Steady-state and Nonlinear Stability Analysis of a Single-phase Rectangular Natural Circulation Loop

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Abstract: The natural circulation loop is an experimental setup where the fluid flow is caused by the density difference between the hot and cold fluid. A mathematical model for a single-phase rectangular natural circulation loop (NCL) is developed to study steady-state behavior and flow instabilities. The numerical model incorporates the mass, momentum, and energy equation with the state equation. The steady-state and nonlinear stability analysis includes an implicit finite difference methodology using a fixed spatial and temporal grid distribution while discretizing the convective terms by backward or forward difference scheme. The steady-state analysis has captured the variation of mass flow rate with respect to power. It identifies the operating conditions where maximum mass flow rate occurs in an NCL. A comprehensive numerical study of the nonlinear stability analysis is performed with various parametric studies, which include the effect of loop diameter, loop height, operating pressure, orientation of heater and cooler and power profile. Furthermore, the stable operating zones are investigated by taking appropriate geometrical and operating conditions via stability analysis.

***IndexTerms* – Flow instability, Marginal stability boundary, Natural circulation loop, Supercritical water.**

I. INTRODUCTION

The Supercritical water-cooled reactor (SCWR) is a Generation-IV nuclear reactor. The SCWR is intrinsically reliable, financially sustainable, long life, and proliferation-resistant. The supercritical water (SCW) is utilized as a coolant in SCWR, which has excellent heat transfer coefficient, provides high thermal-efficiency, reduces the size and eliminates the steam-generating components of the reactor. These features of SCW attain the attention of the scientific community; thereby, it is utilized as a coolant in a natural circulation loop (NCL) (Chatoorgoon, 2001, Ambrosini and Sharabi, 2008, Sharma et al., 2010a, Sarkar et al., 2014). The steady-state, linear and nonlinear stability analysis examined the feasibility of SCW in the environment of NCL. The steady-state analysis identifies the operating points to provide the maximum mass flow rate for the loop. However, linear and nonlinear stability analysis provided a stable and unstable zone for the NCL. The unstable region is undesirable because it exhibits unwanted mechanical vibration, which can cause a severe failure of mechanical and electronic components and leads to flow instability in the system (Pilkhwal et al., 2013, Sharma et al., 2010b).

The NCL is an experimental configuration, in which the coolant flows due to the buoyancy effects caused by the density difference between the hot and cold limbs. It eliminates the requirement of a pump for the natural circulation systems (NCSs). In a nuclear reactor, heat is transferred from nuclear fuel to coolant by forced circulation systems (FCSs) and NCSs. The heat transfer rate of NCS is lower than FCS; however, FCS required additional power to run the pump. In accidental conditions, when there is no power available to run the pump, NCSs can transfer heat from the reactor and ensure the system's safety. This inherent safety features of NCSs draw attention to the scientific and industrial community. Therefore, NCSs are configured in various industrial applications like single-phase NCSs in solar water heaters, transformer cooling, and nuclear reactor core cooling. Whereas two-phase NCSs in Natural Circulation Boiling Water Reactors (NCBWRs), Natural Circulation Boilers (NCBs) in fossil-fueled power plants, Natural Circulation Steam Generators (NCSG) in Pressurized water reactors (PWRs) & PHWRs and thermo-syphon reboilers (Basu et al., 2014, Bragt and Hagen, 1998, Bhambare et al., 2007, Jain and Uddin, 2008, Sharma et al., 2014, Upadhyay et al., 2018, Upadhyay et al., 2020, Raghuvanshi et al., 2019).

In the last two decades, various experimental and numerical works have been performed on NCL. The work includes the steady-state, linear and nonlinear stability analysis with different coolants for NCL. In the field of NCL, the most prominent work is done by Chatoorgoon (2001). Chatoorgoon considered a constant area rectangular loop geometry for NCL with a horizontal heater and cooler orientation. Thereafter, steady-state and nonlinear stability analysis is performed considering water as a working fluid for the loop geometry. The analysis concluded that the threshold of instability is estimated by the peak of mass flow rate versus power curve of steady-state analysis. Sharma et al. (2010a) performed steady-state, linear and nonlinear stability analysis for supercritical water NCL. Firstly, Sharma et al. (2010a) validated the proposed model with the prominent Chatoorgoon's model (2001). Afterwards, Sharma et al. (2010a, 2010b) developed a linear stability analysis code SUCLIN and a nonlinear stability analysis code NOLSTA to perform various parametric studies for SCWNCL. The linear and nonlinear stability analysis results are compared to analyze the effective working region for the SCWNCL (Sharma et al. (2010a, 2010b)). Sarkar et al. (2014) drafted a state-of-the-art survey for recent advancements in SCNCLs. The survey reported the various heat transfer aspects and stability analysis of NCLs using frequency and time-domain methodology. The state-of-the-art review presented various numerical modelling schemes to assess the stability behavior of NCL with 1-D codes (Basu et al. 2014). Jain and Corradini (2016) analyzed supercritical water and carbon dioxide as a

