A Sensitivity of Methodology for Density Wave Oscillation Analysis using MARS-KS Code

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1. Introduction

The density wave oscillation (DWO) is one of the undesirable phenomena considered as possible and common two-phase flow instability, and therefore of importance in design of a water-cooled reactor core especially such as BWR reactor core and/or closed type multi-channel core. The cause of DWO has been well known, which is the self-sustained cyclic flow oscillations due to multiple regenerative time-delayed feedbacks between the mass flow rate, void fraction, and pressure drop between single phase liquid and two-phase mixture [1]. DWO can be representatively classified into Type I and Type II instability occurred at low and high qualities. Among them, Type II DWO has a characteristic in which the marginal stability boundary (MSB) appears as an L-shape in flow stability maps. Generally, there are two approaches that have been proposed to predict such DWO phenomena: time-domain analysis and frequency-domain method. Despite the theoretical consistency and explainability of frequency-domain analysis, the linearization of governing equations is inevitable when using Laplace transformation to find stability criteria with frequency domain formulation [2], which is widely employed in control theory. Conversely, the calculation cost can increase with time-domain approach, which directly solves governing equations in the time coordinate, and numerical instability can become an issue due to its complex non-linear nature. Apart from this, a new methodology for prediction of stability boundary of Type II DWO was recently proposed by the authors[3], which has a feature that discrete Fourier transformation (DFT) is applied to the simulations of a time-domain code and detection of unstable flows are conducted based on the spectrum analysis. The MARS-KS code, a best-estimate thermal-hydraulic system code developed by KAERI based on RELAP5/MOD3.2 was adopted and validated with data of mass fluxes and frequencies at onset of DWOs, which was measured at EREC (Electrogorsk Research and Engineering Center for NPP Safety) [2-3]. In this study, the results of sensitivity analysis of the proposed methodology are described, which highlights model parameters importantly considered in development of DWO analysis methodology using MARS-KS code.

2. Methods and Results

2.1 Methodology – Mosaic Approach

A detailed description of the methodology is provided elsewhere [4]; here, we present only a brief introduction (Fig. 1). Similar to procedures used in OFI experiments, the typical time-domain code analysis approach for generating a flow stability map involves transient calculations with stepwise changes from an initially stable flow condition to states characterized by flow oscillations [5-9]. The stepwise change of a selected system variable (e.g., heating power or inlet subcooling) is applied at enough time intervals to see system responses in experiments or numerical convergences in simulations until the oscillating conditions are reached (named the "stepwise searching approach"). In these cases, the size of the change and the time interval for waiting for responses can have an impact on the results of OFI detection. In the other studies, perturbations of power were intentionally applied in the vicinity of OFI and determined the occurrence of flow instability based on whether flow converged or not [10-11]. In this methodology (named the "perturb-response approach"), however, qualitative judgment (rather than quantitative determination) seems to also be inevitably incorporated since ambiguous behaviors can occur at transition regimes. In this study, therefore, we attempted to establish the procedure to find the onset of DWOs in a more systematic and consistent way: null transient multi-case runs without disturbance and judgement based on spectrum analysis (named the "mosaic approach"). In the proposed methodology, calculation costs can be greatly increased because enough simulation time for determination of flow state should be required for numerous cases. In order to reduce calculation costs, we developed automation processes, including MPI processing using Python language.

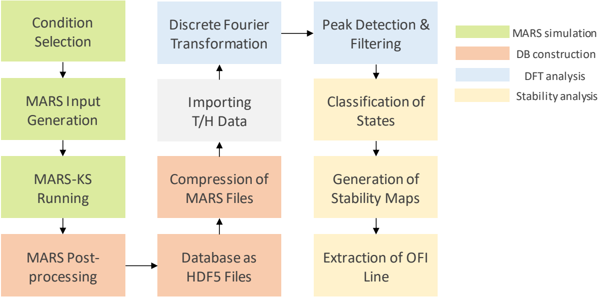

Fig. 1. Methodology – Mosaic Approach

2.2 Sensitivity Analysis

2.2.1. Time Step Control

We intentionally set time step control option to “000000” to examine the effect of coupling of hydrodynamics and thermal dynamics (see Fig. 2). In this case, the maximum time step (=0.1 s) is attempted for heat structure advancement and the semi-implicit scheme is used to advance the hydrodynamics simulations, ensuring the time advancement remains below the material Courant limit (Co<1.0). In addition, both thermal behavior and hydrodynamics are separately calculated and coupled explicitly. The Courant number is defined as

$$Co = u\frac{\Delta t}{\Delta x} \qquad (2.1)$$

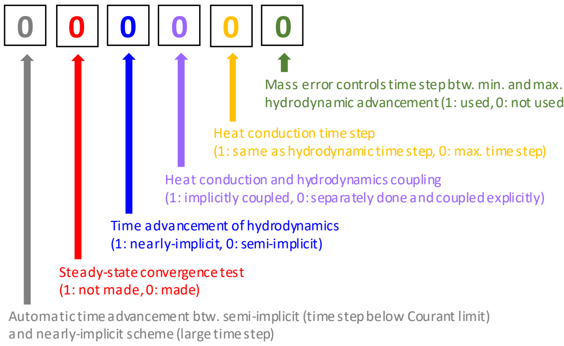

Fig. 2. Time step control option of MARS-KS code.

