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ScienceDirect
Engineering Applications of Artificial Intelligence 21 (2008) 1144–1152
Engineering Applications of ARTIFICIAL INTELLIGENCE
www.elsevier.com/locate/engappai

# Application of CHMMs to two-phase flow pattern identification

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Received 22 December 2006; received in revised form 10 August 2007; accepted 2 February 2008
Available online 15 April 2008

**Abstract**

In this paper, the application of continuous hidden Markov models (CHMMs) in identifying two-phase flow patterns is investigated. Air–water two-phase flows were realized in a transparent vertical tube with a 2 m length and a 19 mm inside diameter. Local void fraction signals were collected using a single-step index multimode optical fiber probe located at the center and mid-length of the tube. Walsh–Hadamard transform, an autoregressive model and an innovative method based on the passage length of the phases were used to extract signal features required in the CHMM implementation. CHMMs were trained for nine reference flow conditions, and were used to identify the flow patterns of 60 different flow conditions. Two different approaches were compared to treat log-likelihood results: maximum total likelihood and maximum likelihood. The results from the passage length-based method, in combination with the maximum total likelihood approach, were in relatively good agreement with a theoretical flow pattern map and photographs of the flow captured during the experiments. In sum, the results showed that a CHMM has a good potential in identifying two-phase flow patterns.


*Keywords:* Pattern recognition; Two-phase flow; Hidden Markov model; Optical probe; Feature extraction

## 1. Introduction

When two different fluids are simultaneously flowing together, this phenomenon is called two-phase flow. Two-phase flows very often exist in industrial applications such as filtration, lubrication, spray processes, natural gas networks and nuclear reactor cooling. In the study of two-phase flow, flow patterns indicate how the phases are distributed and mixed due to the physical nature of the system. The two-phase flow regimes depend on the type of fluid–fluid combination, the flow rates and direction, the conduit shape, size and inclination. In addition, heat and mass transfer rates, momentum loss, rate of back mixing and pipe vibration all vary greatly with the flow regimes. Therefore, it is quite important and necessary to identify the regimes and discern their correlation with the flow properties.

Many experimental and theoretical researches have been done in this area and, as a result, there are several classification methods. The early experimental works were mostly based on direct observations such as high-speed photography and X-ray attenuation pictures. Although these methods are inexpensive and, in most cases, easy to perform, they are to a great extent subjective. Increased objectivity can be obtained from indirect observation methods that deal with the fluctuating properties of the two-phase flow. It has been proven that there is correlation between flow regimes and fluctuation properties such as local pressure and instantaneous two-phase mixture ratio. Thus, in most cases, flow regimes are determined by means of mathematical and statistical analyses of these fluctuation properties. Indirect observation methods include pressure fluctuation analysis, X-ray attenuation fluctuation analysis, electrical impedance method and so on (Rouhani and Sohal, 1983).

Experimental methods are rather effective for detecting clearly established flow regimes. However, in conditions close to a transition between two regimes, detecting the flow regime is crucially difficult and most works were done on theoretical bases. In these methods, mechanisms of transition in two-phase flow are used to define the transition criteria. Due to the complex nature of two-phase

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0952-1976/$ - see front matter 
doi:10.1016/j.engappai.2008.02.005

flow, theoretical analyses have not been able to describe the system perfectly. Therefore, a technique is still required that, whether experimentally or theoretically, will detect and describe the flow regime in conditions near regime transitions.

In this research, a new method is developed for identifying internal two-phase flow regimes, from the local void fraction signals gathered by an optical fiber probe system inside a vertical channel. The basic idea of this method is to detect flow regimes through signal pattern analysis. As mentioned, there is correlation between the fluctuation characteristics of two-phase flow properties and the flow regimes. Moreover, the signals are interpretations of such fluctuating properties. Therefore, the signal patterns can be considered as representatives of the flow patterns. By analyzing and distinguishing these signal patterns, the flow patterns can be detected, and flow regimes can be identified. In most of the previous methods of this type, statistical properties such as probability density function (PDF) were used for detecting flow patterns (Kelessidis and Dukler, 1989; Costigan and Whalley, 1997). In these methods, the statistical features of a given fluctuating property of the flow were obtained for each regime and were then used for comparing different regimes. In the present work, signal patterns were analyzed in an enhanced and objective manner using hidden Markov models (HMMs), and flow regimes were recognized through flow patterns.