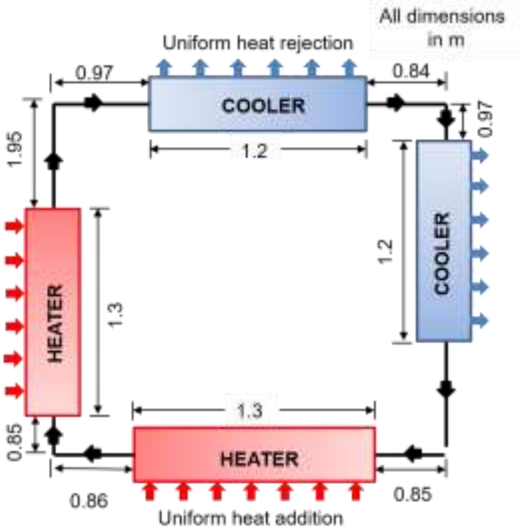


Fig. 1. Schematic of natural circulation loop geometry.

working fluid in the environment of NCL. The steady-state analysis results show the contradiction with the Chatoorgoon's model (2001), as the instability is not strictly related to the peak of flow rate versus power curve. Afterwards, linear stability analysis is performed to obtain the marginal stability boundary for NCL. Gomez et al. (2008) presented thermal-hydraulic linear and nonlinear stability analysis of a uniformly heated pipe, operating at supercritical pressure. The analysis explained that if a supercritical water system follows a density wave instability, then Ledinegg excursive instability and pressure drop oscillations will not occur. Sudheer et al. (2018) considered a homogeneous equilibrium model for two phase flows in NCL. They performed the steady-state analysis at atmospheric and sub-atmospheric conditions to evaluate the effect of operating pressure, heat flux and heater inlet temperature for NCL. Sharma et al. (2013) conducted experiments in a closed loop SPNCL with supercritical carbon dioxide as working fluid. They have developed the computer code (NOLSTA) and performed the steady-state and nonlinear stability analysis of open and closed-loop natural circulation at supercritical conditions.

The literature reveals steady-state and nonlinear stability analysis of various fluids for NCLs. In the present paper, the steady-state and transient solution procedures are stated along with the steady-state and nonlinear parametric studies for the NCL geometry. Authors have incorporated various feasible geometric and operating conditions, and examined the feasibility of SCW for the NCL. The nonlinear stability analysis provided the marginal stability boundary to capture the stable and unstable zone for NCL.

II. Loop Geometry

The geometry considered for the analysis is a single channel, uniform diameter rectangular SCWNCL as shown in Fig. 1 (Sharma et al., 2010a). The loop diameter is very small as compared to the length, hence one-dimensional analysis is considered with x co-ordinate. The constant inlet enthalpy and pressure are the boundary conditions for the NCL, however, the inlet and outlet pressure should be equal for the NCL. Hence, for NCL analysis, heater inlet temperature, operating pressure of loop, and the power are stated along with the complete geometry like hydraulic diameter, flow area, and length of each pipe. In the proposed methodology, the amount of heat supplied to the heater is equal to the amount of heat rejected by the cooler without evaluating the exact capacity of the heat. The combination of various orientations of heaters and coolers like Horizontal Heater and Horizontal Cooler (HHHC), Horizontal Heater and Vertical Cooler (HHVC), Vertical Heater and Horizontal Cooler (VHHC), and Vertical Heater and Vertical Cooler as shown in Fig. 1, are utilized for steady-state and nonlinear stability analysis of NCL. Kindly notice that there can be only one heater and one cooler for a particular orientation.

III. Mathematical Formulations

The TH model of natural circulation loop has following mass, momentum, and energy conservation equations:

Mass conservation equation:

$$\frac{\partial(\rho A)}{\partial t}+\frac{\partial(\rho A u)}{\partial x}=0 \qquad (1)$$

Momentum conservation equation:

$$\frac{\partial(\rho A u)}{\partial t}+\frac{\partial(\rho A u^2)}{\partial x}=-A\frac{\partial p}{\partial x}-A\rho g-\tau_w P_w A \qquad (2)$$

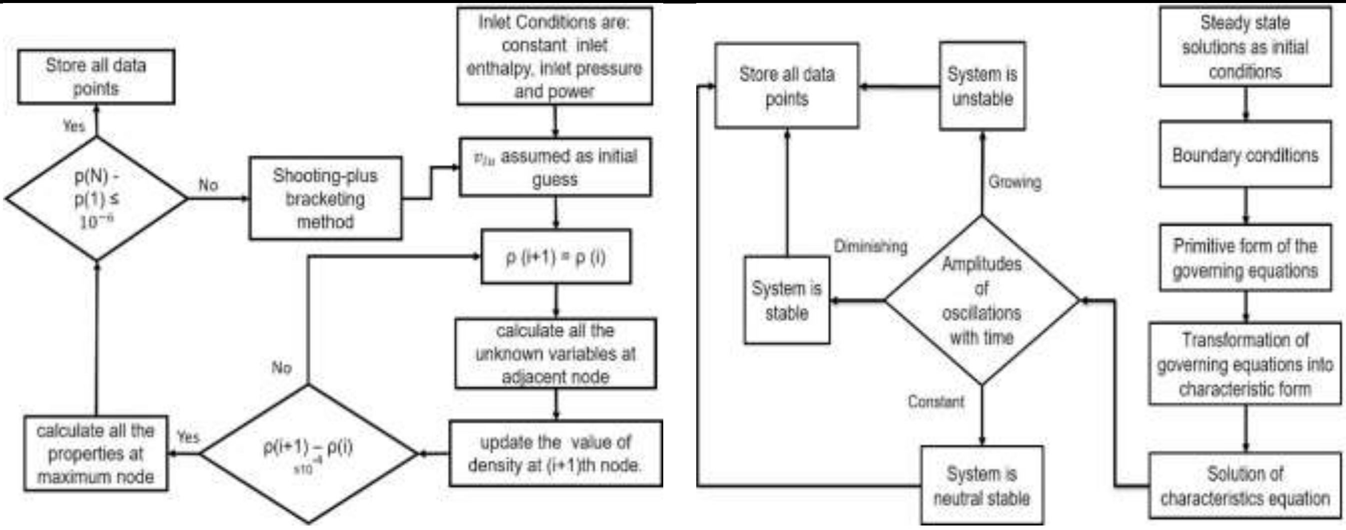
Energy conservation equation:

$$\frac{\partial(\rho A e)}{\partial t}+\frac{\partial(\rho A u e_f)}{\partial x}=q_w'' P_h \qquad (3)$$

