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Two-phase flow bubble detection method applied to natural circulation system using fuzzy image processing

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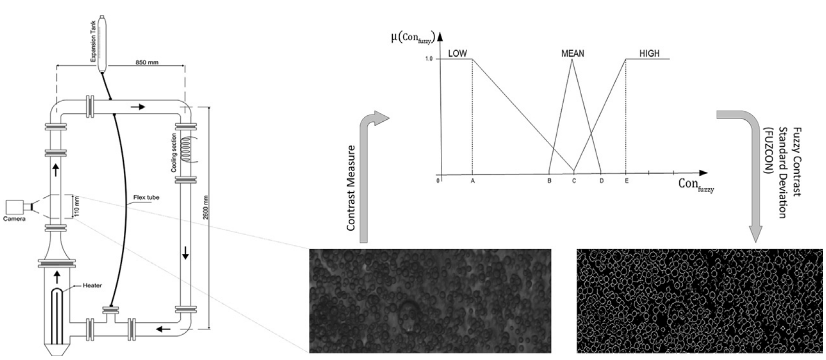
GRAPHICAL ABSTRACT



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ABSTRACT

Natural circulation cooling systems are currently used in new nuclear reactors. Over the last decades, research in these systems has focused in the study of flow and heat transfer parameters. A particular area of interest is the estimation of two-phase flow parameters by image processing and pattern recognition using intelligent processing. Several methods have been proposed to identify objects of interest in bubbly two-phase images. Edge detection is an important task to estimate flow parameters, in which the bubbles are segmented to obtain several features, such as void fraction, area, and diameter. However, current methods face difficulties in determining those parameters in high bubble-density two-phase flow images. Here, a new edge detection method is proposed to segment bubbles in natural circulation instability images. The new method (*Fuzzy Contrast Standard Deviation – FUZCON*) uses Fuzzy Logic and image standard deviation estimates of locally measured contrast levels. Images were obtained through an experimental circuit made of glass, which enables imaging flow patterns of natural circulation cycles at ambient pressure. The results indicated important improvements on edge detection efficiency for high void fraction estimation on high-density two-phase flow bubble images, when compared to classical detectors, without the need to use smoothing algorithms or human intervention.

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1. Introduction

The cooling system is a critical component of a nuclear power plant, which requires an efficient process of heat exchange. Recently, studies have focused on the phenomenology involved with the nuclear reactor cooling systems and their respective control. A significant portion of new reactor designs uses natural circulation systems for this purpose (Andrade et al., 2000). In such a critical system, it is important to have knowledge about limiting conditions of the two-phase flow regimes to manage heat transfer of the reactor coolant. Within such context, it is of particular interest the study of flow regimes using image processing (Mesquita et al., 2012). In order to determine the void fraction, the image segmentation process can be used to divide the image into sub-regions to obtain the region of interest (ROI). So, in this paper, edge is regarded as a set of connected pixels about the contour between two regions. Here, a methodology to detect bubble edges in images with high void fraction in a two-phase bubbly flow is presented. It was applied to the natural circulation experimental circuit (NCC) (shown in Fig. 1) in the Nuclear and Energy Research Institute (IPEN), Brazil. This circuit is made of glass, which allows to image flow patterns under ambient pressure.

