (11) for a long SHSGT, the length of the superheated steam region should be quite large, resulting in a small difference between the sodium-side inlet and the water/steam-side outlet temperature. Since the correlations have been derived from this small temperature difference assumption, they should not apply to short SHSGTs. The results of the present study qualitatively indicates that a SHSGT with a length smaller than 13.9 m appears to be short. In order to predict the ICDWO in such SHSGTs, the correlations given in refs. [6, 7, 11] or the use of a stability model are recommended.

AVERAGE ICDWO

Equations (8) and (9) apply to a single tube of a large capacity sodium-heated steam generator and the mass flow and outlet temperature both on the sodium-side and on the water/steam-side of the tube are not equal to those of the steam generator. The average ICDWO are the steady-state operating conditions in a sodium-heated steam generator just before DWO appear in one of its tubes. These conditions have been measured with TU6, TU8 and TU9 [2, 4, 7] for G_a = 144–802 kg m^{-2} s^{-1}, $(W_n/W_w)_a$ = 11.6–38.1 and X_a = 1.07–1.50. Examination of these measurements indicated that the average water/steam-side outlet temperature in each of these units at the inception of DWO is not much different from the water/steam-side temperature at the outlet of its tube in which DWO were detected first. Therefore the data obtained can be correlated with an equation similar to equation (8), i.e.

$$X_a = [1.02 - 0.27 \ln(1 - P/P_c)]\left[0.063 + 0.73\frac{T_i}{t_l}\right]. \tag{12}$$

If the average steam quality at the outlet of a long, large capacity sodium-heated steam generator exceeds that predicted by equation (12), DWO will occur in one of the tubes of the unit.

The average outlet steam quality was determined from the measured outlet pressure and average outlet temperature on the water/steam side using a Steam Table [16], with the exception of four data. For these four data, the average outlet steam quality was predicted from a heat balance, since the average outlet temperature on the water/steam side was almost identical to the saturation temperature at the system pressure.

The power at the inception of DWO is

$$Q_a = G_a A(h_l - h_i + rX_a) \tag{13}$$

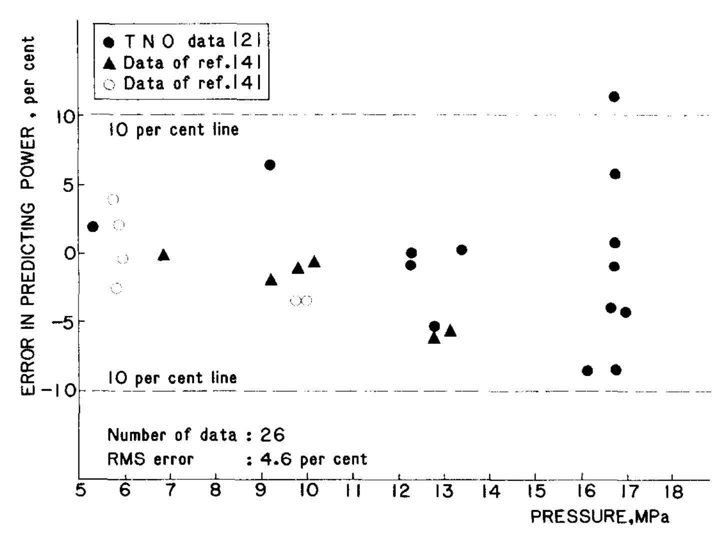

FIG. 3. Correlation of the average ICDWO-data.

where X_a is given by equation (12). The results of comparing the 26 data for the average ICDWO with equation (13) are shown in Fig. 3. This equation predicts the power at the inception of DWO from these data accurate to about 10% with a RMS error of 4.6%.

Equation (13) is of practical significance, at least, for a quick estimation of the average-ICDWO for a long, large capacity sodium-heated steam generator.

SUMMARY AND CONCLUSIONS

Two correlations have been established to predict the ICDWO for SHSGTs longer than approx. 13.9 m. They have been verified with the 363 ICDWO-data obtained for the following ranges of conditions: geometry: straight vertical tubes, tubes comprising a vertical and a horizontal tube, helically coiled tubes and a serpentine tube; L = 13.9–68.1 m; d = 7.9–24.2 mm; D/d = 32–83; K = 0–665; P = 5.3–19.1 MPa; X = 1.10–2.38; T_i = 341–648°C; Δt = 3–168 K; G = 187–1020 kg m^{-2} s^{-1}, and W_n/W_w = 8.8–29.5. With the correlations, the power can be derived at the inception of DWO from these data accurate to about 4.5% for 98% of the time. The RMS error is about 2%.

