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Research Article

Nonlinear Analysis of Onset of Nucleate Boiling in Natural Circulation under Different Pressure Conditions

Cheng Sheng, Tao Zhou, Lei Zhang and Zhongyun Ju
Institute of Nuclear Thermal-Hydraulic Safety and Standardization, North China Electric Power University, Beijing 102206, China

Abstract: In this study, we obtain the flow signals before and after the ONB through natural circulation experiments under pressure conditions of 0.15MPa and 0.3MPa. Researches were conducted by applying nonlinear analysis techniques. Results revealed that the power spectrum of volume flow data declined exponentially over time in semi logarithmic coordinates, the autocorrelation coefficient declined gradually and the phase diagram exerted the subtle structures of chaotic movement, which might prove the existence of chaos in natural circulation system. The natural convection of single phase appeared before the occurrence of ONB belonged to a non equilibrium process which showed remarkable random features. The occurrence of ONB was a process containing the beginning of chaotic motion and the continuing occurrence of bubbles at ONB and the tendency of phase change to become nucleation boiling would achieve certain states, which embodied the characteristics of chaos. In addition, the intense density difference environment of natural circulation could accelerate the occurrences of both chaotic motion and ONB. While the density difference of heated liquid decreased with the increase of pressure, which could delay the occurrence of ONB.

Keywords: Chaos, natural circulation, nonlinear, onset of nucleate boiling

INTRODUCTION

As a passive operation mode, natural circulation has being gained increasing attentions especially after the occurrence of serious radioactive leakage accident in Fukushima nuclear power station in Japan (Swapnalee *et al.*, 2012; Nematollahi and Rezaiean, 2012). In natural circulation, the Onset of Nucleate Boiling (ONB) is a key transition point from natural convection of single phase to natural circulation of two phases, which has great influence on the subsequent flow and heat transfer characteristics (Tao *et al.*, 2010). There have been lots of investigations of ONB (Hapke *et al.*, 2000; Basu *et al.*, 2002), while most of which were focused on forced circulation. Through theoretical analysis and experimental researches, some investigators proposed many prediction models based on grasping the main influencing thermo technical factors. But most of the attentions which paid on these researches were macroscopic observation of experimental phenomenon and data fitting of correlations, which were lack of mechanism analysis that reflected the nature of the phenomenon. Due to the complexity of the nonlinear heat transfer process in phase transition, the nonlinear mathematical tools could be applied to study the research object. Based on the chaos theory, the method applied in researches about the nonlinear dynamic behaviors which seemed random in deterministic systems is called uncertainty analysis of chaos. Different from traditional mathematical models, this method is not in consideration of every variable's influence on the system, while a typical variable which can represent the long-term evolution of the system is selected as the study object. Thus the chaotic behavior can be discovered through the time sequence of a single variable. Some researchers had applied this method in chaotic analysis both qualitatively and quantitatively based on experimental signals such as pressure, heat transfer coefficient and mass flow, etc (Cammarata *et al.*, 2000; Cho *et al.*, 2001; Bofeng *et al.*, 1999, 2001). Through applying the theory of state space reconstruction, the time sequences of the variables which have the characteristics of chaos can be reconstructed in a nonlinear dynamic system with low orders and the evolution rule hidden in the chaos of the attractor can be discovered. Thus the existing data can be put in a describable structure. The flow of natural circulation is formed by density difference of working medium. From the flow static in the initial heating stage to the subsequent single-phase and two-phase natural convections, flow signal contains large quantities of information about heat flux, pressure difference and fluid temperature, thus can be used as the study object of nonlinear analysis (Kim *et al*., 1999).

Corresponding Author: Tao Zhou, Institute of International Education, North China Electric Power University, Beijing 102206, China

In this study, the nonlinear characteristics of ONB occurrence in natural circulation was studied through applying the uncertainty chaos analysis, which provided a new method in the study of time series and also offered a basic theory support for further researches of ONB in natural circulation.

