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Frequency analysis of chugging condensation in pressure suppression pool system with pattern recognition

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Abstract

Direct contact condensation (DCC) phenomena in boiling water reactor (BWR) pressure suppression pool systems need to be understood to properly assess the performance of the pool as a heat sink and as a safety critical structure. Condensation oscillations in the form of chugging are challenging to predict by computational fluid dynamics (CFD) methods but safety relevant because of associated high dynamic loads on in-pool structures and the pool itself. Recently, new measurement methods for CFD validation purposes have become available. One of these techniques is visual observation using the high-speed cameras and suitable data processing method. Pattern recognition is a well suited technique for the determination of large oscillating bubble dynamics in a pressure suppression pool.

In this work, the formation and collapse of the steam bubbles in chugging condensation mode are evaluated by using the pattern recognition algorithm. The pattern recognition algorithm is based on video material recorded during the direct contact condensation experiment DCC-05 of the PPOOLEX test

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facility. The formation speed, the shape and size of the steam bubbles and the acceleration of collapsing bubbles are estimated with the algorithm. Fast Fourier transform (FFT) is used for frequency analysis of the pattern recognized data. The frequencies found are compared to the frequency data of the pressure transducers collected during the experiment and to the previous results of the NEPTUNE_CFD simulations of the same experiment.

The frequency analysis shows that the chugging frequencies of the steam bubbles range from 1 to 3 Hz, as predicted. Also the natural frequencies of the bubbles are visible around 53 Hz. Another frequency spike was observed close to the 125 Hz. This frequency is close to the mechanical resonance frequencies of the suppression pool and the blowdown pipe. Because of neither the pressure suppression pool nor the blowdown pipe are visible to the pattern recognition, the spike of the higher frequencies is most likely from the interfacial area of the bubble which resonates with the suppression pool system, affecting rapid condensation at a certain point.

Keywords: Two-phase flow, suppression pool, Chugging, Pattern recognition, FFT

Nomenclature

Variables		Abbreviations	
A	surface area	BWR	boiling water reactor
d	diameter	CFD	computational fluid dynamics
f	frequency	DCC	direct contact condensation
f_0	natural frequency of oscillating bubble	FFT	Fast Fourier Transform
P_0	steady state pressure	LOCA	loss of coolant accident
p_1, p_5	pressure transducers p_1 and p_5	LUT	Lappeenranta University of Technology
r	radius	PACTEL	parallel channel test loop
R_0	steady state radius of the bubble	(P)POOLEX	condensation pool experiments
t	time		
V	volume		
$ Y(f) $	dimensionless absolute value of amplitude		
γ	ratio of the specific heat of the water		
ρ_w	density of the water		

1. Introduction

The small size of the BWR containment bring on the possibility that a large amount of steam should be rapidly condensed into the suppression pool during the loss of coolant accident (LOCA). Injected steam causes structural loads to the suppression pool and demands a lot of its strength. One main cause of these structural loads are the pressure oscillations and chugging of condensed steam, which have been studied through the decades. Test facilities small (Aya et al., 1980; Aya and Kobayashi, 1983; Aya and Nariai, 1987; Simpson and Chan, 1982; Gregu et al., 2017) and large size (Utamura et al., 1984; Kukita et al., 1984, 1987; Pellegrini et al., 2016) have been used to study these condensation modes. DCC is present in all of the modes, which emphasizes the need to validate and develop condensation models being able to capture interfacial condensation rate correctly with the CFD software.