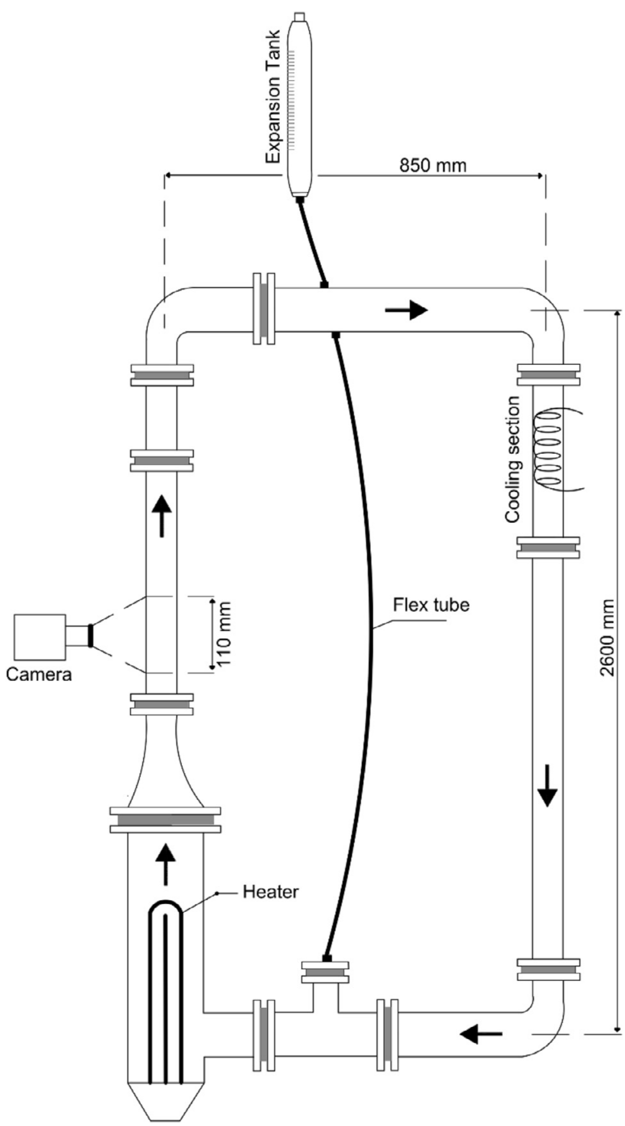

Fig. 1. Experimental setup (NCC) used to capture images on simulation of natural circulation cycles at the Nuclear and Energy Research Institute (IPEN, Brazil).

The paper is organized as follows. Section 1 discusses the conventional method for bubble edge detection, Section 2 details the new methodology, Section 3 presents experimental results using this methodology, and finally Section 4 summarizes the results.

1.1. Bubble edge detection

Two-phase flow pattern transitions have been studied using techniques derived from artificial intelligence or image processing (Mesquita et al., 2012; Abdallah, 2009; Crivalero et al., 2002; Mesquita et al., 2009; Carl and Avdic Senada, 2005; Wu et al., 2006; Sarkar et al., 2005; Zhang and Huang, 1988; Heydarian et al., 2009), such as artificial neural networks, Fuzzy Logic, neuro-wavelet, support vector machine (SVM), and genetic algorithms. Many of those methodologies (Barbosa et al., 2010; Dinh and Choi, 1999; Shi, 2007; Shi et al., 2004; Wenyin et al., 2008) can describe useful patterns by segmenting bubbles and identifying their edges in order to get some parameters, such as bubble area and diameter. However, those methods are limited to bubble edge detection in two-phase flow images, where bubbles are isolated from each other.

There is an increasing demand to improve information on bubble contour to obtain precise parameters in two-phase bubbly flow, such as the void fraction. Void fraction estimation needs the detection of all-round bubble contour and subsequent volume measurement. This detection is challenging when bubbles are close to each other, which can cause over-segmentation (Crivalero et al., 2002; Carl and Avdic Senada, 2005; Wu et al., 2006) due to low contrast present in images, hampering bubble identification (Delacroix et al., 2016; Huang et al., 2007). Other methods (Mishima and Hibiki, 1996; Wang and Dong, 2009) use contrast, entropy, and power with the purpose to identify flow patterns without considering the bubble shape.

In some methodologies that can identify bubbles in high void fraction flow images (Wu et al., 2006; Shi, 2007; Wang and Dong, 2009; Do Amaral et al., 2013; Lau et al., 2013), the edge detection is needed to estimate flow parameters, such as diameter, volume, mass velocity, trajectory geometry, distance between bubbles, and their lifetime. However, those methodologies may fail when intensity changes are abrupt or when objects are very close to each other, as illustrated in Fig. 2. Additionally, lighting inhomogeneity and oscillation are elements that hamper the recognition of objects.

Other methodologies have also been proposed to improve identification of objects of interest in high void fraction two-phase flow images (Wenyin et al., 2008; Barkhoda et al., 2009). They use the Canny operator, combined with other techniques, to establish a smoothing criterion (based on signal noise, good detection, and low spurious response) to identify those objects. However, they can only detect edges in images where bubbles are isolated from each other. Statistical methods, associated with other techniques such as the Watershed method, have been used to deal with the difficulty in detecting heterogeneous light (Zhang and Huang, 1988; Do Amaral et al., 2013; Lau et al., 2013).

Even using statistical methods, some problems, such as image super-segmentation, still arise for heterogeneous lighting. Some investigations have used techniques based on artificial intelligence, such as Support Vector Machine (SVM) (Wu et al., 2006; Sarkar et al., 2005) and Fuzzy Logic (Andrade et al., 2000; Barkhoda et al., 2009; Patel et al., 2011; Jzau-Sheng et al., 1996), using fuzzy inference to assist the segmentation process.

Bhardwaj and Mittal (2012) have reviewed edge detection techniques such as Roberts, Sobel, Prewitt, Canny and especially Declivity ones. Particularly, the Declivity operator has been used in many investigations (Miché and Debrie, 1995; Bensrhair et al., 1996; El Ansari et al., 2010; Cabani et al., 2006). The Declivity proposed in reference (Miché and Debrie, 1995) involves the evaluation of intensity magnitudes of a set of contiguous pixels between two local extremes in an image line. One of the main features of this operator is its ability to