Issues associated with DWO in recent studies

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Abstract: Extensive studies have been carried out on instabilities, particularly Density Wave Oscillation (DWO). These studies investigated their negative effects on nuclear systems and found ways of minimizing them. The present work discussed the major types of DWO and their mode of occurrence. Recent experimental and analytical work done on DWO were also analysed together with the key issues and discoveries made in the various studies. Effects of system parameters on DWO require further study to determine mechanisms responsible for the various observations made. Also, more studies on DWO using RELAP5 code are needed to ascertain if the numerical diffusion employed in the code affects results of simulation.
Keyword: density wave oscillation; instabilities; stability map; RELAP5

1 Introduction

Extensive studies have been carried out on two-phase flow instabilities in which Density Wave Oscillation (DWO) is the most investigated. Various experiments and numerical analyses have been done on DWO, including experiments on helical tubes, straight tubes, single channel, multiple channels, vertical and horizontal tubes.

Though, few authors mentioned disturbances in single and multiple channels in the Fifties, not until the Sixties did systematic study of this instability began ([1]). Foremost work on DWO started with the work of Jeglic and Yang [2] and Stenning and Veziroglu [3] who studied Type II DWO using air/water system.

One of the most popular study of DWO is the work of Yadigaroglu and Bergles [4] who reported Type III DWO in interaction with Type II DWO. Also, Fukuda and Kobori [5] presented an interesting study of Type I and Type II DWO in forced and natural circulation, in which they showed that cross connections at the outlet of the system improved its stability. The authors also, using a frequency domain analysis, described five different modes of DWO [6]

The objective of the present work is to examine some issues encountered in the study of DWO in both experimental and analytical work. In section 2, we discuss the various types of DWO and their mode of occurrence. Experimental and analytical work done on DWO in recent years are discussed in sections 3 and 4, with discussions and conclusions in sections 5 and 6 respectively.

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2 Types of DWO

Instabilities are classified as static and dynamic. Static instabilities occur when there is a change of flow to a new level as a result of sudden change in amplitude. Dynamic instabilities are of many types but the most studied type is DWO. Occurrence of DWO is dependent on the delay in transportation of disturbance and also, the parameters of the system at the inlet. There are three types of DWO based on the mechanisms causing them: DWO due to gravity, DWO due to friction and DWO due to momentum. This classification is in line with the research of Boure and Mihaila [7] and the work of Fukuda and Kobori [6].

2.1 Type I DWO - DWO due to gravity

This instability is observed at low quality and low pressure. At these low parameters, a little disturbance causes a great change in the void fraction and the flow rate. Also, the hydrostatic head respond quickly to variations in the flow rate at low pressures. The interactions between all these give rise to the instability.

2.2 Type II DWO - DWO due to friction

DWO due to friction is the most studied type of DWO. It is observed at high power. Different propagation speeds of disturbances in single phase and two phase regions give rise to this instability. Pressure drop, resulting from variation of void fraction and flow rate in two phase region, moves slowly through the system and is out of phase with the pressure drop in the single phase region, giving rise to the instability.

2.3 Type III DWO - DWO due to momentum

This DWO is the least studied by researchers. It was first discovered by Yadigaroglu and Bergles [8] and the region where it occurred was termed "stability island" by Achard *et al.* [9]. It results from feedbacks between inertia, momentum, pressure drop terms and thermal hydraulic propagation delays.

3 Experimental work on DWO

Dorao [10] carried out an experiment to observe the effects of system parameters on the period of DWO. He observed that the period increased with an increase in both inlet pressure and temperature. Also, the flow regime distribution also caused changes in the period. He suggested that more work should be done to observe this effect at different conditions.

Sorum and Dorao [11] experimented on the effect of DWO on the heat transfer coefficient of a heated channel. They observed that the heat transfer coefficient worsened with the occurrence of DWO especially at low system parameters. This effect was observed to be minimal at high system parameters. They also observed that DWO initiated a premature CHF and suggested further work to study the mechanisms causing the effects observed.