Already, even in the old experiments, movie cameras were used for visual observation, but the observation results were hardly published. At first, the data analysis concentrated for pressure data analysis, but the arrival of the CFD made possible to model the physical behavior of the condensation more accurately than with simplified analytical models (Lahey and Moody, 1993; Lahey, 2005). Different condensation modes have been modeled by using CFD (Patel et al., 2017; Mimouni et al., 2011). As the modeling of two-phase flows using CFD has challenges (Bestion, 2014), a new measurement methods for CFD model validation purposes has been put into operation. Lately, the high-speed cameras have been started to use to record the experiments in more thorough manner (Issa et al., 2014; Tanskanen, 2012) to make data analysis more feasible. The measured data is used to evaluate different features diameter, velocity, position of the condensing bubbles (Issa et al., 2014). At Lappeenranta University of Technology (LUT) a preliminary pattern recognition algorithm was created for the use of former condensation pool test facility POOLEX (Tanskanen et al., 2014b). Later on, the pattern recognition and data analysis algorithm has been upgraded to evaluation of diameter, surface area, volume, velocity, acceleration and frequencies of the condensing steam bubbles (Hujala, 2013; Hujala et al., 2013, 2018).

This paper presents the frequency analysis of the recorded video data of direct contact condensation experiment DCC-05-4 of the PPOOLEX test facility using FFT on the volume data evaluated by using the upgraded pattern recognition and data analysis algorithm. The results are briefly compared to the NEPTUNE_CFD code simulations and the pressure transducer data. The source of some frequency spikes have also been tracked by applying hammer

tests to the PPOOLEX facility.

2. Experiments and Methods of Analysis

2.1. PPOOLEX Test Facility and DCC-05 Experiment

The PPOOLEX test facility is a scaled down test facility of Nordic type BWR containment. The schematic view of the PPOOLEX test facility is shown in Fig. 1.

Figure 1: Schematic view of the PPOOLEX test facility

The 31 m³ stainless steel pressurized vessel has the total height of 7.45 m and diameter of 2.4 m. It consists of two main parts, the dry well compartment and the wet well compartment separated by an intermediate floor, an inlet plenum and air/steam piping. A route for air/steam flow from the dry well to the wet well is created by a vertical blowdown pipe attached non-axisymmetrically underneath the floor. The different lengths and widths of the blowdown pipe can be used depending on the needs of the ongoing experiment. Steam needed in the experiments is produced by near PACTEL test facility, which has the core power of 1 MW. The more detailed description of the PPOOLEX test facility is presented in (Puustinen et al., 2013).

DCC-05 experiment was one part of the direct contact condensation test program. The main purpose of the DCC-05 was to obtain measurement data for the validation of the DCC models used in CFD, and to make a high-speed video recording to be used in the development work of the pattern recognition algorithm (Hujala, 2013; Hujala et al., 2018). The aim of the DCC-05 experiment was to keep the pool water temperature as constant as possible and change the steam flow rate in a wide range. The goal was achieved by adjusting the steam flow rate quickly to a new value for the recorded periods, but when the data was being transferred from the camera memory, the steam flow rate was reduced to almost zero to prevent unnecessary heat-up of the pool water. Regardless, the pool water at the blowdown pipe outlet rose about 10 K. DN100 blowdown pipe was used in the experiment. The more detailed description of the DCC-05 experiment is presented in (Tanskanen et al., 2014a).

DCC-05 experiment was recorded by using three high-speed cameras at

Figure 2: Simplified principle of the pattern recognition algorithm.

framerate of 300 frames per second. Places of two side cameras and the bottom camera are shown in Fig. 1. DCC-05 consists of six parts named DCC-05-1...DCC-05-6. DCC-05-4 part was chosen for closer investigation due to the best quality of the video material. 48 seconds of video material was recorded during that part. The video was cut in frames of the resolution of 768×768 pixels. MATLAB software was used to create the pattern recognition and data analysis algorithm, which recognizes the shapes of the steam bubbles pushed through the blowdown pipe and evaluates the volume and the surface area of each bubble using voxel-based method (Windreich et al., 2003) and smoothing. Algorithm also evaluates the diameter, growth and break up velocities and accelerations of the bubble. The simplified principle of the algorithm is presented in Fig. 2 and explained more accurately in (Hujala et al., 2018).

