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Two-phase flow regime assignment based on wavelet features of a capacitance signal

Kathleen De Kerpel [a,*], Sven De Schampheleire [a], Timothy De Keulenaer [b], Michel De Paepe [a]

[a] Department of Flow, Heat and Combustion Mechanics, Ghent University-UGent, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium
[b] INTEC/IMEC, Ghent University-UGent, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

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ABSTRACT

In this work, a new method is proposed to determine the two-phase flow regime based on the capacitance trace of the flow. The experimental data set contains 123 capacitance traces measured for a horizontal tube with an inner diameter of 8 mm. The tested refrigerant is R134a. The mass flux is varied between 200 and 500 kg/m^2 s and the vapour quality x is varied between 0 and 1. For each capacitance signal the wavelet variance is estimated based on the maximum overlap wavelet transform of the signal. The used wavelet function is a D8 wavelet of the Daubechies family. A feature space is generated based on the wavelet variance values associated with frequencies below 100 Hz. Principal component analysis and linear discriminant analysis are subsequently applied to this raw feature space, after which the Fuzzy c-means clustering algorithm is used to divide the feature space into clusters corresponding to different flow regimes. The resulting flow regime assignment shows a good agreement with a visual classification of the data set based on flow visualisations. Finally, the classification was performed based on variable training data to show the robustness of the method.

1. Introduction

For two-phase flow, the flow behaviour can typically show a range of configurations depending on the vapour quality x, the mass flux G, the channel geometry and the fluid properties. These different configurations are mostly designated as flow patterns or flow regimes. There is a close link between the two-phase flow regime and the two-phase heat transfer coefficient (Wojtan et al., 2005a, 2005b) and pressure drop (Quiben and Thome, 2007a, 2007b). It is therefore important to have knowledge of the flow behaviour and flow regime in order to gain insight in the two-phase heat transfer and pressure drop. Furthermore, the more recent models to predict the two-phase flow heat transfer and pressure drop require knowledge of the flow regime, for the correlations differ for each flow regime (Wojtan et al., 2005b; Quiben and Thome, 2007b). Furthermore, the determination of other two-phase properties might also require the knowledge of the flow regime, one example being the flow regime based void fraction measurement technique as proposed by De Kerpel et al. (2013, 2014).

In many cases, the flow regime is assigned based on a flow visualisation (Wojtan et al., 2005a; Szczukiewicz et al., 2013; Julia et al., 2011; Padilla et al., 2013). This method is relatively simple, the visualisations can be assessed without any prepossessing of the data. To obtain these flow visualisations a sight glass has to be installed in the setup and a relatively high-speed and high-resolution camera is needed. This sight glass limits the system pressures and thus the applicability and the need for a high-end camera implies a relatively high cost. Next to these practical drawbacks, the subjectiveness of the visual classification is probably the most important drawback. The classification is quite sensitive to the person performing it, even if this is a two-phase flow expert. Due to the importance of the two-phase flow regime for two-phase flow research the recent trend is to find a more objective method to discern between flow regimes. Some authors tried to attain this by processing the flow visualisations. Jassim et al. (2006) processed a single frame of a flow visualisation and assigned a flow regime based on this single frame. This limits the computational cost, however, for flow regimes showing a large variation in the flow structures over time, such as e.g. slug flow, this method could lead to assigning a wrong flow regime (Ameel et al., 2012). Ameel et al. (2012) processed entire flow visualisations, this method was effective, however, it was very computationally intensive and showed a high sensitivity to the quality of the camera and the sight glass. Other methods to assess the flow

* Corresponding author. Tel.: +32 9 264 33 55; fax: +32 9 264 35 75.
E-mail address: Kathleen.DeKerpel@UGent.be (K. De Kerpel).

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Nomenclature

F	frequency (Hz)
G	mass flux (kg/m^2 s)
C	number of clusters (–)
C	cluster centre (–)
D	number of data points (–)
F	feature (–)
$F_{correct}$	ratio of correctly assigned data points (–)
J	Fisher determinant (–)
J_m	objective function clustering algorithm (–)
M	feature vector (–)
S_B	between class scatter matrix
S_W	within class scatter matrix
U	membership grade (–)
X	vapour quality (–)
Δt	sample time (s)

Greek symbols

μ	average (–)
ν	wavelet variance estimate (–)
$\tilde{\nu}$	reduced wavelet variance estimate (–)
τ	scale (samples)

Acronyms

CWT	Continuous Wavelet Transform
DWT	Discrete Wavelet Transform
LDA	Linear Discriminant Analysis
MODWT	Maximum Overlap Discrete Wavelet Transform
PCA	Principal Component Analysis

regime can be based on e.g. pressure fluctuations (van Rooyen et al., 2010; Shen et al., 2015), hot film anemometry (Shen et al., 2012) or impedance (Hervieu and Seleghim, 1998). Another promising technique is a capacitance probe (Canière et al., 2007), which is – in contrast to some of the previously mentioned methods – non-intrusive to the flow, low cost and robust (De Kerpel et al., 2013).