EXPERIMENT DEVICE AND METHOD

Experimental loop and tset section: Figure 1 and 2 show the structures of experimental loop and test section respectively. The experimental loop includes test section, preheater, pressurizer and condenser, etc. The vertical up flow heating channel is 1000mm in length and has a cross-section of narrow rectangle which has a dimension of 40×2 mm, as can be seen in Fig. 2. The front of the vertical channel is a visualized quartz glass which has a visible area dimension of 1000×40 mm from the front view. Through the quartz glass, the whole flow field of the heating channel can be observed and recorded. The reverse side of the heating channel is a heated metallic where 20 thermocouples with separation distance of 5 cm are installed in the lateral of it from inlet to outlet of the channel. In the condenser, the working fluid flows in the tube side and the coolant water flows in the shell side. The flow of coolant water can be controlled through adjusting the low-pressure pump and value and then the cooling capacity of the loop could be kept in an expected range. The height and the wide of the experimental loop are 3.3 m and 2.0 m respectively. In this study, the experiments were carried out at atmospheric pressure, the power ranges of test section and preheated were 0-30 kW and 0-40 kW respectively and the heat efficiency of test section was about 60%.

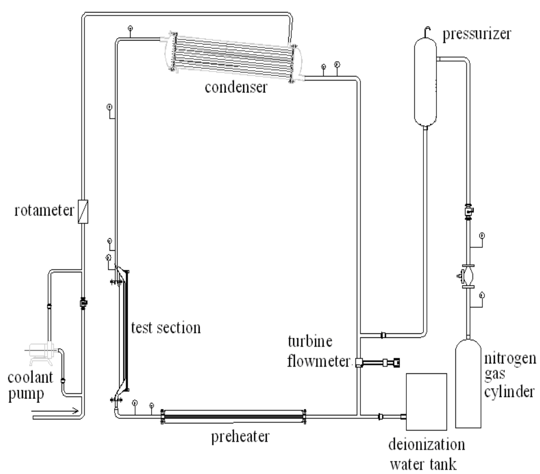


Fig. 1: Experimental loop of natural circulation

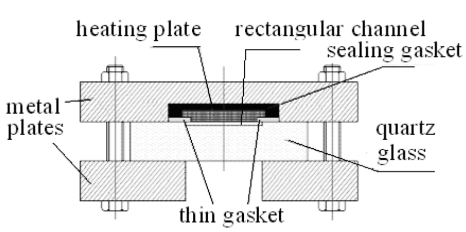


Fig. 2: Structure of test section

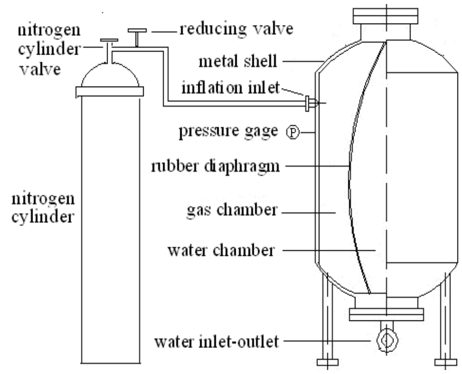
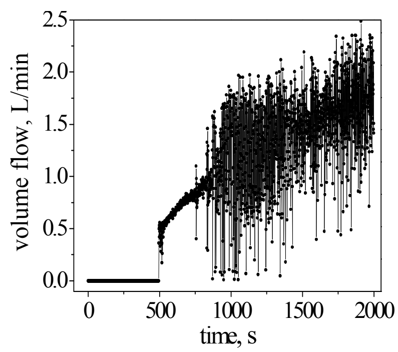
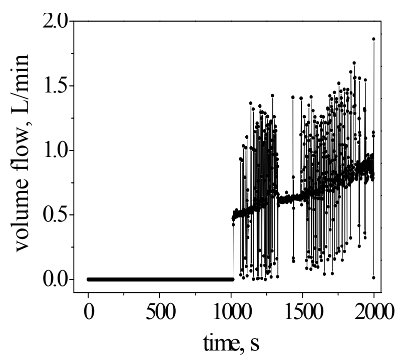


Fig. 3: Schematic diagram of pressurizer system



(a) 0.15MPa



(b) 0.3MPa

Fig. 4: Experimental data of volume flow

Pressurizer system: Figure 3 shows the structure diagram of pressurizer system. The pressurizer system consists of nitrogen cylinder, reducing valve and pressurizer, et al. High purity nitrogen which is up to 5MPa is stored in nitrogen cylinder. The outflow values and pressure in pressurizer of nitrogen were controlled through adjusting the nitrogen cylinder valve and reducing valve respectively. The pressurizer consists mainly of inflation inlet, pressure gage and rubber diaphragm. The interior of pressurizer is divided into 2 separate rooms called gas chamber and water chamber. The gas chamber could expand through being input high purity nitrogen. As a result, the neighboring water chamber would be squeezed and the pressure of which increased. Because the water chamber was connected with the experimental loop, the pressure of loop would also increase simultaneously.

