Application of cross recurrence plot for identification of temperature fluctuations synchronization in parallel minichannels

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Abstract. The temperature fluctuations occurring in flow boiling in parallel minichannels with diameter of 1 mm have been experimentally investigated and analysed. The wall temperature was recorded at each minichannel outlet by thermocouple with 0.08 mm diameter probe. The time series where recorded during dynamic two-phase flow instabilities which are accompanied by chaotic temperature fluctuations. Time series were denoised using wavelet decomposition and were analysed using cross recurrence plots (CRP) which enables the study of two time series synchronization.

1. Introduction

Two-phase flow boiling instabilities are present in every heat exchanging system equipped in small diameter channels. Instabilities are associated with formation of different flow patterns. During instabilities various pressure drop and wall temperature oscillations were reported [1, 2]. Flow oscillations may cause undesirable effects such as mechanical vibrations, burn-out and thermal fatigue. In parallel minichannels also flow maldistribution phenomenon takes places [3]. Those effects reduce heat transfer effectiveness. This paper presents a method for the analysis of temperature oscillations in parallel minichannels system. The temperature fluctuations occurring during flow boiling in two parallel minichannels with diameter of 1 mm have been experimentally investigated and analysed. Each minichannel has an individual surge tank. The temperature time series were recorded at each minichannel outlet wall by thermocouple with 0.08 mm diameter probe. Time series were denoised using wavelet decomposition method and were analysed using cross recurrence plots (CRP) which enables the study of synchronization. Cross recurrence plot revealed the times when channels oscillated alternately and the times when one of the channels wasn't oscillating.

2. Experimental setup

Schematic diagram of the boiling system has been shown in figure 1. Working fluid (distilled water) was pushed out from a supply tank by the compressed air. Proportional pressure regulator (Metal Work Regtronic with the 1 kPa accuracy) was used to maintain the constant overpressure in supply tank - the overpressure was 30 kPa. The ball valve installed between the supply tank and flow meter

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(Bronkhorst Cori-Tech M13) was used to regulate the liquid flow rate. Water pushed out from the supply tank flowed to two surge tanks. Each surge tank was weighed. Surge tanks were connected with heated minichannels. figure. 2 shows the cross section A-A of heated block.

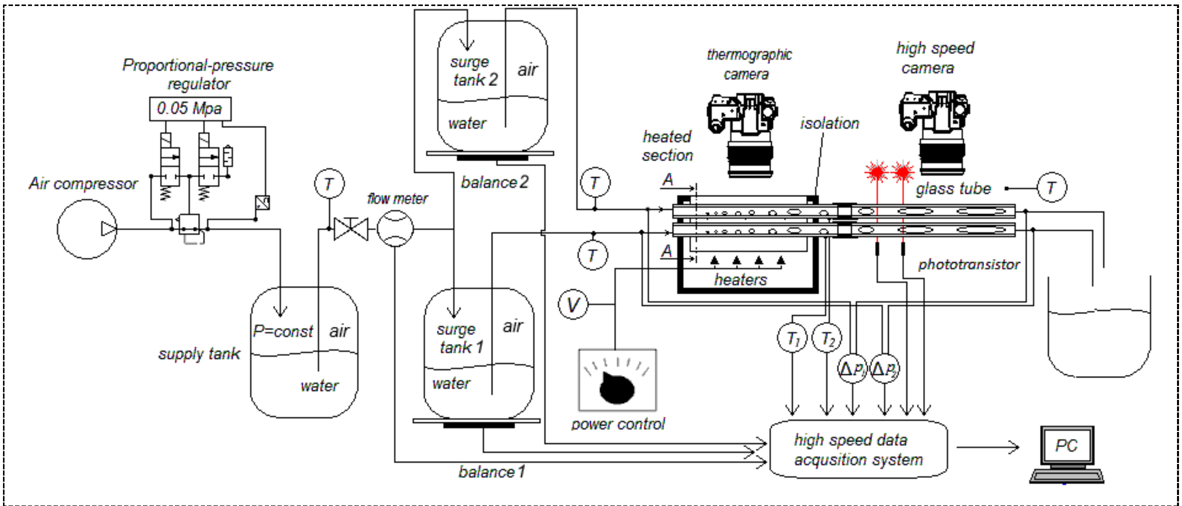

Figure 1. The schema of experimental system

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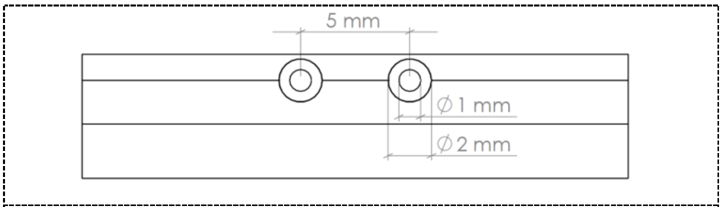

Figure 2. Cross section of heated block with two parallel minichannels.