The correlations are fixing a region where stable conditions occur for 2039 test runs carried out to produce the foregoing 363 ICDWO-data.

Both correlations do not well fit the data obtained from a so-called short SHSGT. The reason for this has been explained.

For a quick estimation of the average-ICDWO in a long, large capacity sodium-heated steam generator, a tentative correlation has been proposed.

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DEUX RELATIONS SIMPLES POUR LA NAISSANCE DES OSCILLATIONS DE PESANTEUR DANS DES TUBES LONGS DE GENERATEUR DE VAPEUR, CHAUFFES AU SODIUM

Résumé—Deux formules sont établies pour prédire les conditions de naissance de DWO dans des tubes de générateur de vapeur chauffés au sodium et plus long que 13,9 m environ. Ceci a été vérifié avec 363 tubes droits, en hélice et serpentins et ceci comprenant un tube vertical et horizontal; longueur du tube: 13,9–68,1 m; diamètre intérieur: 7.9–24,2 mm; pression: 5,3–19,1 MPa; qualité de la vapeur sortante: 1,10–2,38; température d'entrée du sodium: 341–648°C; sous-refroidissement à l'entrée: 3–168°C; rapport des débits masse sodium/eau. La puissance à la naissance de DWO est prédite avec une précision de 4,5% pour 98% des cas. L'erreur quadratique moyenne est d'environ 2%. Les formules incluent les conditions stables pour les 2039 essais conduits pour fournir les 363 données précédentes.

ZWEI EINFACHE KORRELATIONEN FÜR DAS EINSETZEN VON DICHTEWELLEN-OSZILLATIONEN IN LANGEN NATRIUMBEHEIZTEN DAMPFERZEUGERROHREN

Zusammenfassung—Es wurden zwei phänomenologische Korrelationen entwickelt, um die Bedingungen für des Einsetzen von Dichtewellen-Oszillationen in natriumbeheizten Dampferzeugerrohren, die länger als 13,9 m sind, vorherzusagen. Die Korrelationen wurden mit 363 Datensätzen verifiziert, die innerhalb der folgenden Bereiche erhalten wurden. Geometrie: gerade, spiralförmige und serpentinenförmige Rohre und Rohre, die vertikale und horizontale Stücke enthalten; Rohrlänge: 13,9 bis 68,1 m; Innendurchmesser: 7,9 bis 24,2 mm; Druck: 5,3 bis 19,1 MPa; Austrittsdampfgehalt: 1,10 bis 2,38; Natriumeintrittstemperatur: 341 bis 648°C; Eintrittsunterkühlung: 3–168°C; Massenstromverhältnis Natrium/Wasser dampfseitig: 8,8 bis 19,9. Die Leistungsvorhersage beim Einsetzen der Dichtewellen-Oszillationen hat eine Abweichung von ungefähr 4,5% für 98% der Zeit. Der Fehler des quadratischen Mittelwerts ist ungefähr 2%. Die Korrelationen beinhalten stabile Bedingungen für die 2039 durchgeführten Testläufe, um die 363 Datensätze zu erhalten.

ДВА ПРОСТЫХ СООТНОШЕНИЯ ДЛЯ НАЧАЛА КОЛЕБАНИЙ ВОЛН ПЛОТНОСТИ (КВП) В ДЛИННЫХ, ЗАПОЛНЕННЫХ НАТРИЕМ, НАГРЕТЫХ ТРУБАХ ПАРОГЕНЕРАТОРОВ

Аннотация—Найдены два феноменологических соотношения для расчета условий начала КВП в заполненных натрием нагретых трубах парогенераторов длиной более 13,9 м. Результаты подтверждаются 363 опытами для следующих диапазонов параметров: геометрия: прямые, спиральные каналы и змеевики, а также каналы, состоящие из вертикальной и горизонтальной труб; длина трубы: 13,9–68,1 м; внутренний диаметр: 7,9–24,5 мм; давление: 5,3–19,1 МПа; паросодержание на выходе: 1,10–2,38; температура натрия на входе: 341–648°C; недогрев на входе: 3–168°C; отношение массового расхода к расходу воды или пара: 8,8–19,9. По результатам рассчитывается мощность в начале колебаний волн плотности с точностью ~4,5% для 98% случаев. Среднеквадратичная ошибка составила примерно 2%. Выражения включают условия устойчивости 2039 испытаний, полученные при проведении упомянутых выше 363 опытов.