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THE PERIOD OF DENSITY-WAVE OSCILLATIONS IN FORCED CONVECTION STEAM GENERATOR TUBES

H. C. ÜNAL
MT-TNO, P.O. Box 342, Apeldoorn, The Netherlands

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NOMENCLATURE

d, inside or hydraulic diameter;
G, mass velocity;
K, inlet throttling coefficient;
L, tube length;
l, length of a heat transfer region;
l_b, length of boiling region;
m, sodium-to-water/steam-side mass flow ratio;
P, pressure;
p, period;
t, transit time of a fluid particle;
t_t, total transit time of a fluid particle;
X, steam quality;
X_o, outlet steam quality;
z, axial coordinate;
α, void fraction;
ρ, average density in a heat transfer region;
ρ_l, density of saturated liquid;
ρ_v, density of saturated vapour.

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). These oscillations are due to multiple regenerative feedback between the flow rate, the vapour generation rate and the pressure drop [1], 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. The DWO have been extensively studied during the last two decades. For a detailed literature survey on the subject, the reader is referred to [2]. In the following, only the literature data found pertinent to the present study are briefly mentioned.

A stability model is used mostly to predict both the period and the inception conditions of the DWO, and it is, in general, a simultaneous solution of 1-dim. non-steady state, linearized or non-linearized continuity, momentum and energy conservation equations with appropriate boundary conditions and subsidiary equations. The last mentioned equations are correlations 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 are presented as 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 inception conditions of the DWO, as demonstrated, for instance, in [1, 3]. This may be due to following reasons:

(1) 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 [1, 4, 5]. This assumption implies a continuous fluid [5]. A two-phase flow medium is not homogeneous but heterogeneous, at least, for slug-plug and annular flow.

(2) 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 [4].

(3) In most models, a slip ratio is used. This again is controversial to the assumption used for the derivation of the conservation equations.

(4) Most models are based on linearized conservation equations. The conservation equations, however, are highly non-linear; therefore a stability model should be, by definition, unsuitable for predicting the period of the limit cycle oscillations.

Considering these shortcomings of the stability models, more accurate correlations based on the physical mechanism of the DWO have been established in [6–8] to determine the inception conditions of the DWO (i.e. power, mass velocity, inlet subcooling and pressure at the start of the DWO) in forced circulation steam generator tubes for quite a wide range of geometries and operating conditions.

This paper deals with the period of the DWO in forced circulation steam generator tubes. After presenting the experimental data, a correlation is established to predict the period of the DWO in such tubes.

EXPERIMENTAL DATA

The data were obtained in two sodium heated test tubes. The first test tube (TT1) was a 20.45 m long tube of 13.12 mm i.d. and 17.1 mm o.d., and was comprised of a 9.4 m long vertical tube and an 11.05 m long, V-shaped horizontal tube. It was manufactured from ferritic steel. The sodium side surrounding the test tube was constructed of 4 successive annuli. The inner wall of each annulus was formed by the test tube. The i.d. of the outer tube of each annulus was 29.7 mm. A 0.8 m long piece at the inlet and a 0.4 m long piece at the outlet of the test tube were not heated.

The second test tube (TT2) was a 44.43 m long helical coil of 18 mm i.d. and 26 mm o.d. It was manufactured from stainless steel – 316, and was placed concentrically in another helical coil of 49 mm i.d. Sodium flowed in the annulus between these coils. A 2 m long piece at the inlet and a 2.3 m long piece at the outlet of the test tube were not heated.

Both test tubes operated in forced convection and once-through mode. The flow orientation on the sodium side was downward and that on the water/steam side upward. A by-pass pipe was built around each test tube in order to keep the pressure drop in the test tube constant. The inlet throttling coefficient was adjusted by means of flow control valves mounted at the inlet of each test tube. Each test tube was installed in a heat transfer rig, the description of which is given elsewhere [7, 8].