Experimental method: Figure 4 shows the time series of volume flow acquired from the experimental study carried out at pressures of 0.15MPa and 0.3MPa.

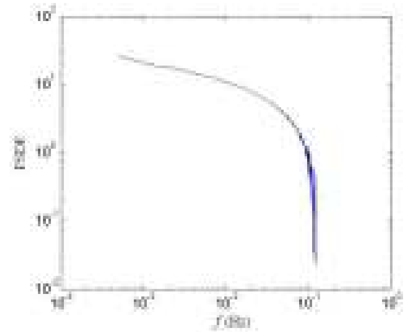
As can be seen in Fig. 4, the volume flow was kept zero and the natural circulation had not yet formed until heat flux was increased to a certain value and the flow fluctuated continuously. More heat would be needed to make phase change occur under higher pressure condition because as pressure increased, the saturated temperature of liquid would also increase accordingly. In addition, the driving force of natural circulation would decrease because the saturated density of liquid and density difference between liquid and steam decreased. Thus an obvious flow phenomenon occurred in a later time.

NOLINEAR ANALYSIS

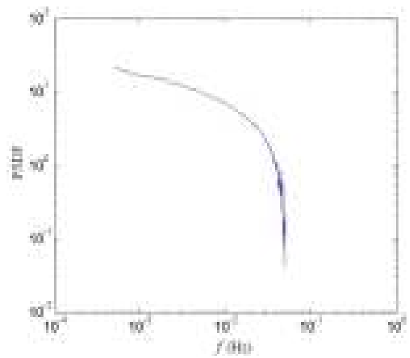
Analysis of power spectrum: Power spectrum is the analytical means to judge whether the dynamic system is chaotic or not. For random motion, the sequence signal of which may contain all possible frequencies. In semi-log coordinates, the chaos exerts an exponential declining trend. In this study, power spectrum was obtained through using Fast Fourier Transform method (FFT), the power spectrums under different pressures based on volume flow data in Fig. 4 are shown in Fig. 5.

As can be seen in Fig. 5, the power spectrum presents an exponential decline in semi log coordinate, which reflects the characteristics of chaotic motions. In addition, it can be discover in Fig. 5 that as the pressure increases, the values of power spectrum decrease in the whole range of frequency and the range of frequency broadband decreases either.

Analysis of autocorrelation: Autocorrelation coefficient represents the degrees of system's linear correlation and predictability between physical signals at the same measuring point in different instantaneous. The autocorrelation coefficient will present periodic changes in periodic motion and will change in a sudden way due to few relationships between physical signals at the same measuring point in random motions. The autocorrelation coefficient of chaotic motion will

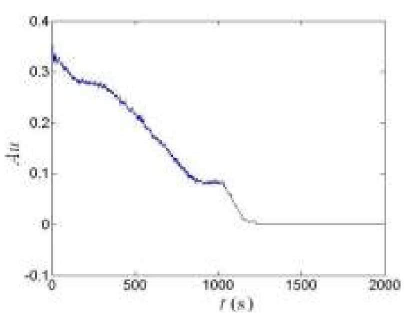


(a) 0.15MPa

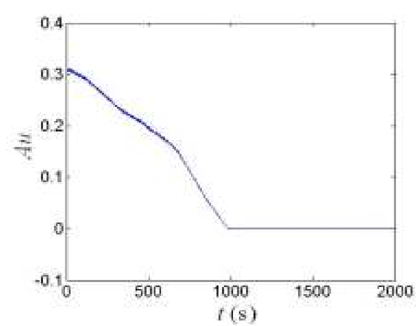


(b) 0.3MPa

Fig. 5: Power spectrum chart of volume flow in natural circulation



(a) 0.15MPa



(b) 0.3MPa

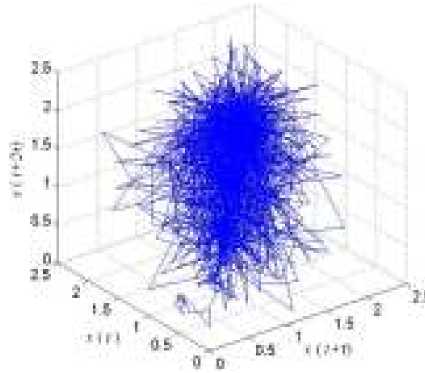
Fig. 6: Autocorrelation coefficient chart of pressure difference in natural circulation

