THE IMPORTANCE OF DIFFERENT TIME CHARACTERIZATIONS IN INVESTIGATING DENSITY-WAVE OSCILLATIONS

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ABSTRACT

This paper discusses the use of different time characterizations in investigating density-wave oscillation. It introduces some new concepts that are useful to investigate density-wave oscillations. Usually the mixture transit time is compared with the oscillation period, but this comparison is not useful, because the relation between the two cannot be directly interpreted. Instead two intermediate step should be taken, by looking at the so-called pressure-drop transit time, and the so-called perturbation transit time. The pressure-drop transit time is determined by the phase difference between inlet and outlet pressure-drop perturbations. The perturbation transit time is determined by the phase difference between inlet flow perturbations and outlet void-fraction perturbations. By comparing the pressure-drop transit time with the oscillation period the importance of the channel-exit pressure drop in the dynamics of the system can be investigated. By comparing the pressure-drop transit time with the perturbation transit time it can be investigated whether the mixture velocity or mixture density dominates the dynamics in the channel-exit pressure drop. By comparing the perturbation transit time with the mixture transit time it can be investigated whether the perturbation travels faster, slower, or at the same speed as the mixture itself. The examples in the paper are given as illustrations of the use of the time characterizations discussed above. The goal of this paper is to divide the problem of how to relate the oscillation period to the mixture transit time in three separate subproblems. It appears that even these subproblems are quite complicated and need extensive research to clarify them.

1. INTRODUCTION

Density-wave oscillations in boiling channels, which have been extensively studied for the last decades [e.g. 1,2,3,4,5], are the basis of boiling water reactor (BWR) instabilities. Density-wave oscillations are explained by the feedback and interaction between the various pressure drop components in combination with the lag introduced by the finite speed of the two-phase mixture [6]. To investigate the physics of density-wave oscillations one often uses the ratio between the oscillation period and the transit time in the boiling channel as an important parameter. In this paper we will try to show that the oscillation period cannot directly be compared with the transit time when one wants to understand the physics of the boiling channel. Instead one should make the comparison in three steps.

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2. COMPARING THE DIFFERENT TIME CHARACTERIZATIONS

2.1 STEP 1: OSCILLATION PERIOD VERSUS PRESSURE-DROP “TRANSIT” TIME

In the first step of the comparison one should compare the oscillation period with the phase difference that occurs between the different pressure-drop terms. In this paper we will consider the inlet and outlet pressure drop in order to investigate whether the dynamics of the system is governed by the inlet pressure drop and the exit pressure drop in the boiling channel. The phase difference is used to determine the pressure-drop “transit” time as this is the time that it takes for a pressure-drop perturbation to travel from inlet to outlet of the boiling channel. For the simple picture of a boiling channel with the pressure drops concentrated at the inlet and the outlet of the channel the ratio between oscillation period and pressure-drop transit time is expected to be approximately 2. For a complete picture of the importance of the different pressure drop terms one should perform a more detailed comparison as has been performed by Zboray et al. [7] showing the relative importance of the different pressure drop terms and how this changes with operating condition.

2.2 STEP 2: PRESSURE-DROP "TRANSIT" TIME VERSUS PERTURBATION “TRANSIT” TIME

The second step is to relate the pressure drop transit time with the phase difference between inlet perturbations in the flow and outlet perturbations of the void fraction. This phase difference is used to determine the perturbation "transit" time as the time that it takes for an inlet perturbation in the flow to result in a perturbation in the exit void fraction. Note that an increase in inlet mass flow leads to a decrease in the void fraction. Then at a first glance one would expect a decrease in pressure drop at the outlet of the channel, but because the mass flow also varies this is not necessarily true. This comparison clarifies the importance of either the density or the mixture velocity in determining the pressure drop at the riser exit. Rizwan-uddin [5] has shown that the variation in mixture velocity plays in general a more important role than the variation in mixture density.

2.3 STEP 3: PERTURBATION “TRANSIT” TIME VERSUS MIXTURE TRANSIT TIME

The next step to investigate density-wave oscillations is to relate the mixture transit time in a system with the perturbation transit time. Perturbations in the inlet mass flow rate cause density waves in the boiling channel whose maxima/minima in density may be seen at the outlet earlier or later than one would expect based on the mixture velocity. This is caused by the fact that the density wave has not only a pure travelling character but variations in local void production also contribute to it. As the mass flow decreases at the inlet the mass flow throughout the whole channel decreases and thus the specific heat added to the fluid is influenced throughout the whole channel.