Two circular brass pipes with inner diameter of 1 mm, outer diameter of 2 mm and length of 150 mm were fitted into heated section. Distance between channels was equal to 5 mm. The pipe was installed in the copper block with dimensions of 25x9x100 mm. The copper block was electrically heated and isolated by ceramic fibre wool. The outlet of brass pipes (length 25 mm) was isolated and the thermocouples (type K with diameter of 0.081 mm and ± 0.8°C accuracy, response time 0.025 s), was placed in the distance of 10 mm from the pipe outlets. The inlet water temperature was measured using the temperature sensor DS18B20 (±0.5°C accuracy for temperatures from -10°C to 85°C) and in the experiment it was 19.1°C. The outlet pressure was the atmospheric pressure. The outlets of brass pipes were connected to the glass pipe (length of 150 mm, inner diameter of 1 mm and outer diameter of 5.7 mm) which allowed to visualize the flow patterns (condenser). Liquid flowed freely from the glass pipes to the atmosphere. Flow patterns were recorded with using the Phantom v1610 camera at 1000 fps (1152 x 128 pixels). Pressure difference between the brass pipe inlet and glass pipe outlet was

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measured using the silicon pressure sensor MPX5050DP (range 0 - 50 kPa, response time 1 ms, accuracy ±1.25 kPa). The amount of vapour flowing through the glass pipes was measured by laser-phototransistor sensors placed 20 mm downstream from minichannels outlets. Data from sensors was acquired by the acquisition system (Data translation 9806, an accuracy of 1 mV for voltages in the range of -10 V to 10 V) at a sampling rate of 1 kHz. The air temperature in the distance of 10 mm from the glass pipes was controlled by digital temperature sensor DS18B20. The measurement was carried out at the constant air temperature - when the system reached the steady state.

3. Data characteristics

This paper will focus on the analysis of the signals recorded by the thermocouples during two-phase flow instability in two parallel minichannels. The experiment conditions in which the measurement was carried out has been show in Table 1.

Table 1. The conditions of the experiment.

Parameter	Value	Unit	Uncertainty or relative error
Flow rate	352.6	g/h	±4
Heat input	62.7	W	±0.02
Overpressure in supply tank	30.0	Mpa	±0.1
Room temperature	19.6	°C	±0.5

Flow patterns recorded during those conditions has been shown in Figure 3.

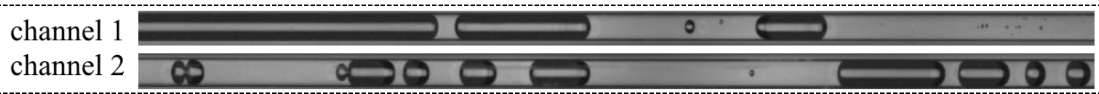

Figure 3. Flow patterns observed in both channels.

Signals form thermocouples were denoised using wavelet decomposition method. The wavelet decomposition uses a family of wavelets, after proper transformation (scaling and shifting), to describe the analysed signal. Each wavelet is a sort of band-pass filter that can be used for decomposition of the original time series into different frequency bands, thus allowing a multi-resolution analysis of the signal [4]. The main challenge of using wavelet transform is to select the proper mother wavelet for the given task. The maximum correlation coefficient criterion proposed by Ngui et al. was applied to select the most optimal mother wavelet for this analysis [5]. Signals were decomposed using Daubechies wavelets (db6). Variances of details for different levels of decomposition for signal recorded during water flow and flow boiling were compared to define noise level in examined data. The level of approximation for which the variances of details for boiling are lower than variance details for water flow is treated as a proper for denoising procedure [6].Wavelet Toolbox™ built on the MATLAB® was used for calculations. The proper level was equal to 4. In figure 5 the original signal and denoised signal have been shown. Signals from both thermocouples after denoising were analysed using cross recurrence plot [7, 8]. The method starts from the attractor reconstruction. The image of the attractor in n-dimensional space depends on the time delay - τ. The mutual information between time series: $x(t)$ and $x(t+\tau)$ can be used to determine proper time delay for the reconstruction of attractors. As τ is increased, the mutual information decreases and then it rises again. The time delay for which the mutual information obtains the first minimum is a proper value of τ. The mutual information of $x(t)$ and $x(t+\tau)$ can be defined as [9]:

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$$I(x(t),x(t+\tau))=\sum_{x(t+\tau)}\sum_{(x(t)}p[x(t),x(t+\tau)]\times \times\log_2\left\{\frac{p[x(t),x(t+\tau)]}{p[x(t)]p[x(t+\tau)]}\right\} \quad (1)$$

where $p[x(t),x(t+\tau)]$ is the joint probability distribution function of $x(t)$ and $x(t+\tau)$, and $p[x(t)]$ and $p[x(t+\tau)]$ are the marginal probability distribution functions of x and $x(t+\tau)$.The mutual information is equal to zero if $x(t)$ and $x(t+\tau)$ are independent random variables.