O'Neil *et al.* [12] carried out an experiment in which they observed the effect of DWO on the behaviour of a boiling system. In the single phase region, disturbances observed resulted from the vibrations of mechanical parts of the system while in the two phase region, oscillations resulted from DWO. It was also observed that DWO had a great influence on the pressure, flow rate and the parameters of the system. The authors showed, through comparison, that stability maps developed by other authors could not represent the system adequately and then developed three stability maps for the system.

In Shi *et al.* [13], instabilities observed in a BWR-type modular reactor were examined. Instabilities were observed at low pressure and they were basically flashing and DWO. Flashing was observed after the single phase natural circulation while DWO was observed at the onset of the two phase natural circulation. DWO decreased with an increase in pressure. With no instability observed at higher pressure, it was concluded that instability can be removed with pressurized start up process.

Papini *et al.* [14] carried out an experiment to observe the behaviour of DWO in helical tubes. The main observation was pressure oscillated with a frequency twice that of the flow rate. A stability map developed from the experiment showed the stabilising effect of an increase in inlet subcooling and system pressure. As also observed in straight channels, increase in thermal power and decrease in mass flow rate produced DWO in the tube. Superposition of Ledinegg and DWO was observed at high pressure. A model, also developed by the authors, agreed well with the experimental results at high pressure. When the results were compared with RELAP5 code, an overestimation of the inception of DWO was observed, which was credited to extreme numerical diffusion used by the code. Figure 1 shows the results.

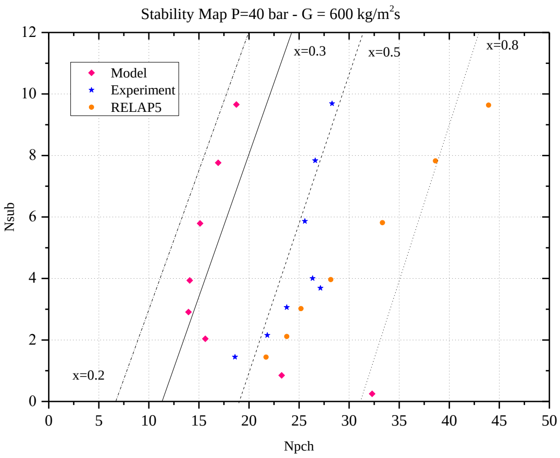

Fig.1: Stability map for DWO in helical tubes ([14]).

4 Numerical and analytical work on DWO

Paul and Singh [15] carried out an analysis of DWO in heated channel using Drift Flux Model (DFM). They employed simpler equations by using linear-linear approximations to reduce the number of equations.

They observed that a higher Froude number increased the stability of the system. Also, a high inlet loss coefficient and a low outlet loss coefficient both had a stabilising effect on the system. Furthermore, both void distribution parameter and drift flux velocity substantially affected the stability of the system. Figure 2 shows the stability map obtained using nondimensional numbers, Subcooling number (N_{sub}) and Phase change number (N_{pch})

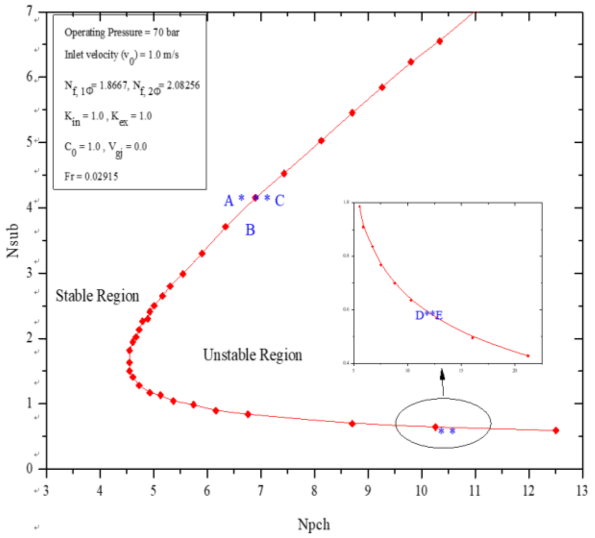

Fig.2 Stability map for DWO in heated tube([15]).