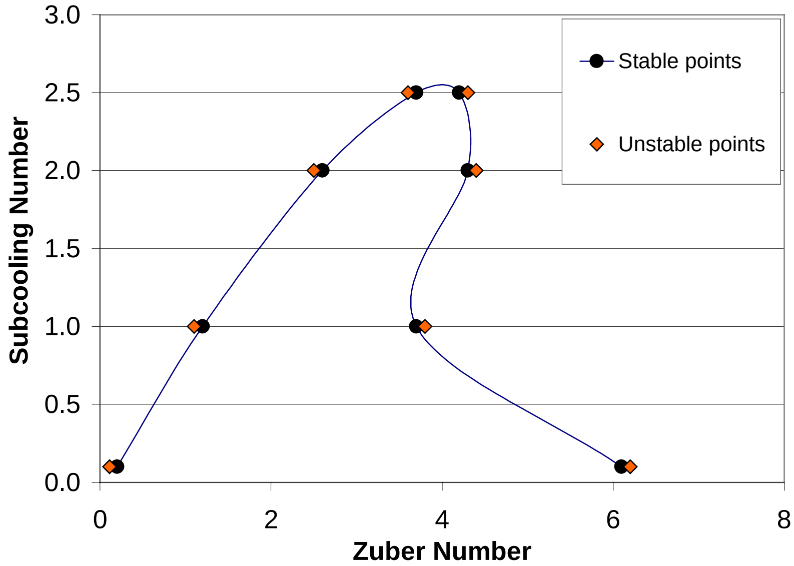

Figure 1: Stable and unstable points as predicted by the reduced-order model for a reference reactor model [8]. The stable region is approximately bounded by the line, drawn to guide the eye.

3. EXAMPLES

3.1 ANALYSES WITH A REDUCED-ORDER MODEL

As a simple example of how to analyze density-wave oscillation data we studied a boiling channel with a constant external pressure drop using a reduced-order model [8]. Figure 1 shows the calculated stable and unstable points for this system in the neighbourhood of the stability boundary taken from reference [8]. For the stable points in this figure the oscillation period is compared with the pressure-drop “transit” time, and the pressure-drop transit time is compared with the perturbation transit time (table 1). These characteristic times have been obtained by noise analysis. Table I shows that the oscillation period is not twice the pressure drop “transit” time. Other pressure-drop terms are also important for this specific case to understand the dynamics of the system. To understand the relation between pressure drop terms and the oscillation period a much more extensive study has to be done. Table I also shows that the pressure-drop transit time is almost equal to the perturbation transit time. This means that minimum void at the riser exit is associated with maximum outlet pressure drop. This contra-intuitive result is caused by a corresponding maximum in the riser exit mass flow rate in accordance with the results obtained by Rizwan-uddin [5]. Note that this is in contradiction with the explanation for density-wave instabilities that is given in reference [9]. Since our simplified model uses a limited number of spatial nodes, numerical diffusion effects do not allow a comparison between the mixture transit time and the perturbation transit time.

Table I: Oscillation period and pressure-drop "transit" time for stable points in Figure 1.

Zuber Number	**Subcooling Number**	**Oscillation Period T (s)**	**Pressure-Drop Transit Time t1 (s)**	**Perturbation Transit Time t2**	**T/t1**	**t1/t2**
6.1	0.1	0.4	0.7	0.6	0.6	0.9
3.7	1.0	0.9	1.3	1.3	0.8	1.0
4.3	2.0	1.7	1.4	1.5	1.2	1.1
4.2	2.5	2.3	1.7	1.8	1.3	1.1
3.7	2.5	2.8	2.0	2.1	1.4	1.0
2.6	2.0	3.5	2.5	2.7	1.4	1.1
1.2	1.0	4.4	3.4	3.3	1.3	1.0
0.2	0.1	3.2	3.2	3.4	1.0	1.1