Where $e = e_f - \frac{p}{\rho}$ and $e_f = h + \frac{u^2}{2} + gH$

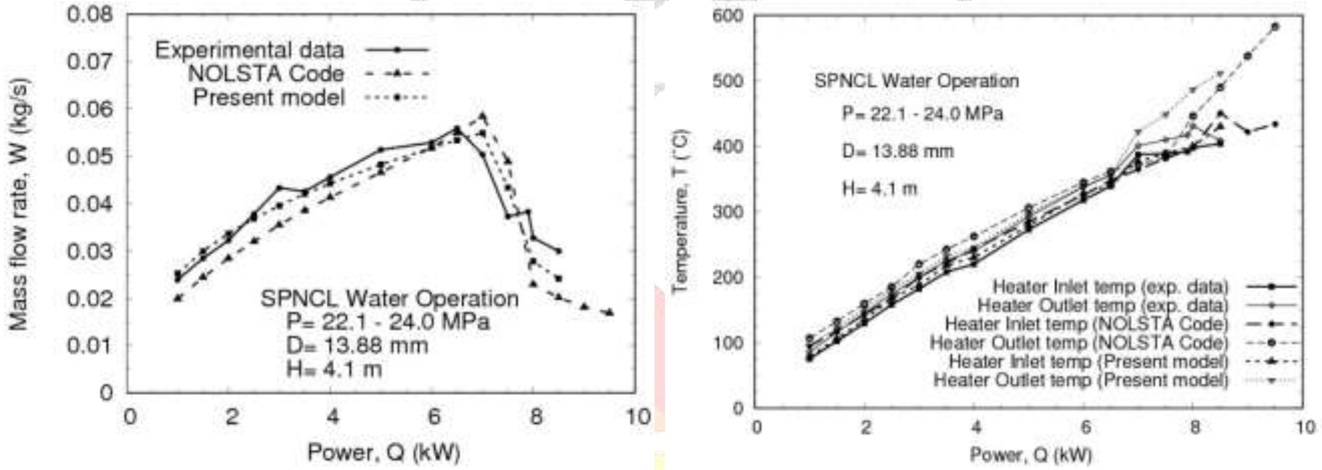
These equations are solved along with the equation of state, which is used to calculate properties (density) of coolant at axial grid points:

$$\rho = \rho(p, h) \qquad (4)$$



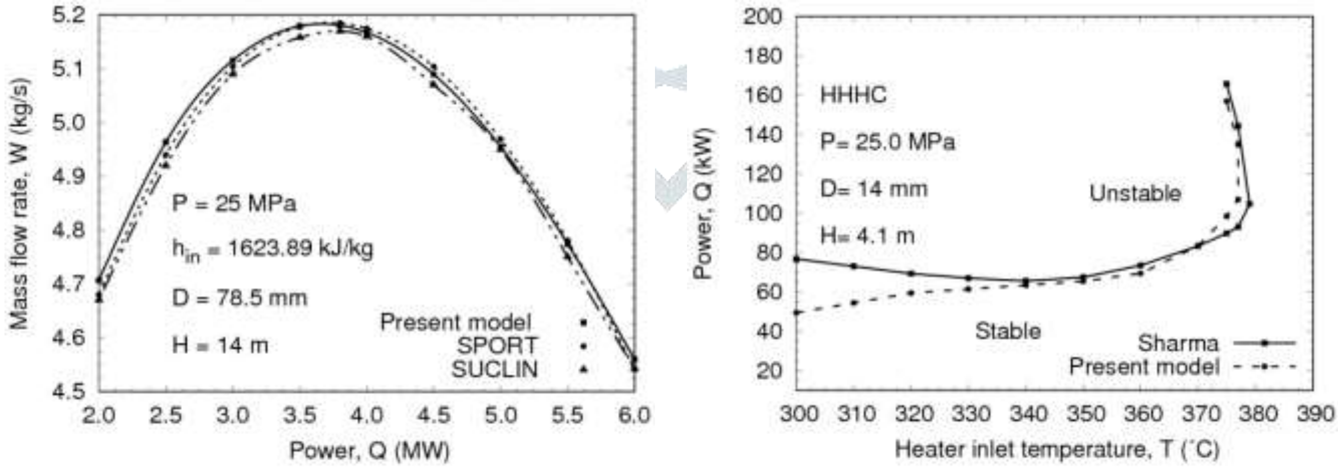
(a) (b)

Fig. 2. (a) Steady-state solution procedure (b) Transient solution procedure.



(a) (b)

Fig. 3. Experimental validation of SCW in supercritical pressure NCL for HHHC orientation: (a) steady state mass flow rate; (b) heater inlet and outlet temperatures (Pilkhwal et al., 2013).



(a) (b)

Fig. 4. Code to code validation of NCL (a) Steady-state validation with supercritical water (Chatoorgoon, 2001), (b) Nonlinear validation of SCWNCL (Sharma et al., 2010b).