Vinai et al [16] carried out an analysis of self-sustained DWO by coupling three simulation codes, RELAP5, CASMO-4E and CORE SIM. This was particularly to overcome the difficulty encountered in analysing DWO which is, the radially extremely localised behaviour of this disturbance. Its effect on the neutron flux was also expected to be localized as well. Though the amplitude of the density fluctuations were maximum at the middle of the core, they observed that that of the induced neutron flux fluctuations was larger in the lower half of the core(at low void fraction). This discrepancy was attributed to the different macroscopic cross sections combined with the different weights which were axially dependent as well

Dutta et al [17] carry out an analysis of DWO in CANDU (CANada Deuterium Uranium) Supercritical Water Reactor using THRUST model. They observed that a rise in power enhanced the occurrence of DWO. Also a reduction in flow rate destabilised the system. The observations made were in agreement with observations made in FC BWR (Forced Circulation Boiling Water Reactor). However, at supercritical conditions, increase in pressure destabilized the system unlike what happened in a BWR.

Wang and Yang [18] undertook a study, using RELAP5,comparing the characteristics of DWO in different channels and discovered that 3x3 channel represented well the stability boundary of DWO. Figure 3 shows the stability boundaries of the different channels. The transit time, which is used to measure the decrease in CHF resulting from flow oscillations, was found to be different when calculated using various correlations, only one gave a result similar to RELAP5. The transit time increased with the subcooling number and decreased with an increase in pressure, and then became constant. Figure 4 shows the results of the various transit time calculated by different correlations.

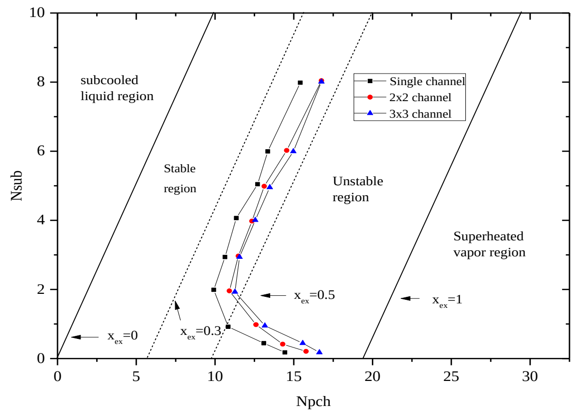

Fig.3 Diagram showing stability boundaries of different channels[18].

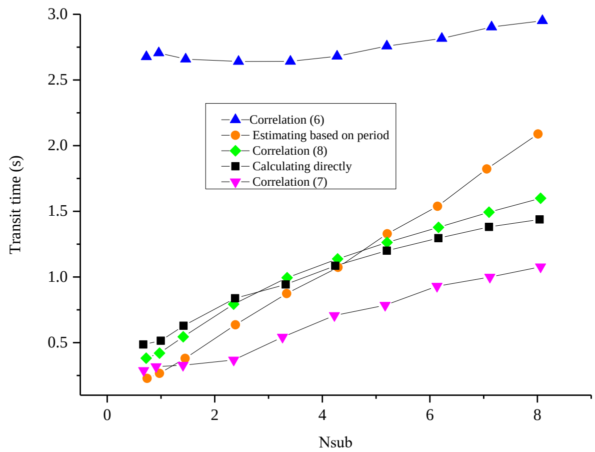

Fig.4 The transit time calculated by different correlations[18].

Dong *et al.* [19] analysed the characteristics of DWO in straight and helical tubes using both RELAP5 and frequency domain method. The observations made for both tubes were similar for the thermal hydraulic parameters of the systems. They concluded that helical tubes were better option because of their good heat transfer characteristics. Unlike what was obtained by Papini *et al.*[14], the RELAP5 code gave results that were in conformity with experimental results for helical tubes especially at low mass flux. Figure 5 shows the results for both experiment and RELAP5 code.

