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Fourier analysis of the RELAP5/3D adaptive time-stepping scheme on a natural circulation loop

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ABSTRACT

The use of natural convection as a passive heat removal mechanism has been widely explored as a safety system of nuclear power plants. Characteristics like low complexity and economy makes Natural Circulation Loop (NCL) an encouraging technology which is being investigated for the Generation IV nuclear energy systems. As a manner to enhance the performance prediction of NCL, this study provides an evaluation of the adaptive time-stepping scheme that the RELAP5/3D code uses to calculate the time-step size applied during a transient simulation. Additionally, the Fast Fourier Transform (FFT) and the Root-Mean-Square Deviation (RMSD) procedures were conducted in order to investigate the agreement between the numerical and experimental data during the time frame when two-phase flow instabilities appear. Temperature measurements extracted from an experimental facility were used as the baseline data. For this evaluation, four different maximum time-step sizes were considered and their effect on the prediction of NCL temperatures was analyzed.

1. Introduction

The use of passive systems such as natural convection has been extensively studied for reactor cores as a heat removal mechanism. Besides the no needed power supply, the simplicity and low cost at the application make the use of Natural Circulation Loop (NCL) a promising technology for the Generation IV nuclear energy reactors (Hittner, 2006; Vaghetto and Hassan, 2014). Therefore, a proper evaluation of the prediction of the main characteristics of this type of fluid flow is essential for the design of new nuclear safety systems (Braaten and Shyy, 1987). Also, due to its advantages, NCL has been found in other areas such as geothermal plants, processing plants for liquefied natural gas and electronics cooling. The work of Basu et al. (2014) provided a thorough review of NCL, including future applications and new trends for this research field.

Numerous studies related with NCL have been addressed recently, and the research of Vijayan (2002), Misale and Garibaldi (2012), Sabundjian et al. (2011), Sarkar and Basu (2016) and Rabiee et al. (2016) are some of the studies that could be emphasized.

Moreover, it has been seen in the literature that the use of adaptive time-stepping scheme is a common practice applied to transient problems. The work of Prebeg et al. (2017) proposes an extension of the Large Time Step Roe scheme and later applied it to fully explicit problems. It was concluded that the proposed scheme lead to a higher accuracy and to a more efficient solution when no source terms are presented in the modeling. Loy and Bourgault (2017) assessed three different time-stepping schemes under typical bi-dimensional and incompressible problems found in fluid mechanics, such as the external flow around a cylinder. Focusing on the simulation of phenomena with multiple time scales, Li et al. (2017) proposed a new adaptive time-stepping scheme based on the discrete maximum norm of the difference between two consecutive time step numerical solutions. Later, the scheme performance was demonstrated in problems with different number of dimensions.

It is known that RELAP5/3D code considers the semi-implicit solution as the time-marching numerical method for the thermal–hydraulic modeling named Two-Fluid Model (TFM). Thus, the final solution of the flow field depends directly from the previous time-step and it is expected that each time-step size provides a different accuracy level, when compared to a baseline data. In order to ensure the numerical convergence during the simulation, the RELAP5/3D code uses its own adaptive time-stepping scheme where the time-step size applied to the semi-implicit method is calculated based on the Material Courant Limit (MCL) and on mass residuals. This time-stepping scheme has the objective of compromising between code stability and low computational cost. Moreover, two-phase natural circulation consists in a complex type

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Nomenclature

BPLU	Border profile lower–upper
FFT	Fast Fourier Transform
GMRES	generalized minimum residual
NCL	natural circulation loop
PSD	Power Spectrum Density
RMSD	Root-Mean-Square Deviation
STHX	spiral tube heat exchanger
TFM	two-fluid model

of heat transport, where buoyancy forces combined with nucleate boiling generate temperature and mass flow oscillations. More precisely, bubbles generated at the heat source nucleate and then coalesce to form vapor slug at the vertical hot leg, providing a local flow blockage and decreasing the loop mass flow (Belchior et al., 2000). Then, the sudden reduction of the mass flow results in an increase of the temperature difference between the heat source and sink, heightening the buoyancy forces which drive the fluid flow. As a result, the mass flow increases, the interfacial momentum transfer provides the movement of the vapor slug towards the cold leg and a dynamic behavior is established for the two-phase flow. Thus, the evaluation of a NCL is fundamentally a dynamic problem, and due to this reason the chosen time-step size plays a strong influence on the quality of the results, especially when two-phase flow instabilities occur.

