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# Dynamic response of a single-phase rectangular natural circulation loop to different excitations of input power

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ABSTRACT

Dynamic analyses of system responses during sudden change in input power for single-phase natural circulation loops are only a very recent concept. The present study theoretically investigates the transient behaviour of rectangular loops, subjected to direct heat addition and convective cooling. Non-dimensional forms of governing equations have been used alongside suitable closure relations. Three fundamental signals, having step, ramp and exponential profiles, and a newly-defined modified exponential signal have been applied on input power during power increase and decrease. Step and exponential changes have been found to lead the system towards instability during power up-surge, due to the impulsive nature of transition. The system also takes long time to attain steady-state for power decrease to a stable state following a step change. Step signal can be broken into equal increments for better performance. Increasing the number of increments and time-lag between successive steps, higher power operation can be sustained for a longer duration. Modified exponential signal has been found to be superior compared to others, both during power increase and decrease. It allows a moderately increasing gradient during power transients and hence the rate of oscillation growth is much smaller.

## 1. Introduction

Natural circulation loop (NCL) has become an attractive option in different engineering applications for transferring energy from a heat source to a heat sink, without bringing them in direct contact. Hence single-phase loops have recently found extensive use in different technical fields such as electronic chip cooling [1], refrigeration [2] and core cooling of nuclear reactors [3,4]. Due to the absence of any prime movers, such loops ensure a high reliability and enhanced passive safety desirable in nuclear engineering. However, the operation of NCL is always susceptible to unstable fluctuations and precise design-level analysis is essential to ensure stable zone of operation during normal system run, as well as during probable abnormal behaviour. Two-phase loops generally offer much larger circulation rates; however, they may experience the possible appearance of different types of instabilities and hence very precise and complicated design procedures need to be followed. Therefore it has become vital to analyse different aspects of any NCL-based system focusing on the interaction of all the forces involved in system dynamics.

The operation of a single-phase loop is mainly a result of the interaction between buoyancy and frictional forces. But, even its normal running is closely associated with instability, as was explained by Zvirin [5]. He demonstrated that the motion in NCL is initiated by the favourable instability of the second kind, out of four possible types. Most of the early observations on instability in such loops were reported for near-critical fluids [6]. The first experimental proof under normal temperatures, with water as working fluid, is credited to Creveling et al. [6]. They identified two different regimes of stable operation with the region of instability matching the transition from laminar to turbulent flow. Experiments by Britt and Wood [7] also confirmed three distinct zones of operation, namely, stable flow at low power, oscillations at intermediate power and back to stable flow at high power. Recirculation was observed due to a faster change in temperature of fluid elements in contact with the wall compared to those close to the centreline. Sen and Treviño [8] developed a one-dimensional model of an NCL having arbitrary shape and showed that the loop can have both forward and reverse flow under any particular situation, steady-state flow direction being governed by the initial conditions. By subjecting the loop to both point and distributed heat fluxes in their subsequent work [9], they explained that steady-state is possible only under certain conditions and even that might be pulsating in nature. Ramos et al. [10] theoretically analysed a rectangular loop with variable cross-sectional area and showed that flow was possible only by locating heat source at a lower elevation than heat sink. Even such system always

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**Nomenclature**

| | |
|---|---|
| $C_p$ | specific heat (J kg$^{-1}$ K$^{-1}$) |
| $Eu$ | Euler number |
| $g$ | gravitational acceleration (m s$^{-2}$) |
| $Gr_m$ | modified Grashof number |
| $L$ | length (m) |
| $\dot{q}''_w$ | wall heat flux (W m$^{-2}$) |
| $Re$ | Reynolds number |
| $s$ | space coordinate |
| $St_m$ | modified Stanton number |
| $T$ | absolute temperature (K) |
| $u$ | velocity (m s$^{-1}$) |
| $\dot{W}$ | mass flow rate (kg s$^{-1}$) |
| $d_i$ | inner diameter (m) |
| $f$ | friction factor |
| $G$ | mass flux (kg m$^{-2}$ s$^{-1}$) |
| $h$ | heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |
| $\dot{q}''_h$ | heat flux supplied in heater (W m$^{-2}$) |
| $Q_h$ | input power (W) |
| $Ri$ | Richardson number |
| $S$ | non-dimensional space coordinate |
| $t$ | time (s) |
| $T^*$ | non-dimensional temperature |
| $U^*$ | non-dimensional flow velocity |
| Greek symbols | |
| $\alpha$ | slope of function |
| $\beta$ | volumetric coefficient of thermal expansion (K$^{-1}$) |
| $\Delta T_0$ | reference temperature drop (K) |
| $\tau$ | non-dimensional time |
| $\psi$ | fractional change in input power |
| $\theta$ | angular displacement (rad) |
| $\varphi$ | angle of inclination (rad) |
| Subscripts and superscripts | |
| 0 | reference |
| $c$ | coolant stream |
| $h$ | heater section |
| $mod$ | modified |
| $t$ | total |
| $av$ | average |
| $fnl$ | final |
| $inl$ | initial |
| $ss$ | steady-state |
| $v$ | vertial |