3.1 Steady-state solution methodology

The conservation Eqs. (1-3), are discretized by a finite difference method (FDM), after disregarding the variation of variables with respect to time. The discretized equations of steady-state are as follows:

$$\rho_{i+1}A_{i+1}u_{i+1} = \rho_i A_i u_i \quad (5)$$

$$P_i - P_{i+1} = \frac{1}{2}\left(\frac{1}{A_i} + \frac{1}{A_{i+1}}\right)\left[(\rho A u^2)_{i+1} - (\rho A u^2)_i\right]$$

$$+\frac{1}{2}[\{\rho(F+g)\}_i+\{\rho(F+g)\}_{i+1}](x_{i+1}-x_i) \quad (6)$$

$$\left(e_f\right)_{i+1}+\left(e_f\right)_i=\frac{1}{2}\left[\left(\frac{q_w'' P_h}{\rho A u}\right)_i+\left(\frac{q_w'' P_h}{\rho A u}\right)_{i+1}\right](x_{i+1}-x_i) \quad (7)$$

The shooting plus bracketing method (Dutta and Doshi, 2008) is employed throughout the axial domain to solve the discretized Eqs. (5-7) considering the loop is subjected to fixed inlet pressure, inlet specific enthalpy, and exit pressure as boundary conditions. The steady-state solution procedure is stated in Fig. 2(a).

3.2 Transient solution methodology

For the development of the transient TH solver, the governing Eqs. (1-3) are first transformed into the following primitive form:

$$\frac{\partial}{\partial t}[\underline{\mathrm{U}}]+\underline{\mathrm{A}}(\underline{\mathrm{U}})\frac{\partial}{\partial x}[\underline{\mathrm{U}}]=[\underline{\mathrm{D}}(\underline{\mathrm{U}})] \quad (8)$$

Where $\underline{\mathrm{U}}$ is a vector of unknown dependent TH variables $[W,h,p]^T$, and coefficient matrix $\underline{\mathrm{A}}$ and source vector $\underline{\mathrm{D}}$ are functions of $\underline{\mathrm{U}}$. Because of the determination of the eigenvalues of the coefficient matrix $\underline{\mathrm{A}}$ are real $(u, u+a, u-a)$ where u is the flow velocity and a is the acoustic speed obtained to be a finite value using the definition $a \equiv \sqrt{\left.\frac{\partial p}{\partial \rho}\right|_s}$, the set of partial differential equations (PDEs) of Eq. (8) are classified as hyperbolic in nature and thus, accounts for the compressible flow dynamics of SCW (Dutta et al., 2015). The set of PDEs of Equation (8) are further transformed into the following characteristic form:

$$\underline{\mathbf{B}}\frac{\partial}{\partial t}[\underline{\mathrm{U}}]+\underline{\mathbf{\Lambda}}\ (\underline{\mathbf{B}})\frac{\partial}{\partial x}[\underline{\mathrm{U}}]=[\underline{\mathrm{C}}] \quad (9)$$

Where $\underline{\mathbf{\Lambda}}$ is a diagonal matrix of eigenvalues of $\underline{\mathrm{A}}$ and denotes the characteristics of the respective equations, i.e., $\frac{dx}{dt}=u+a$, $\frac{dx}{dt}=u, \frac{dx}{dt}=u-a$. In the present subsonic flow ($u<a$) situation, the nonlinear stability analysis includes an implicit finite difference methodology (FDM) using a fixed spatial and temporal grid distribution while discretizing the convective terms of equation (9) by backward or forward difference scheme depending on the eigenvalues of $\underline{\mathrm{A}}$. The steady-state solution is considered as initial conditions for the transient solution and simulations are carried out considering the time-invariant inlet pressure and inlet specific enthalpy, and exit pressure as boundary conditions and therefore, ensuring the constant pressure drop condition during the transients across NCL SCW (Dutta et al., 2015). The finally obtain discretized equations are then utilized for the complete domain with the help of given boundary conditions, afterward, the discretized equations are iteratively solved with the updated coefficient matrix and source vector for the same new time level until the convergence is achieved as illustrated in flow chart of transient solution methodology in Fig. 2(b) (Raghuvanshi et al., 2019).

IV. Experimental and Numerical Validation

The stability of NCL is systematically investigated by the effect of various parameters. We have considered the various feasible operating range for parametric studies. It is difficult to obtain a comprehensive view of all the parameters, hence we consider a set of fixed parametric values to understand their effect on the stability. The present model is validated the experimental results available for supercritical water in SPNCL for HHHC orientation at steady-state operating conditions, as shown in Fig. 3 (Pilkhwal et al., 2013, Sharma et al., 2014). Firstly, the steady-state mass flow rate is validated as mentioned in Fig. 3(a) and then heater inlet and outlet temperatures are validated as shown in Fig. 3(b) with the available geometrical and operating conditions (Pilkhwal et al., 2013, Sharma et al., 2014). Thereafter, the numerical study follows the steady state and linear stability analysis. The steady state mass flow rate of the loop at different powers are obtained by keeping inlet pressure as 25 MPa and heater inlet temperature as 350 °C for the available Chatoorgoon's loop geometry (Chatoorgoon, 2001). The steady-state results of the present model are validated first with the Chatoorgoon's (2001) non-linear code (SPORTS) and then Sharma's (2010a) linear stability code (SUCLIN) as shown in Fig. 4(a). The mass flow rate initially increases with power and attains a maximum value at 3.8 MW similarly by SPORTS code, and 3.75 MW by SUCLIN code. The comparison shows a similar nature and thus, validates the steady-state results of present TH model. Afterward, the nonlinear stability analysis is performed for SCWNCL with horizontal heater and horizontal cooler (HHHC) orientation, 25 MPa pressure, 14mm diameter, and 4.1m loop height. Here, for different heater inlet temperatures corresponding marginal stable power is identified with rigorous simulation work. All the marginal stable points are joined to form the marginal stability map. Hence, the nonlinear analysis of SCWNCL is validated with the stability map generated by Sharma's (2010b) nonlinear stability analysis code (NOLSTA), as shown in Fig. 4(b).