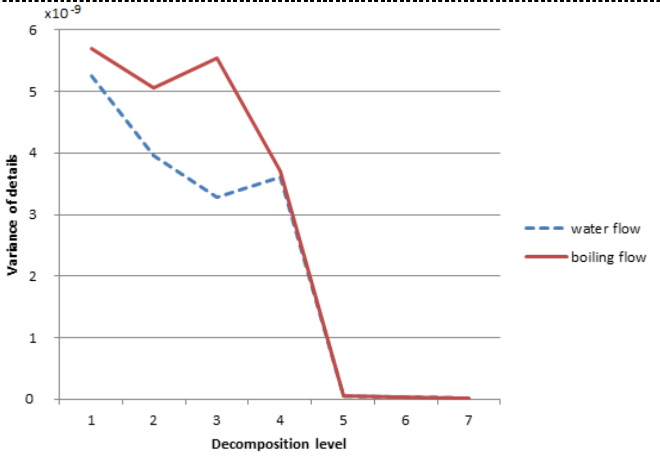

Figure 4. Variance of details for different level of decomposition for signal recorded during water flow and boiling flow.

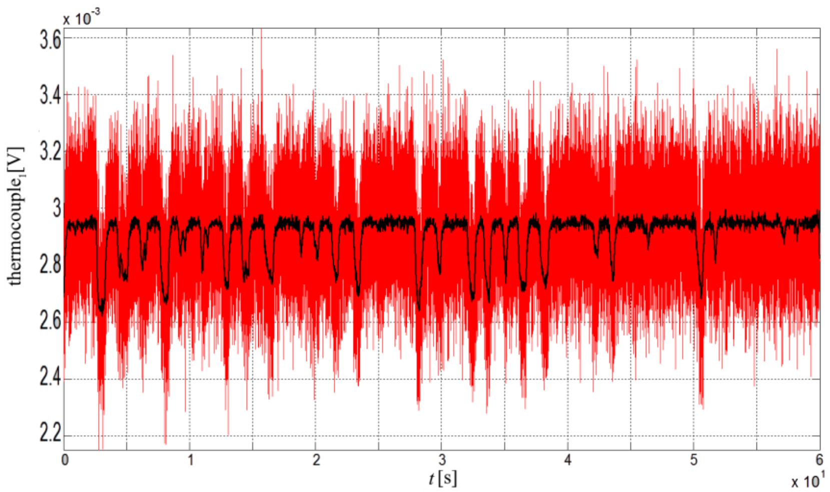

Figure 5. Channel 1 thermocouple signal (a) original, (b) denoised. (Wavelet Toolbox™ built on the MATLAB®)

The false nearest neighbour algorithm has been used for the estimation of the proper embedding dimension of attractors [10]. In this method, the changes of number of neighbours of points in embedding space with increasing embedding dimension are examined. The number of false neighbours is calculated for the whole time series under considerations and for several dimensions until the percent of false points reaches zero. Such dimension is treated as a proper embedding dimension for attractor reconstruction. We apply our analysis with m = 4, τ = 500 and ε = 0.8 (fixed radius, Euclidean distance).

Cross recurrence plot is a technique of visualization of the similarities in phase space behavior of two trajectories x_i and y_i in m-dimensional phase space. A cross recurrence plot (CRP) is method which compares the dynamics represented in two time series. The recurrence plot is defined as [8]:

$$\mathrm{CR}_{i,j} = \Theta(\varepsilon_i - \|x_i - y_j\|), x_i, y_i \in \Re^m, i, j - 1 \ldots N \tag{2}$$

where N is the number of considered states x_i and y_i, ε_i is a threshold distance, || || is a norm and Θ is the Heaviside function.

In figure 8 it has been shown the cross recurrence plots of 30 s long denoised temperature fluctuations. Cross recurrence plots were made using CRP toolbox [11].