2.2. Frequency Analysis

Frequency analysis of the condensing steam bubbles is an interesting area, because that makes possible to connect bubble fluctuations to the other os-

cillating measured quantities. FFT have been used to evaluate different frequencies in the experiment. It works best when the amount of data is large and the recording period is long. FFT can be used for short periods too, but it should be recalled, that in those cases the dominating lowest frequencies are not reliable. FFT is also used to evaluate frequency modes of the PPOOLEX facility. Frequency modes of the facility were evaluated from the pressure transducer data of the hammer tests. In the hammer tests the PPOOLEX tank was hit by the hammer and pressure transducer and strain gauge data were recorded. The hammer test was carried out for the both, drained and filled conditions of the pool. In the filled conditions, the water level was the same as in the DCC-05 experiment. The results of the blow-down experiment were also compared to the frequencies obtained from CFD simulations.

Natural oscillation frequency of the condensing bubbles is one potential research area which may exploit the FFT. The natural frequency of the oscillating bubble f_0 can be expressed analytically (Brennen, 2014), as shown in Equation (1).

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{3\gamma P_0}{\rho_w R_0^2}}, \quad (1)$$

where $\gamma [-]$ is the ratio of the specific heat of the water, $P_0 [\text{Pa}]$ is the steady state pressure, $\rho_w \left[\frac{\text{kg}}{\text{m}^3}\right]$ is the density of the water and $R_0 [\text{m}]$ is the steady state radius of the steam bubble.

3. Results and Discussion

The pattern recognition and data analysis algorithm was used to evaluate the diameter d [cm], surface area A [cm²] and volume V [cm³] of the bubbles. The change of d , A and V during the DCC-05-4 test are presented in Fig. 3.

Figure 3: Estimated diameter d [cm], surface area A [cm²] and volume V [cm³] of the bubbles during the DCC-05-4 experiment.

The diameter d of the bubble is rarely a zero due to the evaluation method which calculates the number of nonzero elements in the figure. The diameter has been evaluated by looking for the row with the largest amount of nonzero elements, even if only a one row – the border of the bubble – of the bubble is visible. The surface area varies between zero to a bit over 2000 cm² and the volumes between zero and 4500 cm³. However, the calculation method based on the side profile of the bubbles underestimates the surface area and volume. Error estimation showed that the errors of the volume and surface

Figure 4: Distribution of the natural frequencies f_0 [Hz] of the bubbles evaluated using the recognized bubble diameters.

area remain under 10 %, when the diameter of the bubble is under 13 cm. For really small bubbles ($d < 4.0$ cm) errors may build up over 20 %, but otherwise lay between 10 to 20 %, (Hujala et al., 2018). However, the uncertainty caused by these systematic errors should remain small in this study, because the bubble size difference between successive frames is more important than the absolute size of a bubble.

Natural frequencies f_0 [Hz] were calculated by using the evaluated diameters of the bubbles using the Equation (1). Frequencies fluctuate between the 53 Hz to the 250 Hz, and the most common natural frequency is around 80 Hz. The distribution of the natural frequencies of the bubbles is presented as a histogram in Fig. 4. The natural frequency cannot be less than 44 Hz, as the natural frequency is lower for larger bubbles and the largest recognized diameter of the bubble in DCC-05-4 test was approximately 24 cm.

Figure 5: FFT of the volume data of DCC-05-4 test. $|Y(f)|$ is dimensionless absolute value of an amplitude and f [Hz] is the frequency. The most probable chugging frequencies 0.293 Hz, 0.897 Hz, 2.09 Hz and 3.31 Hz are marked at their places. (Hujala et al., 2018).

The FFT calculated from the volume data is presented in Fig. 5. The volume data shows only the changes on the bubble volume due to the pattern recognition method. As a part of non-intrusive measurement, the data of it is not contaminated by the oscillations of the pools structures or the blowdown pipe i.e. the obtained frequencies in FFT should be the characteristics of the bubbles. However, it is still possible, that the structures of the pool resonate at the same frequencies as the bubbles and strengthens the influence of the oscillations. In FFT, the lower frequencies under the 10 Hz are dominant and the most probable chugging frequencies were between the 0.29 Hz – 3.3 Hz as marked in Fig. 5. Two larger swells in higher frequencies are visible, one near to the 53 Hz and another near to the 125 Hz.