V. Results and Discussions

5.1 Steady-state analysis

The steady-state analysis has been extensively used for analyzing the effect of loop diameter, height, heater inlet temperature, pressure, power and various orientations of heater and cooler. The steady-state characteristic curve has been plotted for various loop pressure, as shown in Fig. 5(a). The curve shows that initially as power increases the flow rate rapidly increases because of the increase in driving force, so this region is called as driving force dominant region. Afterwards, the flow rate decreases because of the increase in frictional pressure drop, so this region is named as friction dominant region. The curve indicates that while increasing loop pressure, in friction dominant region, the mass flow rate increases as power increases. The steady-state curve indicates that as the loop diameter increases the flow rate also increases with power, as shown in Fig. 5(b). The flow rate rapidly increases with power in driving force dominant region, and power corresponds to the peak flow rate also increases as the loop diameter increases.

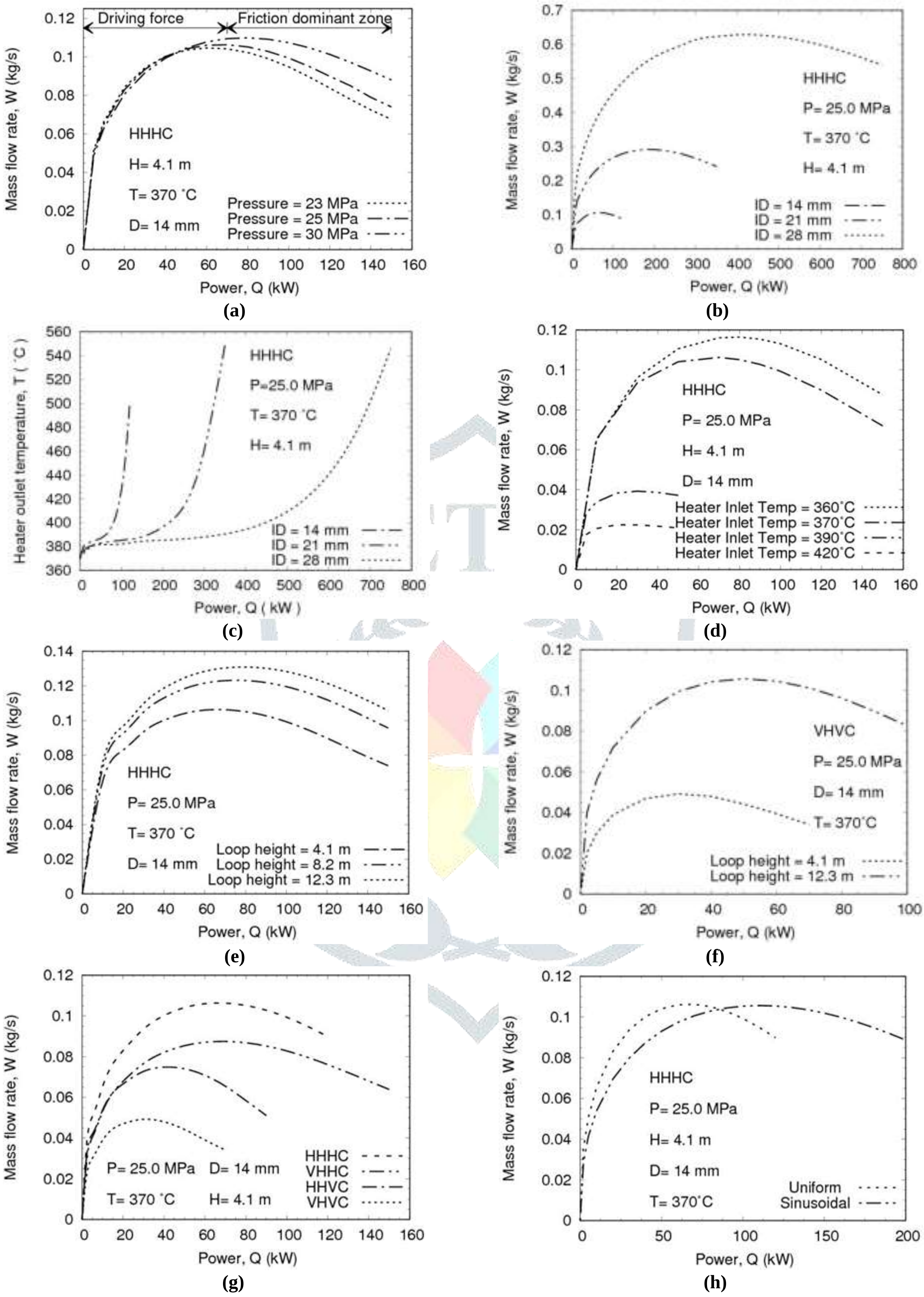


Fig. 5. Steady-state operating conditions with the effect of (a) loop pressure; (b) loop diameter; (c) loop diameter with heater outlet temperature; (d) heater inlet temperature; (e) loop height with HHHC orientation; (f) loop height with VHVC orientation; (g) orientation of heater and cooler; (h) power profile.

