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Research Paper

Dynamic characterization of a single phase square natural circulation loop

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HIGHLIGHTS

- Phase plot, FFT, correlation dimension, LLE are used to conform flow dynamics.
- Phase plots shows limit cycle in the oscillatory regime.
- Phase plot shows Lorenz like strange attractor in the flow reversal regime.
- For oscillatory region correlation dimension is 1 and LLE is negative.
- For flow reversal region correlation dimension is fractional and LLE is positive.

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ABSTRACT

Natural circulation loop (NCL) has many applications in the energy sector as a passive heat transfer system. The passive nature of its operation increases the reliability of natural circulation loops and makes them crucial for the safety of the system. However, depending on the operating conditions, the dynamics of the system can vary significantly. For this reason proper analysis of the fluid flow dynamics in the NCL is very important. In this paper instability associated with the loop fluid flow in the NCL is investigated from a dynamical systems perspective with the help of phase plot, Fast Fourier Transform (FFT), correlation dimension and largest Lyapunov exponent. From the numerical analyses it is found that with the increase in heater power, dynamics of the fluid flow in the loop changes significantly. Loop characteristics remain steady up to a certain heater power level but with the increase in heater power level first it shows periodic oscillations and then it shows chaotic behavior. The existence of periodic and chaotic regimes is established using tools of dynamic systems analysis.

1. Introduction

To deal with the continuous increase of energy demand there is an urgent need to make equipment more energy efficient. For the miniaturization of size in the sector of electronics, communication and computer technology designers need to design compact heat transfer equipment. There is an increased trend towards use of passive cooling systems due to higher reliability of such systems. In view of these, natural circulation loop (NCL) has a huge application in the sector of thermal engineering. The working principle of NCL is to transfer heat from the hot zone (source) to the cold zone (sink) through a closed pipe with the help of natural convection process. Due to the temperature difference between the source and the sink, the buoyancy force is created and the fluid flow is established by the action of buoyancy force and frictional force. In addition to higher reliability, passive systems are relatively noise-free. For these reasons NCLs are being used in various industrial applications like nuclear primary and emergency core cooling systems, solar water heater, geothermal processes, gas turbine blade cooling and cooling of electrical machine rotor to transfer heat from one place to another or to cool down the system [1]. Compact heat transfer equipment operating in passive noise-free mode for thermal management of microelectronic systems also involves NCLs.

As NCL is applied in various fields, it has motivated researchers to investigate the system experimentally and numerically for past several years [2–10]. Spontaneous dynamics of the system plays a very crucial role in the performance of the system, especially, for a passive system like NCL. Low hydrodynamic head makes NCLs inherently less stable leading to instabilities in the flow dynamics. These instabilities may lead to failure of the system. This calls for

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Nomenclature

A	area of cross section (m^2)	h_o	heat transfer coefficient between wall & ambient ($W/m^2{\cdot}K$)
A_{in}	internal cross section area of loop (m^2)	h_{ex}	heat transfer coefficient between wall & coolant ($W/m^2{\cdot}K$)
A_0	external cross section area of loop (m^2)	k_f	thermal conductivity of fluid (W/m·K)
C_p	specific heat of fluid at constant pressure (J/kg·K)	k_w	thermal conductivity of wall (W/m·K)
C_{pw}	specific heat of wall at constant pressure (J/kg·K)	k_{ex}	thermal conductivity of heat exchanger (W/m·K)
C_{pex}	specific heat of coolant at constant pressure (J/kg·K)	L_{loop}	total loop length (m)
d_{in}	internal loop diameter (m)	L_H	loop height (m)
dz	change in length (m)	N_G	length to diameter ratio (L_{loop}/D)
f	friction factor	Re_d	Reynolds number
Gr	Grashof number	$\dot{Q}$	volumetric heat generation (W/m^3)
Gr_m	modified Grashof number ($(D^3\rho_f^2\beta_{av}gL_H\dot{Q})/(A\mu_f^3C_p)$)	v_f	fluid velocity (m/s)
Gz	Graetz number	V_w	wall volume (m^3)
Nu	Nusselt number	V_{ex}	heat exchanger fluid volume (m^3)
Pr	Prandtl number	β_{av}	thermal volumetric expansion coefficient (K^{-1})
t	time (s)	μ_f	dynamic viscosity of fluid (kg/m·s)
T_f	temperature of fluid (°C)	υ	kinematic viscosity of fluid (m^2/s)
T_w	loop wall temperature (°C)	ρ_f	fluid density (kg/m^3)
T_{ex}	coolant temperature (°C)	ρ_w	density of wall (kg/m^3)
T_{ref}	reference temperature (°C)	ρ_{ex}	coolant density (kg/m^3)
T_a	ambient temperature (°C)		
Ra	Rayleigh number		
h_i	heat transfer coefficient between fluid & wall ($W/m^2{\cdot}K$)		