Theoretical natural frequencies of DCC-05-4 experiment at different radii

of the bubbles were calculated by using Equation (1). The highest spike near to the 53 Hz is 53.4 Hz in FFT (Fig. 5), which corresponds to the bubble radius of 10.9 cm. On the other hand, the biggest diameter of the bubble measured from the video data is 24.2 cm, which corresponds to the frequency of 48.1 Hz.

Calculated possible natural frequencies of the bubbles, the most common frequency in FFT of the volume data, and the biggest bubble in the DCC-05-4 video are all presented in Fig. 6. The biggest bubble of the video and the most common bubble size in FFT are so close to each other, that it can be said that the sizes of the bubbles are almost even, recalling the inaccuracies of the pattern recognition and interpretation of the FFT. Visual observation of the video material supports this result.

The change of the frequencies during the time t [s] can be seen by using a spectrogram. The spectrogram of the whole DCC-05-4 test is presented in Fig. 7. Lower frequencies are dominant through the experiment, but higher values can be seen near the 53 Hz and the 125 Hz through the experiment.

The 53 Hz and the 125 Hz frequencies are interesting. Those should not be the most probable natural frequencies of the bubbles, so those are assumed to be linked up to the condensation process. From volume data of Fig. 3, three alternating bubble volume cycles can be seen, types A, B and C. Type A bubble cycle is the simplest one. The bubble grows up in two parts, as a fluctuating part where the bubble builds up oscillating and the rapid growth part, where the fluctuating bubble grows up fast and condensates then completely very rapidly. The volumetric change of type A bubble is presented in Fig. 8A.

Figure 6: Calculated natural frequencies f_0 [Hz] of the bubbles at different radii r [m] are marked in white filled markers. The most common higher frequency in FFT is marked green filled marker and the biggest bubble diameter evaluated from the video material is marked in magenta filled marker

Figure 7: Spectrogram of the DCC-05-4 experiment.

Figure 8: A. The change of the volume V of type A bubble. B. FFT of the whole type A bubble volume data. $|Y(f)|$ is dimensionless absolute value of an amplitude and f [Hz] is the frequency. C. FFT of the first red part of the type A bubble volume data. D. FFT of the latter blue part of the type A bubble volume data. Images 1 to 3 represent different phases of the type A bubble.

Type B bubble cycle consists of multiple oscillating parts of which the final one grows up faster and breaks up rapidly. The volume in the preceding fluctuating parts does not fall to zero at any time. Type B bubble volume change is presented in Fig. 9A.

Type C bubble consists one or multiple fluctuating parts. The bubble oscillates, grows up, and breaks up with comparable rates without having a rapidly collapsing volume period. Type C bubble is presented in Fig. 10A. The images of the different phases of type A, B and C bubbles are presented in Fig. 8, Fig. 9, and Fig. 10.

Animations of the A, B and C type bubbles are available in the Supplementary Material of the online version of this article.

The FFT was calculated for all these three types of bubbles. The FFT of full parts of different types A, B and C are marked as black line and are presented in Fig. 8B, Fig. 9B and Fig. 10B. High, but unreliable low frequency part under the 10 Hz has been cut off to get better view to more reliable frequencies. All of the cases have clearly visible elevation around the 50 Hz. At type A, the 53 Hz spike is not as distinguishable as in type B or C, due to the extremely short time period, but the 53 Hz spike still exists. By contrast, the 125 Hz spike appears in type A and B bubbles, but not in type C bubble.