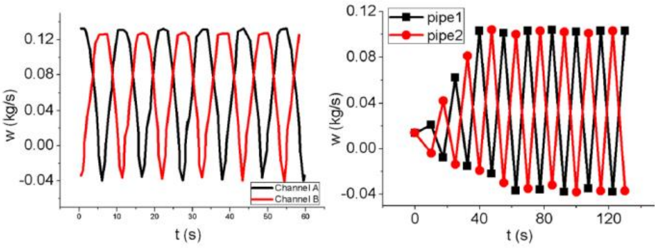

Fig.5: Results for helical tubes: (i) experiment (LHS) (ii) RELAP5 code (RHS).

Xia *et al.* [20] studied flow instability in a multi channel system using RELAP5 code. It was observed that a little disturbance produced flow redistribution among the channel when the system was in the negative slope region of the channel pressure drop versus flow rate curve. The rapid increase in flow rate led to the incidence of Type 1 and Type II DWO. Figure 6 shows the stability boundary for parallel channels obtained in the analysis.

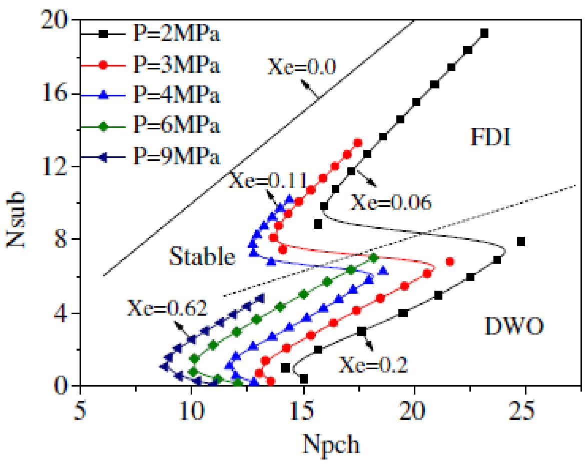

Fig.6: Stability boundary of parallel channel at different pressures ([20]).

Qian *et al.* [21] developed a model to study DWO in parallel channels. The results obtained were compared with results from other authors and they observed that the model was consistent with experiments and also performed better than other theoretical models. The system stability was enhanced with a rise in pressure and with the introduction of inlet throttling.

5 Discussion

From the work of Dorao [10], aside changes caused by pressure and temperature on the period of DWO, flow regime distribution also caused a variation in the period. However, more work needed to be done to observe this effect at different conditions.

Sorum and Dorao [11] observed that DWO caused the heat transfer coefficient of heated channels to deteriorate, though this effect was minimal at high system parameters. The mechanism responsible for this needed to be studied further.

According to the work of O'Neil *et al.* [12], DWO had minimal effect on the single phase region of a boiling system while oscillations in the two phase region were caused basically by DWO and this can be removed by pressurized start up procedure ([13]).

Papini *et al.* [14] attributed the overestimation of the onset of DWO by RELAP5 in their experiment to extreme numerical diffusion used by the code. However, Dong *et al.* [19] in their work observed that RELAP5 predicted results that conformed with experimental result for the occurrence of DWO. More studies on DWO using RELAP5 will further clarify if the numerical diffusion employed in the code affects results obtained in simulation.

Additional analytical studies are as well needed to study the processes and variables determining the occurrence of the Type III DWO. Most work done on DWO have majorly been on Type I and Type II DWO.

6 Conclusion

Most work done on DWO need further study to ascertain the mechanisms responsible for the various observations made. The results from the experiments show system parameters having various effects on DWO, which do not give a consistent pattern, thereby requiring further work. Also, more studies on DWO using RELAP5 code are needed to ascertain if the numerical diffusion employed in the code affects results of simulation.

References

[1] KAKAC, S., and BON, B.: A Review of two-phase flow dynamic instabilities in tube boiling systems, Int. J. Heat Mass Tranfer, 2007, 51:399–433.

[2] JEGLIC, F., and YANG, K.: The incipience of flow oscillations in force-flow subcooled boiling, Tech. Rep. N66-15248, Heat transfer and Fluid Mechanics Institute University of California, 1965.

[3] STENNING, A., and VEZIROGLU, T.: Oscillations in two-phase component two-phase flow, Tech. Rep. CR-72121, NASA Lewis Research Center Cleveland, Ohio, 1967.

