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On the validity of Boussinesq approximation in transient simulation of single-phase natural circulation loops

Mayur Krishnani, Dipankar N. Basu*

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

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ABSTRACT

Application of One-dimensional numerical models with Boussinesq approximation is a common approach for stability evaluation of single-phase natural circulation loops. Present work focuses on assessing the viability of such approximation during nonlinear stability appraisal following transient simulation. Accordingly a 3-D computational model of a rectangular loop is developed, with heating at bottom horizontal arm and isothermal sink around the top. Transient conservation equations are solved, performing simulations both with complete variation of all relevant thermophysical properties and the simple Boussinesq model. System exhibits unstable behavior with increase in both heater power and sink temperature, the nature of the temporal response being significantly affected by the coolant-side condition. Boussinesq model predicts instability for substantially lower power levels, along with bidirectional pulsing in flow rate and presence of secondary motion at the corners of the horizontal arm. The system also takes much longer time to initiate the flow, compared to the model with complete property variation, the deviation being larger at enhanced power levels. Hence the Boussinesq approximation provides a highly-conservative estimate of the stability boundary and is not a practicable tool for transient analyses of single-phase loops, particularly at higher powers.

1. Introduction

Stability appraisal of single-phase natural circulation loops (NCLs) is of interest both to engineers, due to its practical relevance, and mathematicians, as an excellent non-linear test problem. Its inherent reliability and enhanced passive safety have encouraged application in critical fields such as nuclear reactor cooling [1–4] and ship propulsion [5,6], where ensuring a stable zone of operation is an obligation. However, the fully-coupled nature of momentum and thermal transports and dependence on the prevailing body force field, administers high sensitivity to the operating conditions and susceptibility to instability. As was summarized by Zvirin [7], motion in NCL is initiated by the favourable instability of the second kind, among the four possible types. However the third and fourth kinds of instabilities, namely oscillation growth in steady flow and multiple steady-state solutions, are of major concerns in the practical systems. First reasonable explanation about the emergence of oscillations was proposed by Welander [8], assuming the fluid to behave like a pendulum, which was subsequently demonstrated experimentally by Creveling et al. [9]. An exact expression for the steady-state velocity was developed by Sen et al. [10] following a 1-D model, which showed the possibility of having zero to three solutions. These early studies made the path for several future endeavour towards exploring the concept of NCL stability, using both experimental and theoretical frameworks.

Following the development in computational resources over last two decades, numerical simulation using in-house or commercial codes has emerged as the most common approach for NCL characterization. While a few researchers employed the simplistic Lorenz model [11–13], mostly to identify different possible dynamical flow regimes and nature of bifurcations under unstable condition, the applicability is limited, owing to the assumed nature of velocity and temperature fields. Quite a few recent applications of multidimensional system codes can also be found in literature [14–17], which shows encouraging prospects in reproducing experimental results. However, the huge computational cost required for transient simulation has restricted its use generally to steady-state cases. Therefore adoption of 1-D transient model has traditionally been the preferred option for stability evaluation of single-phase NCLs, along with linear stability analysis. Eigenvalues

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* Corresponding author.
E-mail address: dipankar.n.basu@gmail.com (D.N. Basu).

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obtained from the linearized set of conservation equations can only predict the stability threshold, whereas detailed knowledge about the nature of fluctuations and flow reversals can only be identified following the temporal evolution of system variables. Ramos et al. [18] were probably the first to attempt numerical modeling of a loop with variable cross-sectional area. Their approach was subsequently improved by Bernier and Baliga [19], as they coupled 2-D finite volume simulation in the heater and cooler with 1-D loop momentum equation. Development of the pioneering computational model using explicit finite difference method can be credited to Vijayan and Date [20] for a figure-of-eight configuration. Their work, however, was aimed towards steady-state analyses, which was extended towards stability appraisal in their subsequent study [21]. Initial perturbation was provided in two different ways, which resulted in wide disparity between marginal stability curves. That was rectified by Nayak et al. [22], as close agreement was reported between linear and nonlinear stability maps. Similar study was also reported by Mousavian et al. [23], as they discussed about the role of grid spacing on transient prediction and suggested the use of finer meshes. That conclusion was in line with the work of Vijayan et al. [24] employing 1-D system code ATHLET, to facilitate repeated switching between laminar and turbulent frictional correlations. More elaborate discussion about the role of grid spacing, time steps and adopted discretization scheme was presented by Ambrosini and co-workers in a series of studies [25–27]. They suggested the use of explicit upwind scheme and Courant number close to one to circumvent numerical diffusion. The importance of using geometry-specific closure laws was also emphasized [27], supporting the discussion of Vijayan [28]. Such guidelines have since been followed in several subsequent studies [29–31], thereby helping the development of a substantial database on the transient behavior of single-phase NCLs.