In this work, a method to assign a flow regime based on the capacitance trace of the flow is proposed. As shown by Canière et al. (2008), the capacitance time trace of two-phase flow is characteristic of the flow behaviour. However, to limit the computational cost, the capacitance signal is reduced to a limited number of features on which the flow regime is then assigned. Canière (2009) performed such a flow regime discrimination based on a capacitance time trace, however, the feature space for this method was selected and ranked entirely manually. This limits the robustness and the applicability of the method. Furthermore, the method by Canière (2009) was based on the Fourier transform, while De Kerpel et al. (2014) showed that the wavelet variance estimate of the capacitance signal is a better indicator of the flow behaviour. For this reason, the feature space will be composed out of the wavelet variance data. To further optimise and reduce the dimensionality of this manually selected feature space, Principal Component Analysis and Linear Discriminant Analyses are used. The data is then divided into different clusters by means of a Fuzzy c-means clustering algorithm. Finally, the robustness of the method is tested by randomly varying the training data set. Further information on the wavelet analysis, dimensionality reduction and clustering will be given in Section 3 of this work. In Section 2, the capacitance sensor design and the data set are discussed.

2. Capacitance sensor and data set

Fig. 1 shows a cross-sectional view of the sensor used to measure the capacitance of the refrigerant flow. The heart of the sensor are two concave electrodes between which the two-phase flow capacitance is measured. The main role of the remaining parts of the sensor probe is to render the sensor pressure resistant and to shield the electrodes.

The electrodes of the sensor have an angle of 160° each, leaving only 10° at the top and the bottom of the tubes uncovered by the electrodes. The length of the electrodes is 8 mm, in the axial direction of the tube. They are etched out of the copper cladding on a flexible circuit material (Ultralam 3850 from Rogers Corporations®). This flexible material and electrodes are then glued into PVC parts to give structural strength and placed into a stainless steel cylindrical casing. The gaps between the casing and the 3D printed parts are filled up with epoxy resin. For more information on the design process of the sensor design, the reader is referred to Canière (2010).

The capacitance between the electrodes is measured using a transducer which was made in-house. The transducer design is based on the one proposed by Yang and Yang (2002). The output of the transducer is a voltage between 0 and 10 V. The sensitivity of the transducer is 1.16 V/pF and the output accuracy is 4 mV. The capacitance difference between full vapour flow and full liquid flow is dependent on the refrigerant used. For R134a this difference is 1.05 pF. The voltage is logged with a DAQ system. For each measurement the capacitance time trace is acquired for 10 s at a sample frequency of 1 kHz.

Measurements were performed for a mass flux G ranging from 200 kg/m^2 s to 500 kg/m^2 s and a vapour quality x ranging from 0 to 1. Close upstream of the sensor probe, a sight glass was installed through which a matching flow visualisation was made for each capacitance measurement. In total, the data set contains 123 data points. Based on these flow visualisations, each data point is assigned a flow regime. This visual classification of the flow is performed by an expert in two-phase flow, however, it is still subjective. The result of this visual classification is shown in Fig. 2, three flow regimes were discerned: slug flow, intermittent flow and annular flow.

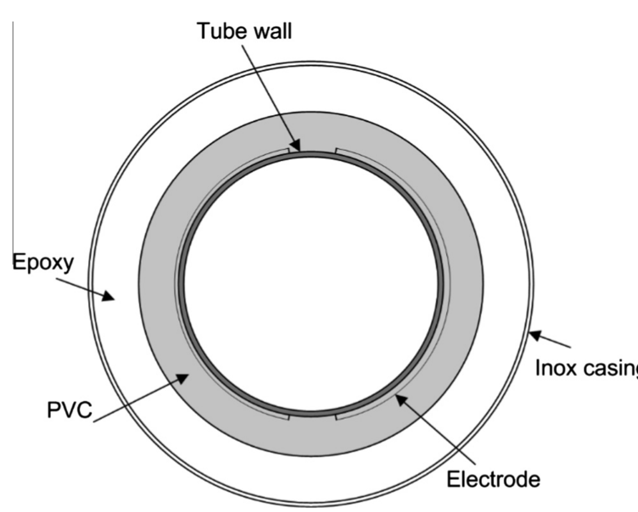

Fig. 1. Capacitance sensor cross section.