3.2 EXPERIMENTS WITH THE DESIRE FACILITY

As a second example to analyze density-wave oscillation data we use the values that we have from experiments with the DESIRE facility [10]. With this facility limit-cycle density-wave oscillations have been measured. The oscillation period is measured and the mixture transit time of the fluid is estimated using the model of Rizwan-uddin [5] based on the assumption of homogeneous flow. Note that in case of limit-cycle oscillations the mixture transit time varies with time [11]. Average operating conditions have been used to estimate the mixture transit time. The perturbation transit time is determined by correlating the measured inlet flow with the measured riser-exit void fraction, determined by the gamma-transmission technique. We have no direct measurements of the pressure-drop transit time, so we will directly compare the oscillation period with the perturbation transit time. The results in table 2 are taken from table 2 in reference [12].

Table II: Different time characterizations for limit-cycle oscillations in DESIRE

Point	**Oscillation Period T (s)**	**Perturbation Transit Time t 2(s)**	**Mixture Transit Time τ (s)**	**T/t2**	**τ/t2**
1	4.88 ± 0.06	2.70 ± 0.05	3.54 ± 0.20	1.81 ± 0.06	1.31 ± 0.10
2	4.55 ± 0.05	2.50 ± 0.05	3.31 ± 0.19	1.82 ± 0.06	1.32 ± 0.10
3	4.76 ± 0.06	2.70 ± 0.05	3.33 ± 0.18	1.76 ± 0.05	1.23 ± 0.09
4	4.55 ± 0.05	2.80 ± 0.05	3.15 ± 0.17	1.63 ± 0.05	1.13 ± 0.08
5	4.36 ± 0.05	2.40 ± 0.05	2.93 ± 0.15	1.82 ± 0.06	1.22 ± 0.09
6	4.66 ± 0.05	2.60 ± 0.05	3.10 ± 0.17	1.79 ± 0.05	1.19 ± 0.09
7	4.45 ± 0.05	2.60 ± 0.05	2.94 ± 0.15	1.71 ± 0.05	1.13 ± 0.08
8	4.36 ± 0.05	2.30 ± 0.05	2.84 ± 0.16	1.90 ± 0.06	1.23 ± 0.10
9	4.18 ± 0.04	2.30 ± 0.05	2.66 ± 0.14	1.82 ± 0.06	1.16 ± 0.09
10	4.55 ± 0.05	2.60 ± 0.05	2.93 ± 0.15	1.75 ± 0.05	1.13 ± 0.08
11	4.36 ± 0.05	2.70 ± 0.05	2.77 ± 0.14	1.61 ± 0.05	1.03 ± 0.07
12	4.27 ± 0.04	2.70 ± 0.05	2.68 ± 0.14	1.58 ± 0.04	0.99 ± 0.07
13	4.10 ± 0.04	2.10 ± 0.05	2.45 ± 0.12	1.95 ± 0.07	1.17 ± 0.08
14	4.27 ± 0.04	2.70 ± 0.05	2.65 ± 0.13	1.58 ± 0.04	0.98 ± 0.07
15	4.18 ± 0.04	3.00 ± 0.05	2.56 ± 0.12	1.39 ± 0.04	0.85 ± 0.05
16	4.10 ± 0.04	2.90 ± 0.05	2.40 ± 0.11	1.41 ± 0.04	0.83 ± 0.05
17	4.18 ± 0.04	3.00 ± 0.05	2.50 ± 0.13	1.39 ± 0.04	0.83 ± 0.06
18	4.02 ± 0.04	2.90 ± 0.05	2.34 ± 0.11	1.39 ± 0.04	0.81 ± 0.05
19	4.10 ± 0.04	3.00 ± 0.05	2.40 ± 0.12	1.37 ± 0.04	0.80 ± 0.05
20	4.10 ± 0.04	2.90 ± 0.05	2.24 ± 0.14	1.41 ± 0.04	0.77 ± 0.06

Figure 2 shows a contour plot of the ratio $T/t2$ in the dimensionless Zuber-subcooling plane. It can be seen that when we move towards higher Zuber and subcooling numbers the ratio $T/t2$ decreases. Although the riser-exit friction is a dominating term in our experiment the ratio is significantly smaller than 2. Apart from the influence of other pressure-drop terms, this could also be due to the fact that the mixture density is not in phase with the exit pressure drop, or by the fact that nonlinear effects become important as the limit-cycle amplitude increases. Figure 3 shows a contour plot of the ratio $T/t2$. For high Zuber numbers the mixture transit time is lower than the pressure-drop transit time, whereas for low Zuber numbers the opposite is true. The perturbation in the flow does not travel with the mixture transit time. To understand the relation between the perturbation transit time and the mixture transit time more detailed analyses are needed with sophisticated models.