## 2. Flow pattern classification and definitions

There are some mathematical models for modeling two-phase flow, none of which describes the two-phase flow perfectly. One of the simplest models is the homogeneous model in which the phases are assumed to be homogeneously mixed and traveling at the same axial velocity through the channel. According to this model two basic definitions are as follows:

*Homogeneous velocity* is the axial velocity of the two-phase mixture.

*Homogeneous void fraction* is the ratio of the gas volume to the total volume of the two-phase mixture.

For simplicity, hereinafter these two terms are referred to as velocity and void fraction.

According to Taitel et al. (1980), flow patterns for an upward gas–liquid flow in a vertical conduit can be categorized as follows (Fig. 1):

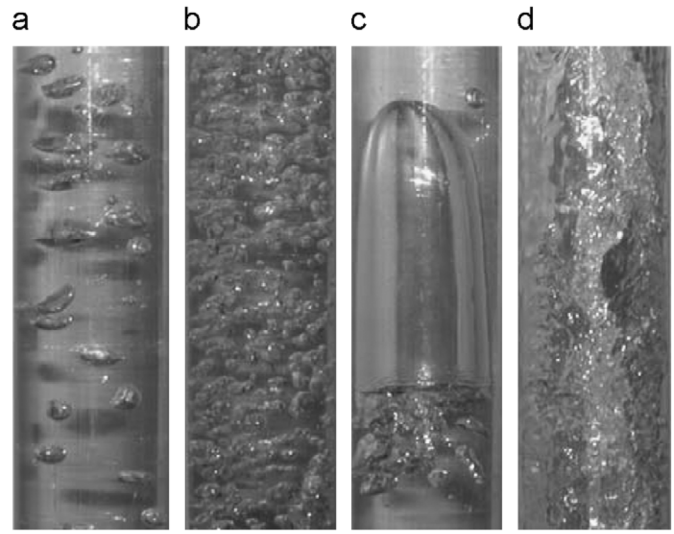

Fig. 1. Two-phase upward flow patterns in a vertical tube: (a) dispersed bubbles, (b) finely dispersed bubbles, (c) slugs, (d) churns.

- *Bubbles* (Fig. 1a): This flow regime occurs at low void fractions and low velocities where the gas phase is rather uniformly distributed in the form of discrete bubbles in a continuum of liquid phase. These large deformable bubbles rise with a zigzag motion. Occasional Taylor-type bubbles can also be observed.
- *Finely dispersed bubbles* (Fig. 1b): At low void fraction but higher velocities, the large bubbles break up due to turbulent forces. The bubbles come in smaller and more dispersed spheres in comparison with the bubbly flow. They behave as rigid spheres.
- *Slug flow* (Fig. 1c): At low velocities and high void fractions, most of the gas appears in large bullet-shaped bubbles, also known as Taylor bubbles, which have a diameter almost equal to the pipe diameter. The liquid slug area between two Taylor bubbles is filled with small bubbles that are very similar to those in bubbly flow.
- *Churn flow* (Fig. 1d): Churn flow is a highly disordered flow that happens at high void fractions and high flow velocities because of instabilities in the slugs. Churn flow can be interpreted as an irregular, chaotic and disordered slug flow. It is also characterized by an oscillatory flow, with the liquid phase moving alternately upward and downward in the channel.
- *Annular flow (not depicted)*: At very high void fractions, the oscillations of the churn flow disappear, and there will be a continuum of gas at the center of the pipe. The liquid phase is continuously flowing upward, and it is distributed between a liquid film, which is on the pipe wall, and a dispersion of droplets in the gas core of the flow.

In this experiment, due to the physical limits of the setup, only finely dispersed bubbly flow, slug flow and churn flow were simulated.

## 3. Hidden Markov models

An HMM is a doubly embedded stochastic process, which has a rich mathematical structure. HMMs have been proven to be very strong pattern identifiers with a good accuracy on most critical applications. HMMs have been used in speech recognition starting from the 1960s. Rabiner (1989) published an insightful tutorial on HMMs and their application in speech recognition. Since then, HMMs have been used in many other fields including mechanical