decrease gradually, which is different from those of the 2 previous motions. In this study, the autocorrelation coefficients were acquired through the convolution theorem of Fourier transform. Figure 6 gives the autocorrelation coefficient chart acquired based on the volume flow data from natural circulation experiment.

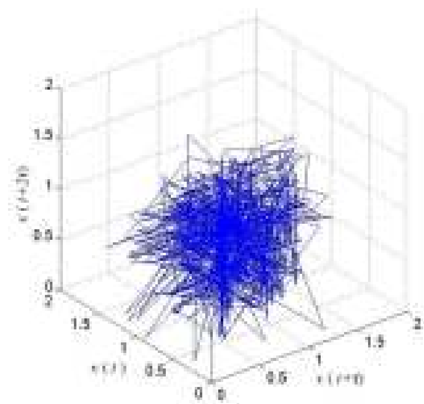
As can be seen in Fig. 6, the autocorrelation coefficients of volume flow reduce gradually over time, which reflects one of the characteristics of chaotic motion. The same point interconnects with itself at different time, while the linear correlation degree reduces as time goes on. In addition, it can be discover that as pressure increases, the value of flow autocorrelation will become zero earlier, which means the linear correlation degree decreases more quickly as time goes on under higher pressure condition.

Analysis of phase diagram: The ultimate evolution states of the dynamic system are called attractors, which were verged to by all unsteady flow trajectories from any bounded sets. Strange attractor is another important characteristic in chaos phenomenon of dissipative system. Chaotic motion contains ordered movements and represents a phenomenon of being stable overall but unstable partially, which embodies one of the main distinctions from uncontrollable random motions. The reconstruction method of state space of delay coordinates (Aihong *et al*., 2005) has been applied widely at present. Taken proved an optimal embedding dimension could be found. If the dimension of delay coordinates satisfies the relationship of $m \geq 2D+1$ (D is the correlation dimension of dynamic system), the regular trajectories (attractors) could be recovered in this embedded space. Figure 7 gives the phase diagram of attractor acquired based on the volume flow data in Fig. 4.

The attractor phase diagram is a regular band in periodic motions and presents a disorderly and unsystematic structure in random motions, while those of the chaotic motions have certain geometrical structures. The process of phase transition may not be the simple periodic motion or the irregular random motion either, but perhaps the composition of them. As can be seen in Fig. 7, the attractor of volume flow before and after the occurrence of ONB is composed of several ring lines. Each ring line represents an independent frequency. The greater the ring line is, the higher the pulse amplitude is. In addition, the attractor has a trend of concentrating into a limit stable ring or point and reveals a structure of tending to be stable as a whole while partially extraordinary unstable. Thus the attractor of volume flow in Fig. 7 is in fact a strange one in a way, which indicates that the generating process of ONB in natural circulation is a dissipation process. In addition, it can also discovered that as the increase of pressure, the number of attractors of larger ring lines decreases, while the smaller ring lines become dominant, which reveals that the bubble volumes will become smaller and will be more difficult to occur under higher pressure condition and the bubbles with large volume will more easily to crack into many small bubbles. The analysis above indicates that more heat flux is needed to make ONB occur under higher pressure condition and the nucleate boiling will happen later.