exhibited multiple steady-state solutions. Experimental verification of the same was reported by Acosta et al. [11] in a tilted square loop. Vijayan et al. [12] demonstrated the dependence of stability behaviour of rectangular NCLs on loop orientation, vertical placement of the heat-exchanging sections always being a better option. Horizontal heater-cooler orientation was observed to have the worst stability performance, even in comparison with an identical toroidal loop, as was shown by Basu et al. [13]. Misale and Frogheri [14] experimentally demonstrated the use of orifices in flow channel to suppress unstable oscillations. Effect of loop diameter on stability response was discussed by Vijayan et al. [15] and Misale et al. [16], whereas Basu et al. [17] presented a detailed analysis about the influence of geometric and operating parameters on stability boundary. Nature of such instabilities and threshold of their appearance for single-phase NCLs has been studied in a number of recent computational studies [18–20]. Stability characterization for transcritical or supercritical $CO_2$ –based NCLs has also gained significant importance over last decade [21–26].

However, another important aspect of stability behaviour of single-phase NCLs, which hardly received an adequate attention, is the nature of system response when subjected to a sudden alteration in operating conditions. It is quite a common situation in real-life systems that the working power level may need to be increased or decreased to suit application demands. But the effect of such an impulsive change is difficult to predict either due to the lack of prior knowledge or because of the complex and uncontrollable nature of concerned application. Possible dependence of steady-state flow direction on the initial condition was demonstrated earlier by Sen and Treviño [8]. Vijayan et al. [12] predicted that a conditionally stable hysteresis region may appear, stability threshold being dependent on heat addition path. Experimental corroboration of the same has also been reported by Bodkha et al. [27]. Rao et al. [28] developed a theoretical model for a fluid-coupled rectangular NCL and imposed different excitations on the hot fluid inlet temperature under steady-state. A delay was observed for the cold stream outlet temperature to respond, the delay period being governed by the nature of excitation. The modified ramp signal was reported to be the slowest to respond. They also compared the dynamic performance of a similar system with direct heat exchanger and fluid-coupled FCL [29]. NCL was found to be the slowest to respond and even more so with ramp signal input. Chen et al. [25] theoretically analysed a trans-critical $CO_2$ loop under unsteady heat input condition and sudden increase in power supply was reported to lead to system instability, with quick increase causing greater level of fluctuations. System stability controlling factors were found to be very much dependent on the nature of change in input. However, similar attempts on single-phase loops with direct heat addition have rarely been reported in the open literature, despite direct correspondence to nuclear and refrigeration fields. Present investigation focuses on bridging this gap through a comprehensive computational analysis of rectangular single-phase NCL having direct heat addition in the lower horizontal arm and convective cooling along the top horizontal arm. The loop was subjected to scheduled increase or decrease in power supply following different nature of excitations. Resulting transient responses of system parameters were studied to reveal the dynamic behaviour of the loop.

## 2. Theoretical model development

As the primary objective of the present work is to investigate the dynamic performance of a single-phase rectangular NCL, the modelling methodology presented by Basu et al. [13] has been adopted. A schematic representation of the concerned loop is shown in Fig. 1. A one-dimensional simulation has been considered, incorporating Boussinesq approximation in order to take care of the temperature dependence of the fluid density on the body force. Viscous dissipation and axial conduction has been neglected. Heat leakage to the surrounding has also been neglected assuming ideal insulation in non-heat-exchanging sections.

Integrating the momentum equation for the working fluid over the entire loop length and setting the pressure drop over the closed path to zero, the non-dimensional form can be represented as,

$$\frac{dU^*}{d\tau} = \left(\frac{L_t}{L_v}\right) Ri \oint T^* \cos(\varphi + \theta) dS - Eu_{ss}(U^*)^2 \qquad (1)$$