Both test tubes were heavily instrumented. It is considered sufficient to mention here that both on the sodium side and on the water/steam side, inlet and outlet temperatures, outlet pressure, inlet mass flow and temperature at 3 different locations along TT1 and at 9 different locations along TT2 were measured with precalibrated instruments, and were collected with an on-line data acquisition system. Sodium side temperatures in TT1 were also measured at 12 additional locations along the tube. Among the other quantities, water/steam side mass flow was recorded with a six-channel line recorder. Errors in measuring temperature, mass flow and pressure were 1.2 K, 1% and 0.03 MN/m^2, respectively.

In order to generate the DWO, steam quality at the outlet of the test tube was increased by very small increments for most of the tests by increasing only sodium-side inlet temperature. For a few tests, the DWO were created by decreasing only water/steam side pressure. The DWO were detected by observing the recordings of the water/steam side mass flow on the six-channel line recorder. In total 2240 tests were carried out. In 160 tests with TT1 and in 146 tests in TT2, the DWO were observed. For this study, all the DWO-tests from TT1 and 16 DWO-tests from TT2 were analysed. The operating conditions for these tests, which were taken one run before the DWO occurred, are:

TT1:
$P = 7.6$–$19\ \text{MN/m}^2$; $G = 439$–$1020\ \text{kg/m}^2\text{s}$;
$\Delta T = 23$–$166.3\ \text{K}$; $X_o = 1.37$–2.20;
$m = 8.8$–19.9; $K = 54.7$–382.9;
by-pass ratio: 0.1–13.

TT2:
$P = 13.9$–$14.3\ \text{MN/m}^2$; $G = 262$–$675\ \text{kg/m}^2\text{s}$;
$\Delta T = 20.4$–$168\ \text{K}$; $X_o = 1.49$–1.96;
$m = 10.3$–25.3; $K = 15$–450;
by-pass ratio: 2.7–9.9.

The period of the observed mass flow oscillations was between 1.3 and 7 s in TT1 and between 5 and 12.5 s in TT2. Peak to peak amplitudes of these oscillations varied from 30 to 200% of the mass flow recorded at the last stable test run. The water/steam side outlet temperature did not oscillate.

In both test tubes, the DWO started when the length of the superheated steam region was about between 70 and 80% of the total tube length. At the start of the DWO, practically no power developed in the last half of this region and sodium side temperature was a few degrees higher than water/steam side temperature. The length of the superheated steam region required to initiate DWO increased with increasing inlet throttling coefficient, that is, inlet throttling delays the DWO.

Further details of the experimental apparatus, procedures and the data obtained may be found in [7, 8].

CORRELATION OF DATA

A first attempt leading to rather approximate correlation was found in the literature [2], indicating that the ratio of the period of the DWO to the transit time of a fluid particle in a tube varies between 1 and 2. This correlation appears to have been based on earlier tests performed mostly in natural circulation tubes in which no superheated steam was produced, and does not fit well the data presented here. The correlation given in [9] does not fit these data well either. In order to correlate the data, dimensional analysis is used. Two dimensionless numbers seem of practical importance, i.e. p/t_t, the ratio of the period of the DWO to the total transit time of a fluid particle in a test tube and K, the inlet throttling coefficient. The physical significance of the first dimensionless number is obvious, while the latter characterizes the delay for the initiation of the DWO. This delay affects the total transit time of a fluid particle. The correlation obtained is

$$p/t_t = (1+K)^{-0.32}\left(1.7 + \frac{1}{1 + 2.45\ 10^8\ e^{-0.57K}}\right). \quad (1)$$

The transit time of a fluid particle in a heat transfer region is calculated by

$$t = 1\rho/G. \quad (2)$$

The lengths of the superheated steam, boiling and preheat regions were determined by plotting the steam quality vs tube length and assuming $X = 1$ and $X = 0$ at the beginning of the superheated steam and boiling regions, respectively. The steam quality was calculated from a heat balance. The variation of the steam quality was assumed to be linear between the calculated two values. The steam quality was calculated at 17 locations in TT1 and at 11 locations TT2. For the superheated steam region, the average density was determined using the arithmetic mean temperature in the region. For the preheat region, the transit time was calculated as the sum of the transit times in the adiabatic and heated parts of the region. In the boiling region, the average density has been calculated with the following formula:

$$\rho = \frac{1}{1_b}\int_0^{1_b} [(1-\alpha)\,\rho_1 + \alpha\,\rho_v]\,dz, \quad (3)$$

assuming a linear axial variation of the steam quality. In TT1, boiling always took place in the horizontal part of the tube. Void fraction in equation (3) was, therefore, evaluated for TT1 and TT2 with the correlation given in [10] for horizontal tubes up to a vapour volumetric rate ratio of 0.9. Thereafter the flow was assumed to be homogeneous. The total transit time is the summation of the transit time in the preheat, boiling and superheated steam region. K, the inlet throttling coefficient, (i.e. the total of the pressure loss coefficients of two flow control valves and a flow meter between these valves) is based on tube diameter.

The results of the comparison of equation (1) with the data are shown in Fig. 1. The correlation predicts the period of the DWO within about 30% accuracy for 96% of the time with a RMS error of 14.25% from these 176 data.

This correlation was also checked with the data of [11] obtained for $P = 4.1$–$8.3\ \text{MN/m}^2$ and $G = 436$–$2088\ \text{kg/m}^2\text{s}$ in a very short steam generator tube in which no superheated steam was produced. With one exception, the correlation predicts the period of the DWO within about 22% accuracy from these 12 data. For these data, void fraction was evaluated from the correlation given in [12].

For the range of throttling coefficients considered, p given by equation (1) varies between $0.81\,t_t$ and $0.38\,t_t$. This does not seem to contradict the results of the experiments reported in the late 1950's and early 1960's [11, 13–15]. These experiments yielded a rough indication that the period of the DWO is approx. 1 or 2 times the transit time of a fluid particle in a tube. However, in these experiments, the inlet throttling coefficient was either zero or negligible, and the experiments were carried out in natural circulation systems, with the exception of those from [11]. The results of the experiments of [11] were considered in establishing equation (1) which equation clearly indicates that the inlet throttling influences the period of the DWO. This is logical since DWO are time delay oscillations [7, 8], and the inlet throttling delays the mechanism of DWO, as stated previously.

The ranges of geometries and operating conditions of the data used to establish and to check equation (1) are summarized below:

Geometry: a tube consisting of a vertical and a horizontal V-shaped circular tube, a circular helical coil and a vertical rectangular tube;

$L = 0.68$–$44.43\ \text{m}$; $d = 4.49$–$18\ \text{mm}$;
$P = 4.1$–$19\ \text{MN/m}^2$; $G = 262$–$2088\ \text{kg/m}^2\text{s}$;
$X_o = 0.27$–2.20; $\Delta T = 2.8$–$168\ \text{K}$;
$p = 0.345$–$12.5\ \text{s}$; $K = 0$–450.

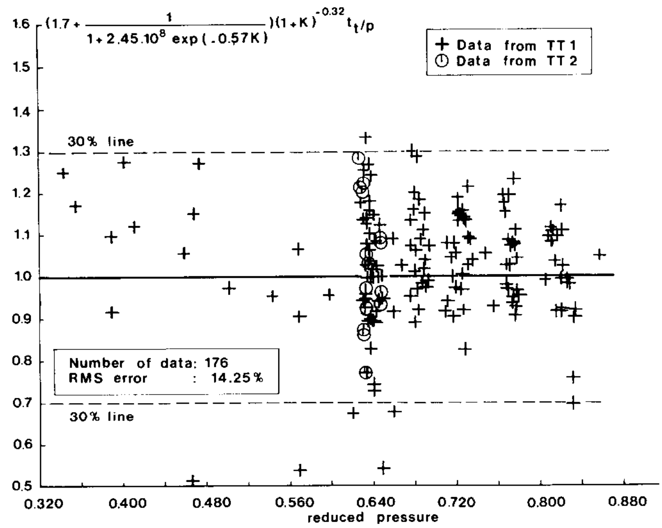

FIG. 1. Correlation of the data for the period of the DWO from TT1 and TT2.

The number of data considered is 188.

The RMS error for the correlation of the data is 15.1%.

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