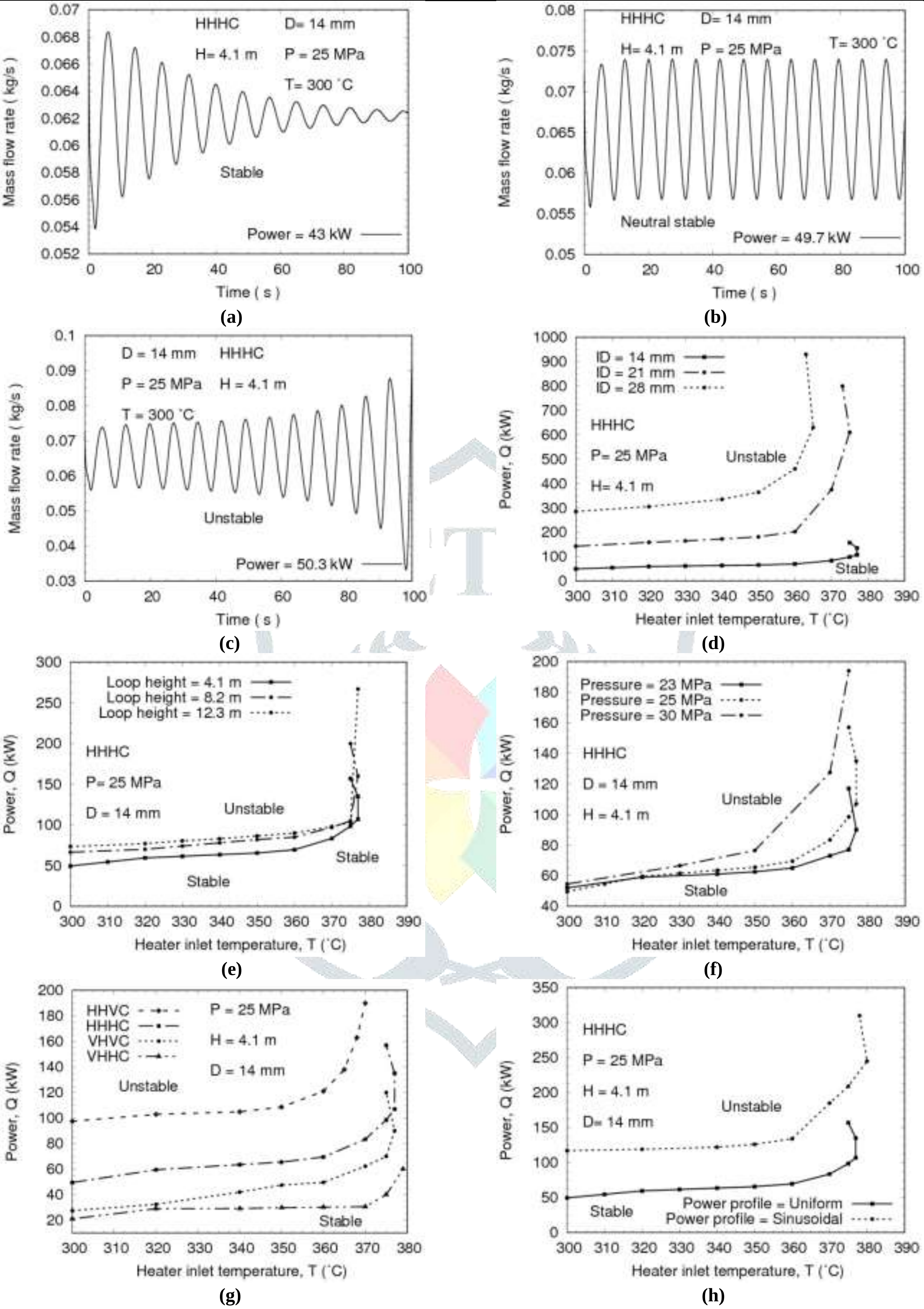


Fig. 6. Nonlinear stability analysis of SCW with (a) Stable operating point, (b) Marginal stable operating point, (c) Unstable operating point, (d) Effect of loop diameter, (e) Effect of loop height, (f) Effect of operating pressure (g) Effect of orientation of heater and cooler, (h) Effect of power profile

The heater outlet temperature increases slightly due to large increment in flow rate, but after the peak of mass flow rate, heater outlet temperature increases rapidly in friction dominant region as shown in Fig. 5(c). The steady-state mass flow rate decreases drastically as the heater inlet temperature increases above the pseudo-critical temperature. The peak of the mass flow rate and the power corresponds to peak flow decreases significantly, as mentioned in Fig. 5(d). The loop height of SCWNCL increases the driving head, as the height increases the peak of mass flow rate also increases. After that, the increment in mass flow rate is not significant due to the frictional and gravitational effect. With the HHHC orientation for 4.1m loop height, the peak of flow rate increases more than the VHVC orientation as shown in Fig. 5 (f). The steady-state characteristics have been predicted for the various heater and cooler orientation. The steady-state curve indicates that the orientation of heater and cooler from HHHC to VHVC drastically decreases the flow rate as well as power corresponding to peak flow, as shown in Fig. 5(g). The VHVC orientation has the lowest flow rate as compared to other orientation. The sinusoidal power variation shifts the power corresponding to the peak flow as plotted in Fig. 5(h).