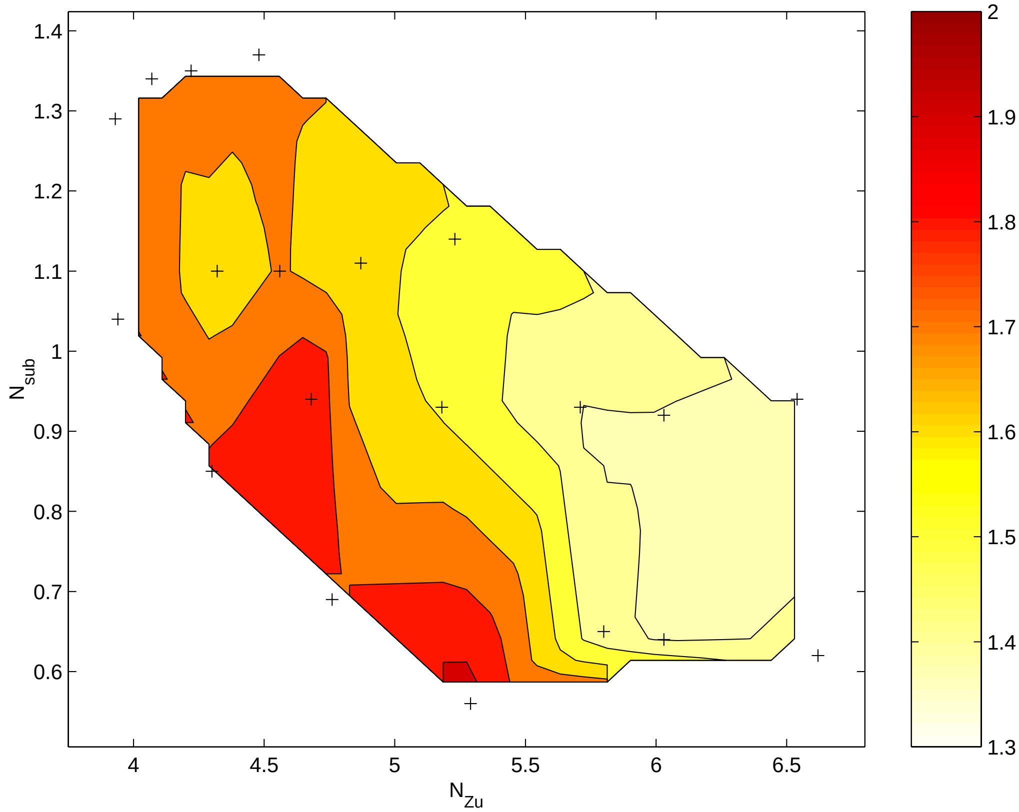

Figure 2: Ratio oscillation period over perturbation transit time $T/t2$ in the dimensionless Zuber-subcooling plane. The plus signs indicate measurement points in table 2.