The volumetric change of each bubble type A, B and C have been divided two or more parts, to investigate how different frequencies split at different parts. Type A bubble were split in two parts. Red line in Fig. 8A, represents the fluctuating part of the bubble, when the bubble volume grew up from zero to over 1000 cm^3 oscillating slightly. The corresponding FFT of the red part

Figure 9: A. The change of the volume V of type B bubble. B. FFT of the whole type B bubble volume data. $|Y(f)|$ is dimensionless absolute value of an amplitude and f [Hz] is the frequency. C. FFT of the 1st green part of the type B bubble volume data. D. FFT of the 2nd yellow part of the type B bubble volume data. E. FFT of the 3rd orange part of the type B bubble volume data. F. FFT of the 4th red part of the type B bubble volume data. G. FFT of the 5th magenta part of the type B bubble volume data. H. FFT of the latter blue part of the type B bubble volume data. Images 1 to 5 represent different phases of the type B bubble.

Figure 10: A. The change of the volume V of type C bubble. B. FFT of the whole type C bubble volume data. $|Y(f)|$ is dimensionless absolute value of an amplitude and f [Hz] is the frequency. C. FFT of the first red part of the type C bubble volume data. D. FFT of the latter blue part of the type C bubble volume data. Images 1 to 3 represent different phases of the type C bubble.

is shown in Fig. 8C. The FFT shows clear spikes around 53 Hz and 125 Hz. Blue line in Fig. 8A represents the fast growth and rapid condensation part and the Fig. 8D shows the corresponding FFT. The latter part of the bubble consists of the 53 Hz and the 125 Hz spikes too, but also other spikes around those are clear.

Type B bubble in Fig. 9 was cut in six parts (green to blue). The first five parts are fluctuating parts and the last part is similar fast growth part with rapid condensation as in the type A bubble. The corresponding FFTs are presented in Fig. 9C...Fig. 9H. The first green part in Fig. 9C contains visible spike around 53 Hz, but no 125 Hz spike. The second part starts near to zero and grows up oscillating, causing a significant 53 Hz spike and a smaller, but visible 125 Hz spike. The third part starts from bigger volume than the second one, but oscillates similarly having 53 Hz spike. The 125 Hz spike is also present, but it does not come out from group of other high frequencies. The fourth part shows some change in the later phase of the cycle. Oscillating bubble grows up, but then loses its volume more rapidly than in previous parts. The corresponding FFT in Fig. 9F presents significant 53 Hz spike with multiple lower level high frequency spikes also poorly distinguishable 125 Hz with the same amplitude. The fifth (magenta) part of the bubble reminds type A bubble cycle. Bubble oscillates, grows up and oscillates more, then it rapidly increases its volume still fluctuating and finally decreases fast oscillating. The FFT of it shows multiple significant spikes around 53 Hz and once more clearly emerged 125 Hz frequency spike. The sixth and last (blue) part represents fast growth and rapid condensation of the bubble. The FFT shows slightly flatten out frequency spikes where

the 53 Hz spike is still significant and the 125 Hz visible, but more leveled out amongst other high frequencies.

Type C bubble in Fig. 10 consists of two very identical oscillating parts, red and blue. Both parts grow up oscillating and decreases their volumes oscillating. Between these two parts, the bubble disappears almost totally inside the blowdown pipe. Both parts FFTs are quite identical too. Both show dominating 53 Hz spikes with no other considerable frequencies.

These three different bubble types A, B and C have similar structures. Oscillating bubbles which grow up and diminish oscillating, as the green part in type B in Fig. 9 and type C bubbles in Fig. 10. These bubbles do not grow up larger than the diameter of the blowdown pipe is, neither change their sizes rapidly nor have the fast growth or rapid condensation parts. In type B bubble, the 53 Hz spike remains through the whole condensation process similarly as in type A bubble. The 125 Hz bubble arises when the oscillating bubble grows up. Similarly type A bubble consists of the 125 Hz frequency spike. The last part of type A and B bubbles are similar. The fast growth and rapid condensation part has both the 53 Hz spike and the 125 Hz spike, but both are already flatten out.

Pressure transducers were used to measure pressure changes in the pool. Transducer p_1 was inside the blowdown pipe near the outlet and the transducer p_5 in the water, 5 cm under the blowdown pipe outlet, relatively near to the surface of the blown bubbles. The FFT clip up to the 153 Hz calculated from the pressure transducer data is shown in Fig. 11.