3.2 Nonlinear stability analysis

The nonlinear stability analysis for the NCL is performed after considering steady-state BCs as an initial condition. The conservation equations of mass, momentum and energy equations are solved to determine the transient behavior of the NCL. The system behavior is recognized by the oscillation amplitude of the mass flow rate. At the selected operating point, the nonlinear stability analysis of the NCL shows the conditions as stable, marginal stable or unstable. When the amplitude of the oscillation decreases with respect to the time it is stable; growing with time then it is unstable; and when it is constant with time, then we recognize it as marginal stable. After identifying the system behavior, all the marginal stability points are joined to get the system's marginal stability boundary. It is observed that for an operating pressure 25 MPa and inlet temperature 300°C; as the power increases inside the heater section, the oscillation amplitude of mass flow rate gradually decreases with respect to time, and makes the system stable at power 43 kW as shown in Fig. 6(a). Whereas at power 49.7 kW, constant amplitudes of oscillations are observed, hence the system is said to be marginally stable as mentioned in Fig. 6(b). Similarly, at power 50.3 kW, the amplitude of oscillations gradually increases with respect to time; hence the system becomes unstable, as shown in Fig. 6(c).

The nonlinear effect of varying loop diameter from 14 mm to 28 mm is shown in Fig. 7d; as the diameter increases, it reduces the loop's pressure loss. Consequently, the driving head increases, which increases the stable zone and shifts the marginal stability boundary upward. When the diameter of the loop increases from 14mm to 21mm, then the marginal stability boundary points increases approximately three times of the previous value as mentioned in Fig. 6(d). Similarly, when diameter increases from 21mm to 28mm, then the marginal stability points are roughly doubled, as shown in Fig. 6(d). The next parametric study is about the loop height, as the loop height increases from 4.1m to 12.3m, the driving head, and flow rate increases, therefore the stable zone increases, and the marginal stability boundary shifts upward, as mentioned in Fig. 6(e). When the loop height increases from 4.1m to 8.2m, then the marginal stability boundary increases by approximately 25% - 40% from the previous value. Similarly, when the height increases from 8.2m to 12.3m, then it increases by 10% - 18% from the former value, as illustrated in Fig. 6(e). The effect of operating pressure on the marginal stability boundary of NCL is shown in Fig. 6(f). The marginal stability boundary slightly shifts upward when the loop operating pressure increases from 23 MPa to 30 MPa. Consequently, a slight increase in both the stable zone and a lower threshold of instability. The pressure has a significant influence on the marginal stability boundary near the pseudo-critical temperature, as illustrated in Fig. 6(f). When the loop operating pressure increases from 23 MPa to 25 MPa, then the marginal stability boundary increases by approximately 6% - 10% from the previous value. Similarly, when pressure increases from 25 MPa to 30 MPa, then the marginal stability boundary increases by 15% - 25% as illustrated in Fig. 6(f). The orientation of the heater and cooler significantly affect the marginal stability boundary of NCL. The density difference between the hot and cold fluid, and the distance between the heater and cooler section, directly influences the driving head and flow rate inside the loop. Therefore the stable zone, unstable zone, and marginal stability boundary shifts accordingly when orientation changes, as mentioned in Fig. 6(g). The sinusoidal power profile greatly influences the marginal stability boundary, as shown in Fig. 6(h). It causes the stability boundary shifted upward, and increases the stable zone.

VI. CONCLUSIONS

A mathematical model is developed to incorporate the effects of steady-state and nonlinear stability analysis of TH model for the NCL. The nonlinear stability analysis has been analyzed with various parametric studies for supercritical water in the environment of NCL. As per the results obtained, the following conclusions are drawn:

- The variation in loop diameter, loop height, heater and cooler orientations (HHHC, HHVC, VHHC and VHVC) significantly affects the mass flow rate at the steady state conditions. As the diameter increases, the friction losses decreases which, in turn, increases the mass flow rate significantly. The increase in loop height also increases the driving head, and consequently, there is significant increase in steady-state mass flow rate.
- The increment in heater inlet temperature (360°C - 420°C) beyond the pseudo-critical point (385°C), drastically reduces the steady state mass flow rate (0.118 kg/s – 0.02 kg/s) of NCL.
- The orientation of heater and cooler significantly affects the steady-state mass flow rate. The horizontal heater and cooler orientation has higher mass flow rate compared to that in vertical orientation.
- The increase in loop operating pressure (23 MPa – 30 MPa) increases the flow rate at higher power in friction dominant region due to an increase in pseudo-critical temperature.
- The nonlinear stability analysis identifies the stable and unstable zones for the analysis of NCL. The various parametric studies recognizes the feasible operating zones for different conditions.
- The loop diameter, orientation of heater and cooler, and power profile significantly affect the marginal stability boundary. As the diameter increases the stable operating zone increases and the lower threshold of instability decreases.
- The loop height and operating pressure slightly affect the marginal stability boundary, however the operating pressure affects significantly near the pseudocritical temperature.

The nonlinear stability analysis may help in improving the design of NCL in future. A key challenge for the future, is to develop a nonlinear model for the stability analysis of coupled SCWNCL.