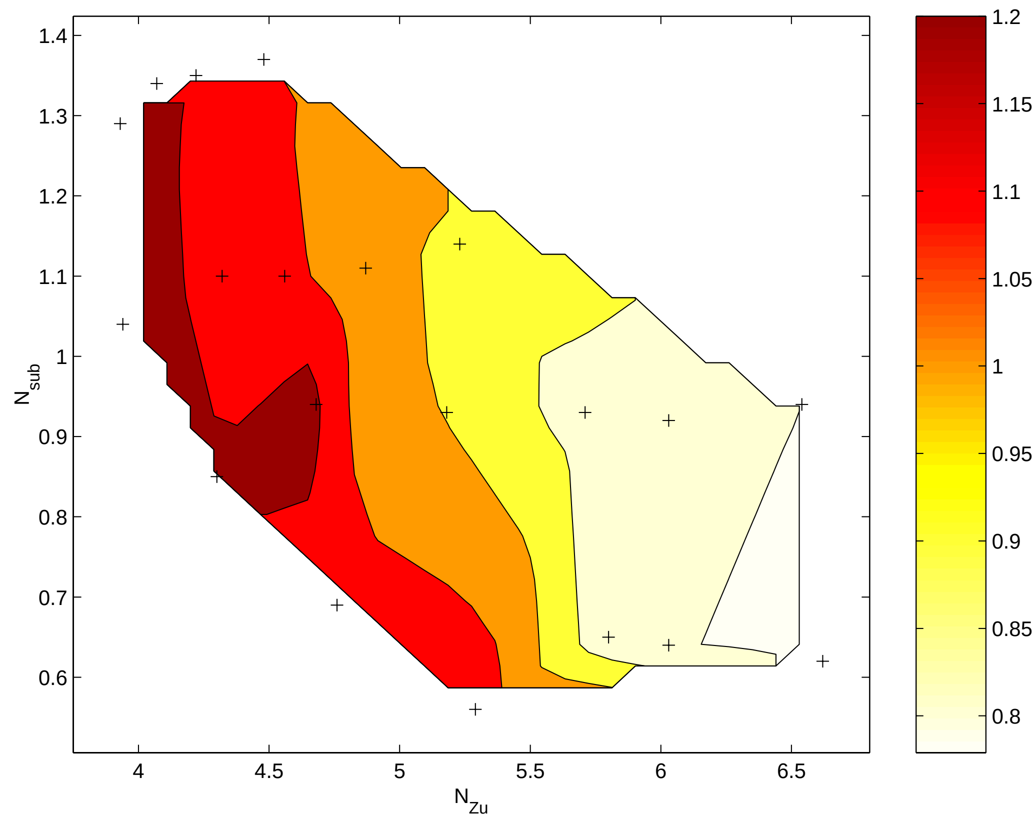

Figure 3: Ratio mixture transit time over perturbation transit time $\tau / t2$ in the dimensionless Zuber-subcooling plane. The plus signs indicate measurement points in table 2.

CONCLUSIONS

This paper discusses the use of different time characterizations in investigating density-wave oscillations. Usually the mixture transit time is compared with the oscillation period, but this comparison is not useful, because the relation between the two cannot be directly interpreted. Instead two intermediate steps should be taken, by looking at the so-called pressure-drop transit time and the so-called perturbation transit time. The pressure-drop transit time is determined by the phase difference between inlet and outlet pressure-drop perturbations. The perturbation transit time is determined by the phase difference between inlet flow perturbations and outlet void-fraction perturbations, taking into account that a positive flow perturbation leads to a negative void-fraction perturbation.

By comparing the pressure-drop transit time with the oscillation period the importance of the channel-exit pressure drop in the dynamics of the system can be investigated. Moreover, by considering the separate pressure-drop transfer functions as is done by Zboray et al. the dynamics of the system can be understood.

By comparing the pressure-drop transit time with the perturbation transit time the importance of either the density or the mixture velocity in determining the pressure drop at the riser exit is studied. The results from our analysis show that the mixture velocity dominates the channel-exit pressure drop. The results are contra-intuitive because a low void fraction is associated with a high channel-exit pressure drop.

By comparing the perturbation transit time with the mixture transit time it can be investigated whether the perturbation travels faster, slower, or at the same speed as the mixture itself. This is a complicated comparison to make experimentally, because it is not straightforward to measure the mixture transit time in a facility, and because this mixture transit time is not well defined in the case of inhomogeneous flow. However, by studying this ratio in calculational studies the understanding of density-wave oscillations can be improved.

In applications of the different time characterizations it appears that our numerical model suffers from numerical diffusion effects and that the mixture transit time and the pressure-drop transit time cannot directly be measured in DESIRE. The next step would be to apply these characterizations in more sophisticated models and to design an experimental setup in which the different time characterizations can be measured directly.

The goal of this paper is to divide the problem of how to relate the oscillation period to the mixture transit time in separate subproblems. It appears that even these subproblems are quite complicated and need extensive research to clarify them.

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