(a) 0.15MPa



(b) 0.3MPa

Fig. 7: Phase diagram of attractor of volume flow in natural circulation

DEVELOPING MECHANISM OF ONB IN NATURAL CIRCULATION BASED ON CHAOS THEORY

Initial stage of fluid heating: In the closed loop of natural circulation, the increase of superheat forms a temperature gradient both perpendicular to the heating wall and between the fluids in up flow and down flow channels, then the natural convection forms along the two directions consequently. During this period the kind of heat transfer is single- phase convection. Chai and Peng (Lihe and Xiaofeng, 1998) found that although the systems which were in the state of convection could present some phenomenon of random fluctuations, they would recover to the previous state in a short period and would also show a stable development tendency. This period was unbalanced and linear and was contained in system's evolution process. Combined with the results obtained by chaos theory, the values of autocorrelation coefficient were relatively high at the beginning of time series but decreased continually, as shown in Fig. 6, which indicated that the natural convection was a non equilibrium process with linear relationship decreasing gradually. As the single-phase natural convection formed, there had been coolant liquid flowing through the heating surface continuously and the density of coolant changed after accepting the heat power, which maintained the existences of driving force caused by density difference and natural convection in the loop. The above process presented the characteristic of periodic motion. For the channels which are of non-circular cross section, the secondary flow movement may occur (Yajun *et al*., 2009), which will affect the states of flow and heat transfer to a great extent by changing the velocity distribution on the cross section and shear stress distribution along the wall. In addition, thermal roundabout flow (Zengyuan, 1992) which occurs in heating channel may also alter the flow state. The influences of these unfixed conditions on the system evolution were approximately be deemed as the causes of random motion involvement in natural circulation systems. The fluctuation amplitudes of volume flow are high while the oscillation frequencies of which are relatively low during the initial stage of time series, as shown in Fig. 4. In Fig. 7, each circle line represents an independent frequency and the ones of longer sizes mean the amplitudes of which were higher than those of shorter sizes. The longer ring lines represent large scale and low frequency of the periodic composition, while the short ones represent the random composition with small scale and high frequency. In addition, the longer ring lines contain a large number of ones of small scale which represents the random composition. Thus from the analysis of the attractor phase diagram, the system evolution of single-phase natural convection and circulation were composed of periodic and random motions. Due to the high and slowly reduced autocorrelation coefficients, this stage could be called non equilibrium process with remarkable periodicity and strong random movement. In addition, the saturated density and density difference both decreased as the pressure increased, which led to the decrease of fluctuation amplitude of flow and the number of long ring lines which represented high amplitude in attractor phase diagram decreased.

Formation of ONB: Along with the increase of heat flux and as time went on, an overheating liquid layer would form on the heating surface. Nucleus of boiling always appears at the locations of cavities and cracks and the critical radius of bubbles could occur at these places under certain superheat conditions. Chai and Peng (Lihe and Xiaofeng 1998) indicated that $\Delta tsat$ was the only parameter which controlled the bifurcation characteristics and the transition from natural convection to nucleate boiling corresponded to the so called sub-critical bifurcation of the steam-liquid interface instability. In this study, ONB was the nucleus of boiling which firstly made this transition. If the random motion occurred due to some factors like geometry and second flow was ignored, the period could be deemed approximately as periodic motion. The occurring process of ONB has proved to be chaotic through calculating its power spectrum, autocorrelation coefficient, chaotic attractor and correlation dimension qualitatively and quantitatively, thus it was believed that the process from natural convection of single phase to the occurrence of ONB was an evolution from periodic motion to the start of chaotic motion and the sudden fluctuation of density caused by vapor generation was the reason for the appearance of chaos when interface instability happened. Otherwise, the natural circulation had an environment of strong density difference, which could also accelerate the occurrences of both bifurcation behavior and chaotic motion. In addition, the density difference between liquid and steam decreased as the increase of pressure, thus the occurrences of ONB and chaotic motion were relatively late.

Bubbles formation after ONB: As heat flux was increased, the wall superheat increased and the critical emerging radius of bubble became smaller, which led to more nucleus of boiling generating on the heating surface. In this stage, the autocorrelation coefficient of time series continued to decrease, which meant the degree of nonlinearity, was enhanced. Besides, the attractor of volume flow had a trend of converging to a limit cycle and the ring lines of small scale occupied most of the phase space, which indicated that the random motions had became dominant. The two aspects referred above indicated that the continuous occurrence of bubbles after ONB and the developing trend to the heat transfer mode of nucleate boiling were difficult to predict. However, the chaotic motion would reach a certain condition in the end, which embodied the dynamic integrations of certainties and uncertainties or orders and disorders. In addition, the decrease of long ring lines and the increase of short ring lines in flow attractor reflected that bubbles whose volumes would become smaller were more difficult to occur and the volume flow decreased due to the decrease of driving force, which displayed in attractor phase diagram.