2.2.2. Model Option

The MARS code basically adopted the two-fluid model (TFM) as a standard model for simulation of two-phase flows (often known as the “UVUT” model). Similar to RELAP5 code, however, the homogeneous equilibrium model (HEM) can be selected in MARS-KS code by inserting appropriate model parameters for each component of volumes and junctions (also called the "EVET” model). In some previous literature, it has been reported that RELAP5 with the UVUT model option predicts relatively lower mass flux for DWO OFI compared to experiment data (i.e., in a non-conservative way), especially at high pressures (> 6 MPa) with rectangular channels [7,10,11] and low pressure conditions (1 & 2 MPa) with round tubes [6]. Conservativeness of EVET model for prediction of stability boundary of DWO than the UVUT model option can be also found in Ref. [5]. In this respect, we also performed a sensitivity analysis of model options on DWO MSB using the MARS-KS code. It turned out that MARS code with the UVUT option also predicts DWO OFI in more non-conservative ways not only than those predicted by the EVET model option but also than those measured in the EREC experiment (Fig. 3). Therefore, the HEM model option has been chosen to validate the MARS-KS code for DWO simulations.

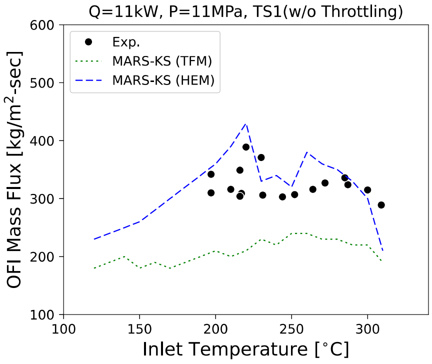

Fig. 3. Model dependency for DWO analysis (TFM vs HEM)

2.2.3. Heat Structure Coupling

In previous studies involving DWO simulation using the RELAP5 code [5,8,10], heat structures introduced to impose heat fluxes into fluid were recommended to be thin, with high thermal conductivity and low heat capacity (i.e., high thermal diffusivity, $\alpha = k/\rho C_p$) to avoid numerical distortions as well as to neglect wall dynamic behavior in the simulation of flow instabilities. In this regards, sensitivity analysis of the MARS DWO simulations upon thermal diffusivity and the thickness of the heat structure, while observing behaviors in the frequency domain based on spectrum analysis. Figs. 4-5 show the results of the sensitivity analysis regarding the thermal coupling effect in MARS-KS. The effects of thickness of heat structures ($\delta = N\Delta x$) on MARS DWO simulation are shown in Fig. 4. In this graph, flow states of MARS simulation are classified into stable and unstable flows based on a specific value of spectrum amplitude in the frequency domain. It apparently shows that noisy scattering with small amplitude involved in the code simulation can be efficiently recognized by the applied spectrum amplitude filtering due to the magnitude differences. Contrary to previous references, however, they can also be effectively mitigated by increasing the heat structure thickness. Fig. 5 depicts the effect of thermal diffusivity of heat structures. As seen in the figure, it was observed that considerable heat losses were inevitably accompanied by an unstable flow regime in code simulation with a common metal such as stainless steel (upper right). In cases with extremely high thermal diffusivity, the heat loss issue can be resolved (lower right); however, it was found in the frequency domain that high-frequency oscillations were additionally activated (lower left). Since OFI data are normally gathered in experiments under well-controlled heat loss conditions, a high thermal diffusive structure is also adopted in MARS-KS code simulations. This result also strongly implies that low-frequency filter (LPF) is required to extract low-frequency DWOs from numerical distortions caused by thermal coupling. Actually, it is well known that a smaller Fourier number ($Fo=\alpha\Delta t/\Delta x^2$) leads to better convergence in the numerical calculation of transient conduction problem [12], such as

$$Fo\left(1+Bi\right)=\frac{\alpha\Delta t}{\left(\Delta x\right)^2}\left(1+\frac{h\Delta x}{k}\right)\le\frac{1}{2} \tag{2.2}$$

Therefore, in the case a high thermal diffusive heat structure is introduced to minimize heat transfer dynamics, a thick heat structure seem to have an advantage for achieving transient thermal conduction convergence. Even though, however it is found that the LPF based on the FFT is still required to recognize low-frequency DWOs from MARS-KS simulation results.