VII. ACKNOWLEDGEMENT

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NOMENCLATURE

A	: Cross sectional area $(m2)$	g	: Acceleration due to gravity $(m/s2)$
D	: Loop diameter (m)	e	: Total specific internal energy (J/kg)
e_f	: Total specific flow energy (J/kg)	f	: Friction factor.
h	: Specific enthalpy (J/kgK)	W	: Mass flow rate (kg/s)
K	: Loss coefficient.	p	: Pressure $(N/m2)$
H	: Vertical height (m)	q''_w	: Heat flux per unit area $(kW/m2)$
e	: Specific internal energy (J/kgK)	v	: Specific volume $(m3/kg)$
P_w	: Wetted perimeter (m)	L	: Length of the section (m)
u	: Velocity vector field (m/s)		

Greek letters

δ	: Dirac-delta operator
ρ	: Density of the fluid
τ_w	: Wall shear stress

REFERENCES

[1] Ambrosini, W. and Sharabi, M. 2008. Dimensionless parameters in stability analysis of heated channels with fluids at supercritical pressures. Nuclear Engineering and Design, 238: 1917-1929.

[2] Basu, D. N. and Bhattacharyya, S. and Das, P. K. 2014. A review of modern advances in analyses and applications of single-phase natural circulation loop in nuclear thermal hydraulics. Nuclear Engineering and Design, 280: 326-348.

[3] Bhambare, K. S. and Mitra, S. K. and Gaitonde, U. N. 2007. Modeling of a Coal-Fired Natural Circulation Boiler, Journal of Energy Resources Technology, 129: 159-167.

[4] Chatoorgoon, V. 2001. Stability of supercritical fluid flow in a single-channel natural-convection loop. International Journal of Heat and Mass Transfer, 44: 1963-1972.

[5] Dutta, G. and Doshi, J. B. 2008. A charactristics-based implicit finite-difference scheme for the analysis of instability in water cooled reactors, Nuclear Engineering and Technology, 40(6): 477-488.

[6] Dutta, G. and Maitri, M. and Zhang, C. and Jiang, J. 2015. Numerical model to predict steady and unsteady thermal-hydraulic behavior of supercritical water flow in circular tubes, Nuclear Engineering and Design, 280: 155-165.

[7] Gomez, T. O. and Class, A. and Lahey Jr., R.T. and Schulenberg, T. 2008. Stability analysis of a uniformly heated channel with supercritical water, Nuclear Engineering and Design, 238: 1930-1939.

[8] Jain, P. K. and Rizwan-uddin. 2008. Numerical analysis of super-critical flow instabilities in a natural circulation loop, Nuclear Engineering and Design, 238(8): 1947-1957.

[9] Jain, R. and Corradini, M. L. 2016. A linear stability analysis for Natural-circulation loops under supercritical conditions. Nuclear Technology, 155:312-323.

[10] Pilkhwal, D. S. and Sharma, M. and Jana, S. S. and Vijayan, P. K. 2013. Experiments in a natural circulation loop with supercritical water at low powers. BARC External Report No BARC/2013/E/013.

[11] Raghuvanshi, N. S. and Dutta, G. and Panda M. K. 2019. Stability analysis of natural circulation based CANDU supercritical water reactor. Proceedings of the 25th National and 3rd International ISHMT-ASTFE Heat and Mass Transfer Conference (IHMTC-2019), 989-994.

[12] Sarkar, M. K. S. and Tilak, A. K. and Basu, D. N. 2014. A state-of-the-art review of recent advances in supercritical natural circulation loops for nuclear applications. Annals of Nuclear Energy, 73: 250-263.

[13] Sharma, M. and Vijayan, P. K. and Pilkhwal, D. S. and Saha, D. and Sinha, R. K. 2010a. Steady state and linear stability analysis of a super-critical water natural circulation loop, Nuclear Engineering and Design, 240: 588-597.

[14] Sharma, M. and Vijayan, P. K. and Pilkhwal, D. S. and Saha, D. and Sinha, R. K. 2010b. Linear and nonlinear stability analysis of a super-critical natural circulation loop, Journal of Engineering for Gas Turbines and Power, 132: 102904-1-9.

[15] Sharma, M. and Vijayan, P. K. and Pilkhwal, D. S. and Saha, D. and Sinha, R. K. 2013. Steady state and stability characteristics of natural circulation loops operating with carbon dioxide at supercritical pressures for open and closed loop boundary conditions, Nuclear Engineering and Design, 265: 737-754.

[16] Sharma, M. and Vijayan, P. K. and Pilkhwal, D. S. and Asako, Y. 2014. Natural convective flow and heat transfer studies for super-critical water in a rectangular circulation loop, Nuclear Engineering and Design, 273: 304-320.

[17] Sudheer, S. V. S. and Kumar, K. K. and Balasubramanian, K. 2018. Two-phase natural circulation loop behaviour at atmospheric and sub-atmospheric conditions. Proc IMechE, Part E: J Process Mechanical Engineering, 233: 687-700.

[18] Upadhyay, R. and Rai, S. K. and Dutta, G. 2018. Numerical Analysis of Density Wave Instability and Heat Transfer Deterioration in a Supercritical Water Reactor. Journal of Mechanical Sciences and Technology, 32(3): 1063-1070.

[19] Upadhyay, R. and Raghuvanshi, N. S. and Dutta, G. 2020. Numerical Analysis of Density Wave Instability and Heat Transfer Deterioration in a Supercritical Water Reactor. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42(3): 1-18.

[20] Van Bragt, D. D. B. and Van der Hagen, T. H. J. J. 1998. Stability of Natural Circulation Boiling Water Reactors: Part I-Description Stability Model and Theoretical Analysis in Terms of Dimensionless Groups. Nuclear Technology, 121: 40-51.