It is quite evident that numerous aspects of nonlinear stability analysis have received thorough attention. However one common factor among different 1-D models is the adoption of Boussinesq approximation to couple the thermal and momentum fields [22–24,28,31]. That considerably simplifies the analysis, as density is considered as a linear function of temperature only during the body force evaluation. All other thermophysical properties are taken as constant, thereby eliminating the exclusive inclusion of the equation-of-state in the solution framework. A suitable reference temperature needs to be selected, sink temperature or ambient temperature being the common choices. However, property variation for common fluids generally exhibit substantial nonlinearity with temperature variation. As can be seen from Fig. 1a, density of water estimated using Boussinesq model provides reasonable value only around the selected reference temperature (= 15 °C in present figure), in comparison to the IAPWS-IF97 standard [32]. Thermal expansion coefficient itself can increase more than 10 times with rise in water temperature from 378 to 388 K (Fig. 1b). Basu et al. [33] suggested the use of loop-averaged fluid temperature as the reference for lessening the error in property estimate. That is also not the greatest option considering the small density differential required in developing the driving force in NCLs and to amplify the transient fluctuations.

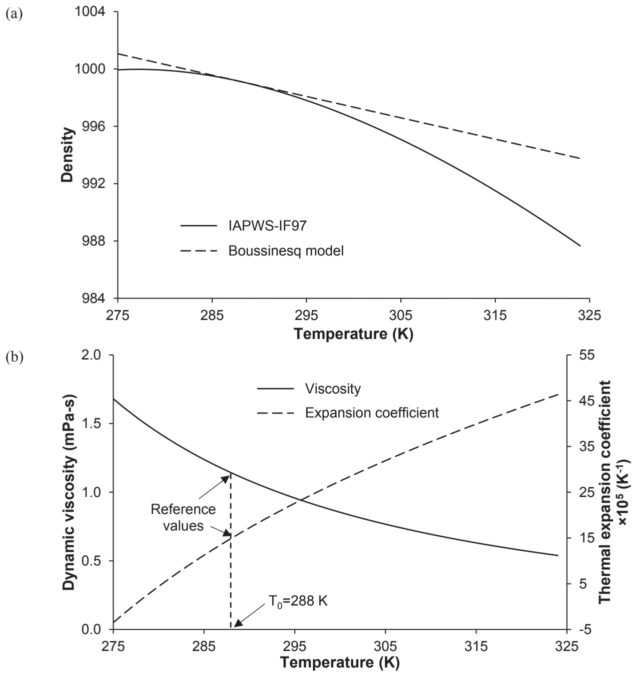

Fig. 1. Variation of thermophysical properties of water with temperature at 1.013 bar and comparison with Boussinesq model.

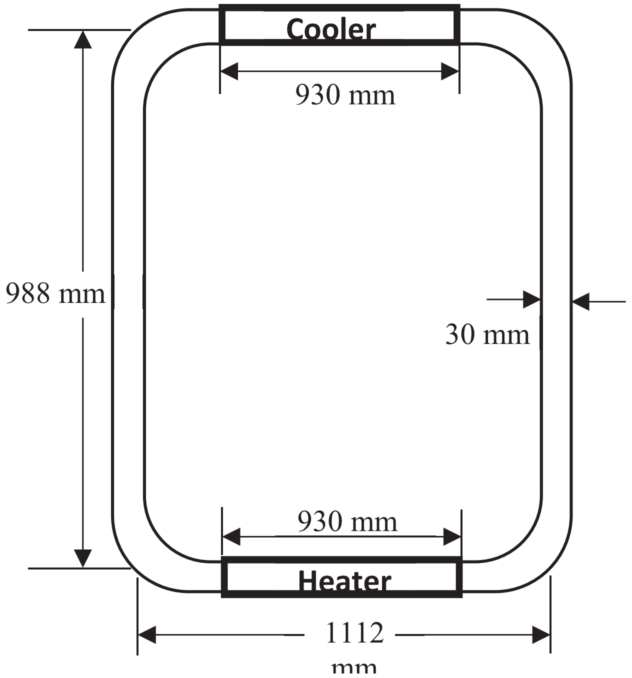

Fig. 2. Schematic representation of the rectangular NCL under consideration (drawing not to scale).

Table 1
Details of the mesh systems adopted for numerical simulation.

	Model 1	Model 2	Model 3
No. of nodes	143,488	255,460	474,496
No. of elements	135,900	240,768	449,280
Orthogonal quality	0.977	0.979	0.982
Skewness	0.13	0.12	0.11
Element quality	0.24	0.50	0.58

Therefore it is essential to perform a comprehensive analysis of single-phase NCLs with the most accurate equation-of-state, to ascertain the viability of Boussinesq approximation and its influence on the transient response of the loop. Presence of local buoyancy forces due to the temperature variation across any cross-section can also affect the stability behavior, thereby necessitating multi-dimensional modeling. The same is performed in the present