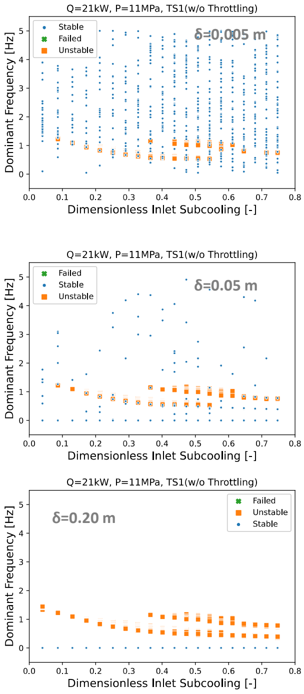

Fig. 4. Thermal coupling effect: heat structure thickness

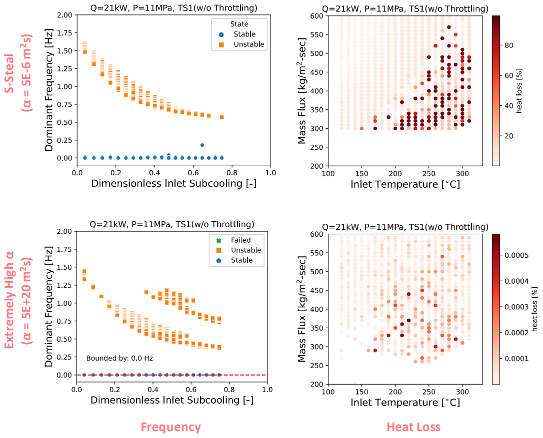

Fig. 5. Thermal coupling effect: thermal diffusivity

2.2.4. Classification Method

Previously, the onset of flow oscillation was determined by the author's judgement based on visual detection, or the states of flow were classified into "stable" and "unstable" using an absolute relative flow deviation as a criterion (i.e., 30% [13] or 100% [8]). In contrast to the previous methods ("Maximum Deviation" in Table I), four classification ways are possible based on spectrum analysis whether low-frequency filtering and/or spectrum amplitude filtering are applied or not (see Table I). In this study, we tried to apply these methods to the simulation results of the MARS-KS code for each condition in order to minimize the ambiguity of the classification of flow states or the detection of DWO OFI. Except for the "Dominant Frequency" method, however, a threshold criteria may be still required to determine flow states. A series of sensitivity analyses have been performed in this regard, not only on the classification methods but also on the threshold of criteria.

Table I: Method of DWO detection

Domain	Method	Frequency Filtering	Amplitude Filtering
Time	Maximum Deviation	N/A	N/A
Frequency	Dominant Frequency	X	X
	Filtered Frequency	O	X
	Dominant Amplitude	X	O
	Filtered Amplitude	O	O

As a result (Fig. 6), it turns out that the methods based on frequency filtering shows better performance which does not need amplitude filtering (RMSRE%: 17.1%). Furthermore, the frequency filtering is found to be a very effective way in improving the capability of prediction for frequencies at OFI (from 25.5% to 15.9% in RMSRE %). Therefore it can be concluded that the LPF is a very effective to decompose low-frequency DWO from simulated oscillations by MARS-KS code. In this regard, the "Filtered Frequency" method is recommended as a classification of flow states (i.e., detection of flow oscillation) for DWO analysis based on the spectrum analysis using the MARS-KS code. In this case, it turns out that no threshold criteria is also required. The root mean square relative error (RMSRE) was defined as

$$RMSRE\ \%=\sqrt{\frac{1}{n}\sum_i\left(\frac{P_i}{M_i}-1\right)^2}\times100 \tag{2.3}$$

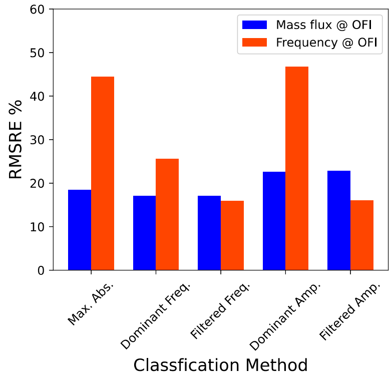

Fig. 6. Validation results on classification methods

3. Conclusions

In this study, a sensitivity analysis was performed on a newly proposed methodology for DWO analysis using the MARS-KS code. The new methodology aims to mitigate noises due to numerical instabilities that may arise from traditional time-domain code simulation, by employing spectrum analysis. The sensitivity analysis demonstrated that the LPF in the frequency domain can be utilized to detect the onset of DWO and is particularly effective in improving the predictive capability of OFI frequency by filtering out irrelevant numerical oscillations. Additionally, it was observed that numerical instabilities related to the difference in time scales in conjugate heat transfer problem can occur when heat conduction is coupled with heat convection in simulation of two-phase flow instabilities.

In conclusion, it was found that when analyzing DWO using a time-domain code such as MARS-KS, sensitivity analysis is necessary to address numerical scattering issues. Also, it was confirmed that spectrum analysis can be adopted to mitigate such numerical distortions possibly caused in DWO simulations using time-domain analysis code.

ACKNOWLEDGMENTS

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