[4] YADIGAROGLU, G., and BERGLES, A.: An experimental and theoretical study of density-wave phenomena oscillations in two-phase flow, Tech. Rep., Department of Mechanical Engineering Massachusetts Institute of Technology Imbridge, Massachusetts, 1969.

[5] FUKUDA, K., and KOBORI, T.: Two-phase flow instability in parallel channels, Proc. 6th Int. Heat Transfer Conf. FB-17, 1978, 369–374.

[6] FUKUDA, K., and KOBORI, T.: Classification of two-phase flow instability by density wave oscillation model, J. Nucl. Technol., 1979, 16:95–108.

[7] BOURÉ, J., and MIHAILA, A.: The oscillatory behaviour of heated channels, EUROATOM, Symposium of two-phase flow dynamics, Eindhoven, 1967, 695–720.

[8] YADIGAROGLU, G., and BERGLES, A.: An experimental and theoretical study of density-wave phenomena oscillations in two-phase flow, Tech. Rep. Department of Mechanical Engineering Massachusetts Institute of Technology Imbridge, Massachusetts, 1969.

[9] ACHARD, J., DREW, D., and LAHEY, R.: The analysis of nonlinear density-wave oscillations in boiling channels, Journal of Fluid Mechanics, 1985, 155:213–232.

[10] CARLOS, A.D.: Effect of inlet pressure and temperature on density wave oscillations in a horizontal channel, Chemical Engineering Science, 2015, 134:767–773.

[11] MIKKEL, S., and CARLOS, A.D.: Experimental study of the heat transfer coefficient deterioration during Density Wave Oscillations, Chemical Engineering Science, 2015, 132:178–185.

[12] LUCAS, E.O., ISSAM, M., MOHAMMAD, M.H., HENRY, K.N., BALASUBRAMANIAM, R., NANCY, R.H., AUBREY, L., and JEFFERY, R.M.: Experimental investigation into the impact of density wave oscillations on flow boiling system dynamic behavior and stability, International Journal of Heat and Mass Transfer, 2018, 120:144-166.

[13] SHI, S.B., JOSHUA, P.S., CALEB, S.B., LIN, Y.C., JAEHYUK, E., LIU, Z., ZHU, Q.Z., LIU, Y., TAKASHI H., and MAMORU I.: Experimental investigation of natural circulation instability in a BWR-type small modular reactor, Progress in Nuclear Energy, 2015, 85:96-107.

[14] DAVIDE, P., MARCO, C., ANTONIO, C., and MARCO, E.R.: Experimental and theoretical studies on density wave instabilities in helically coiled tube, International Journal of Heat and Mass Transfer, 2014, 68:343-356.

[15] SUBHANKER, P., and SUNEET, S.: A density variant drift flux model for density wave oscillations, International Journal of Heat and Mass Transfer, 2014, 69:151–163.

[16] PAOLO, V., CHRISTOPHE, D., and VICTOR, D.: Modelling of a self-sustained density wave oscillation and its neutronic response in a three-dimensional heterogeneous system, Annals of Nuclear Energy, 2014, 67:41–48.

[17] GOUTAM, D., ZHANG, C., and JIN, J.: Analysis of flow induced density wave oscillations in the CANDU supercritical water reactor, Nuclear Engineering and Design, 2015, 286:150–162.

[18] WANG, S.P., and YANG, B.W.: Numerical Investigation on Thermal Hydraulic and Transit time Characteristics of Density Wave Oscillations, Energy Procedia, 2017, 127:291–301.

[19] DONG, R.T., NIU, F.L., ZHOU, Y., YU, Y., and Guo Z.P.: Modeling analyses of two-phase flow instabilities for straight and helical tubes in nuclear power plants, Nuclear Engineering and Design, 2016, 307:205–217.

[20] XIA, G.L., SU, G.H., and PENG, M.J.: Analysis of flow distribution instability in parallel thin rectangular multi-channel system, Nuclear Engineering and Design, 2016, 305:604–611.

[21] QIAN, L.B., DING, S.H., and QIU, S.Z.: Research on two-phase flow instability in parallel rectangular channels, Annals of Nuclear Energy, 2014, 65:47–59.