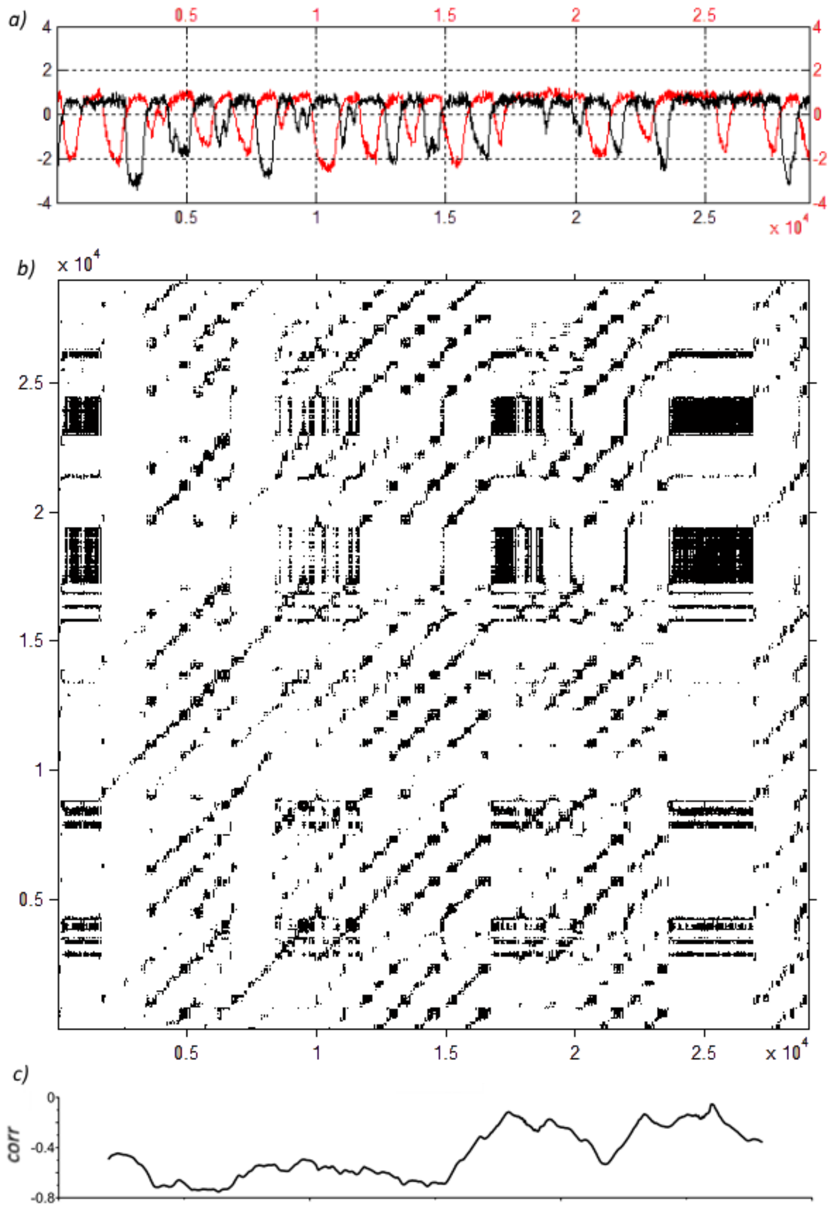

Figure 8. Cross recurrence plot of analysed time series for an embedding of m = 4, τ = 500 and ε = 0.8. a) analysed part of the signals, b) cross recurrence plot, c) correlation of time series

In CRP it is visible several structures and diagonal lines. The rectangular structures of points appear periodically. Those structures correspond to case when temperature of one channel not oscillating. Diagonal structures indicate similarities in both phase space trajectories. The spaces between diagonal lines correspond with oscillations frequency. Also blank spaces can be found in the plot which indicates that states of both trajectories are strongly differing. Correlation graph shown below the CRP plot also detects situation when one of the channel have constant temperature but not so precise as CRP plot. When correlation plot is close to zero value it means that two variables are independent. A negative correlation coefficient means that, for any two variables X and Y, an increase in X is associated with a decrease in Y. When bubble expands rapidly in one of the channel causing temperature rise, in second channel bubble is condensing casing temperature decrease.

4. Conclusions

Result shown that cross recurrence plot can be used in order to analyse the similarity of the dynamical evolution between two different systems. Analysis result showed that signal for thermocouple can be described by 4 independent variables. In this case, the measurement of the correlation coefficient may be insufficient. Cross recurrence plot revealed the times when channels oscillated alternately and the times when one of the channels wasn't oscillating. A disadvantage of this technique is complicated selection of analysis parameters.

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