accurate characterization of the instabilities associated with the flow dynamics of NCLs. Proper identification and characterization of these instabilities are prerequisites for control of instabilities and stable operation of these systems. As the system is highly nonlinear in nature, common characterization tools like Fast Fourier Transform (FFT) cannot fully characterize the systems. On the other hand, nonlinear dynamic systems show certain general characteristic features irrespective of the physical nature of the system. Thus dynamical systems approach has proved to be useful for dynamic characterization of complex systems. This approach has been successfully applied to various engineering systems like combustion systems [11,12], condition monitoring of gear boxes [13] and vibration fault diagnosis of roller bearings [14].

Single phase natural circulation loops have been used in many engineering systems owing to their lower susceptibility to instabilities compared to their two-phase counterparts. Consequently, a significant volume of literature exists on dynamics and control of single phase natural circulation loops [15–24]. Nayak et al. [7] showed that the instability associated with the operation of single phase NCL significantly reduced with the use of Al_2O_3 nano-fluids. By two dimensional numerical analysis, dynamical behavior of fluid flow for a rectangular NCL due to the change in Rayleigh number was performed by Desrayaud et al. [15]. The flow dynamics for the annular thermosyphon was investigated experimentally and numerically by Desrayaud et al. [16]. They found that flow dynamics changes from steady flow to Lorenz-like chaotic flow through periodic motion. Fichera et al. [17–19] carried out experimental and numerical study and find that flow dynamics of the NCL is changing with the change in heater power. But there is only qualitative observation no quantitative studies have been made. Mathematical simulation was done to identify the stable, unstable and neutrally stable points by Nyquist stability criterion for fluid flow by Nayak et al. [20]. Ridouane et al. [21] carried out numerical simulation of the fluid flow in the unstable convection regime for a natural convection loop. The flow reversal phenomenon was observed to grow with the increase in Rayleigh number. Steady state and linear stability analysis for super critical water natural circulation loop using computer code SUCLIN was carried out by Sharma et al. [22]. Vijayan et al. [23] carried out different experiments and numerical simulation by computer code ATHLET to observe that instability grows with the increase in diameter and the flow dynamics changes with the increase in power level. Vijayan et al. [24] studied nature of flow dynamics and stable regime both experimentally and numerically. Experimentally three different flow oscillations were found but numerically only two different flow oscillations were observed. They also observed that the flow dynamics shows a conditionally stable region near the stability threshold.

In spite of the large volume of work on stability and dynamics of NCL, very few works have been reported, which systematically characterize the system dynamics using quantitative tools of nonlinear dynamics. Zhang et al. [25] analysed the time series data using tools of nonlinear dynamics but they considered only periodic regime and not the flow reversal regime.

In the present study, numerical simulations have been carried out for different power levels with the help of Simulink model which was developed earlier by our group [26,27]. The dynamic analysis of loop fluid flow behavior has been carried out to quantify the transition of dynamic states from steady state to chaos through periodic oscillation. For this we use phase plot, Fast Fourier Transform (FFT), correlation dimension and largest Lyapunov exponents as non-linear dynamic analysis tools [11,28–35]. A major motivation for such analysis is to distinguish possibly chaotic systems, which are deterministic in nature from those dominated by noise, which are stochastic in nature. Visual appearance of time series data and FFT cannot make this distinction. Confirmation of deterministic nature has important implications for control of the loop dynamics as different control strategies are required for chaotic and stochastic systems.

Several tools have been suggested for studying stability of stochastic and chaotic nonlinear systems. One of the early works in studying stability of stochastic discreet systems is by Morozan [36]. While Yang and Miminis [37] derived some sufficient conditions for local asymptotic stability and instability for discrete nonlinear deterministic and stochastic systems. Lin and Cai [38]