Fig. 11 shows that both transducers have pressure changes at frequency of the 53 Hz and the 125 Hz. This confirms the FFT result of the pattern

Figure 11: FFT of the pressure transducers p_1 (yellow) and p_5 (magenta).

recognition data, and indicates that the 53 Hz and the 125 Hz spikes are most likely coming from the surface of the oscillating bubbles.

In the hammer tests, the suppression pool was hit by a hammer and frequencies were estimated from the pressure transducer p_6 data. The pressure transducer was placed at the bottom of the pool, where it stands also during the blowdown experiments. The FFT of the hammer tests are shown in Fig. 12.

In the empty pool, FFT shows a couple of sharp spikes: a high spike of 71.5 Hz and a lower one of 150.2 Hz. When the pool was filled with water up to the level 1.03 m above the pipe outlet, a lot more vibrations appeared. The largest downward widen spikes are around 125 Hz, 136 Hz and 151 Hz. Because in the blowdown experiments 125 Hz spike appears only with abruptly condensing type A and B bubbles but not with type C bubbles or as noise in video frames without bubble, it is highly possible that the vibrations of the

Figure 12: FFTs of the hammer tests. The PPOOLEX tank was hit twice with the hammer and the data was recorded using pressure transducers. The amplitudes are comparable. Notice the tenfold difference between the empty tank (left) and the water filled tank (right).

pool resonate with the surface vibrations of the bubbles and strengthens the condensation.

The FFT of the volume data was also compared to the simulation data of NEPTUNE_CFD Patel et al. (2017). The FFT example of the simulation data Patel et al. (2016) is presented in Fig. 13.

The 53 Hz spike is significant in successful CFD simulations too, and the most probable chugging frequencies varies at the same level as in the FFT of the volume data in Fig. 5. However, the 125 Hz spike and actually all frequencies over the 53 Hz are missing in the FFT. If the 125 Hz frequency is strengthened via resonance as it seems to be according to the hammer tests, it cannot be seen in the CFD simulation where the structures of the test facility are rigid. If the 125 Hz spike is the effect of the surface area of the bubble, increase of the grid resolution in the simulations might bring out the higher frequencies, so more research will still be needed.

Figure 13: FFT of the simulation of NEPTUNE_CFD. The data has significant 50 Hz frequency spike, without the 125 Hz spike. The most probable chugging frequencies 0.20 Hz, 0.60 Hz and 2.1 Hz are marked at their places.

4. Conclusions

Frequency analysis of DCC-05-4 experiment of PPOOLEX test facility was made by using upgraded pattern recognition and data analysis algorithm. The chugging frequencies evaluated from the volume data applying FFT were around 1 Hz to 3 Hz, which fitted well to the NEPTUNE_CFD simulation results and theoretical expectations Aya et al. (1980); Aya and Kobayashi (1983). Two different higher frequencies appeared in FFT, the 53 Hz and the 125 Hz. These frequencies turn up through the DCC-05-4 experiment.

The volume data was cut in parts and three different types of bubbles occurred, say, types A, B and C. Frequency analysis showed that the 53 Hz

frequency appeared in all types of bubbles, but the 125 Hz spike only in types A and B. It looks like the 125 Hz frequency most likely leads to the fast growth and rapid condensation of the bubble and it does not exist when the bubble grows up and breaks down calmly oscillating. The most probable explanation is that both frequencies are related to the surface area of the steam bubbles and the condensation process. Both spikes are visible in pressure transducer data, but the 125 Hz spike is missing in CFD simulations assuming rigid pool and piping structures. In 2D CFD simulations, the blowdown pipe was axisymmetrically at the center of the pool and non-condensable gases were not modeled. These might for ones part affect to the results. Hammer tests showed that the mechanical vibrations (flexing) of the containment structures may resonate with the bubble interface vibrations affecting rapid contact condensation. It is possible that fluid-structure interactions might lead to more effective or more stable condensation modes also in an actual BWR suppression pool. Because of this, the frequency analysis is an interesting subject, and more research need to be done.

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