Furthermore, a proper prediction of two-phase instabilities on NCL should consider not only the instantaneous value of the flow temperature but also its dynamic behavior. As an example, a simulation result with constant temperature can predict accurately the temperature of flow instabilities but it fails to represent the nonlinear operation of complex systems dynamically. On the other hand, a good prediction of frequency instabilities is not sufficient for a good prediction of two-phase flow.

Considering all the mentioned aspects, this study intends to provide a computational assessment of the RELAP5/3D code for typical NCL applications, where the influence of the time-stepping scheme on the NCL final results are addressed. Four different maximum time-step sizes were chosen and their effect on the prediction of NCL temperatures and two-phase instabilities were evaluated. For comparison purposes, the experimental data generated by the loop described by Sabundjian et al. (2011) and Braz Filho et al. (2017) was used. The same RELAP5/3D modeling and nodalization considered in the previous work of Braz Filho et al. (2017) was applied in this study.

As a manner to enhance the dynamic analysis of the two-phase instabilities, the Fast Fourier Transform (FFT) and the Root-Mean-Square Deviation (RMSD) procedures were applied to the study of the transient behavior of NCL temperatures. The former enables the comparison of the frequency instabilities, whereas the latter is applied to the comparison of instantaneous temperature values gathered from the experimental and numerical data. The use of these procedures allows an objective evaluation of the influence of the RELAP5/3D adaptive time-stepping scheme on the estimate of NCL performance. To the best of the author's knowledge, there are no studies available in the open literature that propose the use of such statistical tools to predict the dynamic features of the two-phase flow instabilities found in NCL.

2. Governing equations

Regarding the thermal–hydraulic model, the RELAP5/3D code applies the TFM, where each phase (liquid and vapor) is represented by a set of ensemble averaged governing equations. Thus, continuity, momentum and energy equations are solved for each phase. Due to the averaging procedure, details of the interface are lost and constitutive equations are required to represent the interfacial transfer terms. These interfacial terms are represented in the governing equations as source terms. Thus, the continuity equation for a transient one-dimensional flow of phase k is represented as

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_k \rho_k u_k A) = M_k. \tag{1}$$

In Eq. (1), the mass exchange rate is denoted by M and the channel area is represented by A. Variables α, ρ and u denote the volume fraction, density and velocity of phase k. In the RELAP5/3D code, the momentum conservation equation for phase k with the corresponding interfacial exchange terms is represented as

$$\begin{aligned}\alpha_k \rho_k A \frac{\partial u_k}{\partial t} + \frac{1}{2}\alpha_k \rho_k A \frac{\partial u_k^2}{\partial x} = {} & -\alpha_k A \frac{\partial P}{\partial x} + \alpha_k \rho_k B_x A - (\alpha_k \rho_k A) Fw_k \\ & \cdot u_k + \Gamma_k A (u_{k,i} - u_k) - (\alpha_k \rho_k A) Fi_k \\ & \cdot (u_k - u_r) \\ & - \alpha_k \alpha_r \rho_m A \left[\frac{\partial (u_k - u_r)}{\partial t} + u_r \frac{\partial u_k}{\partial x} - u_k \frac{\partial u_r}{\partial x}\right],\end{aligned} \tag{2}$$

where the interfacial drag and the wall drag forces are denoted by variables Fw and Fi. The pressure is characterized by P and the body force is represented by B_x. The velocity of phase r is denoted by u_r, whereas the two-phase mixture density is denoted by ρ_m. Furthermore, the energy equation is characterized as

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_k \rho_k U_k) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_k \rho_k U_k u_k A) \\ &\quad = -P\frac{\partial \alpha_k}{\partial t} - \frac{P}{A}\frac{\partial}{\partial x}(\alpha_k u_k A) + Qw_k + Qi_k + \Gamma i h_k + \Gamma w h_k'' + D_k,\end{aligned} \tag{3}$$

where variable U represents the fluid specific internal energy. The interfacial heat transfer rate is denoted by Qi, whereas the heat transfer rate at the wall is denoted by Qw. Variables h and h'' represent the specific enthalpy and the latent heat of evaporation, respectively. Moreover, the energy dissipation function in Eq. (3) is defined by the term D.

The set of partial differential equations for the TFM are discretized numerically via the finite-difference method. For the transient treatment of the TFM, RELAP5/3D applies the semi-implicit numerical scheme. Thus, the finite difference equations are partially implicit in time. The set of linear equations can be solved by different methods, such as the Border-Profile Lower Upper (BPLU) and the Generalized Minimal Residual method (GMRES). Both linear-equation solvers are available at the RELAP5/3D code settings and were considered in this study. Further details about the RELAP5/3D code governing equations, finite-volume discretization and numerical treatments are described by Roth and Aydogan (2014), and in the Idaho National Laboratory (2012) user's manual.