CONCLUSION

Through applying nonlinear analysis of the volume flow data before and after ONB acquired from the experiments conducted in this study, some concluding remarks are obtained as follow:

- The occurrence of ONB in natural circulation had some of the chaos characteristics under the experimental conditions in this study. The existence of chaos was confirmed through calculating power spectrum, autocorrelation coefficient and attractors of volume flow data acquired under 0.15MPa and 0.3MPa conditions.
- The first period before the occurrence of ONB was a heating process with remarkable periodicity and strong random movements, the second period when ONB began occurring was believed a process from periodic motion to the start of chaotic phenomenon and the state of third period when bubbles appeared continuously and nucleate boiling started to develop were difficult to predict, but would reach a certain state in the end, which embodied the chaotic characteristics from an aspect.
- More heat flux was needed to make ONB occur and the bubble volume became smaller under higher pressure condition. Besides, density differences of both single-phase and two-phase decreased, which led to the decrease of natural circulation flows and fluctuation amplitude. In attractor phase diagram, the number of long ring lines which represented high fluctuation amplitude decrease as a result of the influences of these two factors above.

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REFERENCES

Aihong, Q., L. Mingyan and S. Yongli, 2005. Nonlinear characteristics in vapor-liquid-solid flow boiling. Huagong Xuebao., 56(5): 779-785.

Basu, N., G. Warrier, R. Dhir and K. Vijay, 2000. Onset of nucleate boiling and active nucleation site density during subcooled flow boiling. J. Heat Transf., 24(4): 717-728.

Bofeng, B., G. Liejing and Z. Liang, 1999. Identification of flow regimes in vertical upward steam-water 2-phase flow using differential pressure fluctuations. Huagong Xuebao., 50(6): 799-805.

Bofeng, B., G. Liejing and C. Xuejun, 2001. Effect of heat flux on fluctuating pressure in steam- water 2-phase flow. Hedongli Gongcheng., 22(1): 1-5.

Cammarata, G., A. Fichera and A. Pagano, 2000. Nonlinear analysis of a rectangular natural circulation loop. Int. Commun. Heat Mass Transf., 27(8): 1077-1089.

Cho, Y.J., S.J. Kim, S.H Nam, Y. Kang and S.D. Kim, 2001. Heat transfer and bubble properties in 3-phase circulation fluidized beds. Chem. Eng. Sci., 56: 6107-6115.

Hapke, I., H. Boye and J. Schmidt, 2000. Onset of nucleate boiling in minichannels. Int. J. Thermal Sci., 39: 505-513.

Kim, H.S., R. Eykholt and J.D. Salas, 1999. Nonlinear dynamics delay times and embedding windows. Physica D., 127: 48-60.

Lihe, C. and P. Xiaofeng, 1998. Nonlinear boiling heat transfer-Ⅰ: Theory of dissipative structure. Nat. Mag., 20(4): 243-244.

Lihe, C. and P. Xiaofeng, 1998. Nonlinear boiling heat transfer-Ⅱ: Theory of Bifurcation and mutation. Nature Magazine, 20(5): 305.

Nematollahi, M. and M. Rezaiean, 2012. Experimental evaluation of natural circulation pressure drop in a boiling channel. Fusion. Sci. Technol., 61(1): 174-177.

Swapnalee, B.T., P.K. Vijayan, M. Sharma and D.S. Pilkhwal, 2012. Steady state flow and static instability of supercritical natural circulation loops. Nucl. Eng. Des., 245: 99-112.

Tao, Z., Y. Ruichang, L. Zhenyang and Z. Ming, 2010. Onset of nucleate boiling in natural circulation systems predicted using the second stir theory. J. Tsinghua Univ. Sci. Technol., 15(4): 441-446.

Yajun, G., B. Qingcheng and H. Yongqing, 2009. Experimental investigation on secondary flow of air-water 2-phase flow in straight channel with square cross-section. Hsi An Chiao Tung Ta Hsueh., 43(7): 83-87.

Zengyuan, G., 1992. Thermal Fluid Theory. Tsinghua University Press, Beijing.