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Performance evaluation of conductivity wire-mesh sensors in vertical channels

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ABSTRACT

This article presents a comprehensive and critical discussion of available literature on conductivity wire–mesh tomography as well as some complementary original analysis. Wire-mesh tomographs were first classified into different categories, depending on their principles of operation, and then the discussion was focused on the most commonly used type, namely, the wire–mesh sensor (WMS) in vertical channel flows. The main applications of WMS were outlined and the properties that can be determined from WMS signals were identified, together with the corresponding procedures. WMS performance and the factors that affect this performance were evaluated in detail using results of previous investigations as well as new analysis and data. The principles of operation and main applications of global wire–mesh tomographs were then described. This article finally presents several examples of wire–mesh tomography applications in multicomponent flows.

1. Introduction

The properties of flows of fluid mixtures have been studied extensively, both experimentally and analytically, as such flows are encountered in many engineering applications. Flows of mixtures may be classified into two general classes: multiphase flows, which consist of immiscible fluids with generally distinct velocities and temperatures, and multicomponent ones, in which the constituent fluids are miscible and typically share a common velocity and temperature [9]. Multiphase flows are encountered in many heat exchangers and thermal power generation systems, whereas multicomponent mixtures are present in combustors and chemical reactors.

Available techniques for the measurement of flow properties in multiphase and multicomponent flows may provide either volume–, area– or line–averaged values of a property or local values at discrete locations. Spatially averaged measurements may usually be collected faster and more conveniently than local measurements, and they often include sufficient information for the needs of many applications. On the other hand, the availability of spatially distributed local measurements allows for a more detailed analysis of the flow structure and insight into phenomena and processes that cannot be described by global measurements alone. A number of measurement procedures, commonly referred to as tomographic methods, aim at reconstructing the cross–sectional or volumetric distribution of a flow property from a number of discrete measurements collected simultaneously at many points in the flow. Several tomographic methods have been applied to multiphase and multicomponent flows with the objective of distinguishing the constituents of the mixture.

Multiphase/multicomponent tomographs distinguish between the mixture constituents by detecting differences in electrical properties (impedance, permittivity and conductivity tomographs), radiation attenuation (X–ray and gamma ray tomographs), sound attenuation (ultrasonic tomographs) or light attenuation (optical tomography systems) [57]. Electric tomographs, in particular, comprise a number of electrodes, which are either mounted on the periphery of the flow channel or stretched across its cross–section. In these devices, an electric property is measured in the space between each pair of electrodes and its spatial distribution is reconstructed from these measurements with the use of analytical algorithms.

The subject of the present study is the wire–mesh tomographs (WMT), which measure either the conductivity or the permittivity of the fluid in the vicinity of electrodes stretched across the flow domain [13,41,36]. Past literature on WMT includes numerous experimental studies, most of which have appeared in the last 15 years. Although some previous publications include reviews of applications [32] and measurement uncertainty [4] of a specific type of WMT, an all–encompassing review of WMT applications and a critical evaluation of the performance and measurement uncertainty of various WMT devices operating under wide ranges of flow conditions have not yet become available. The present article is meant to fill this gap by addressing these issues. WMT are particularly suitable for measurements in gas–liquid flows, as gases and liquids that are commonly

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encountered in industrial applications have very different electrical properties. The main focus of the present review is the use of WMT in gas–liquid flows, but the applicability of WMT to the study of multicomponent flows will also be reviewed in a separate section.

In the following sections, we will first describe the different types of WMT, then identify the various flow parameters that may be extracted from WMT signals, overview successful applications of WMT and present an in–depth discussion of the measurement uncertainty of both types of these devices. This information will hopefully be of interest to readers conducting WMT measurements or considering the possible use of WMT in types of systems that are either similar to or different from those of past WMT application.

2. Types of WMT

Wire–mesh tomographs may be broadly classified into two categories, depending on the electrical property that is measured. Conductivity WMT measure a current (or a voltage proportional to this current) that is proportional to the local conductivity of the fluid. Permittivity WMT, sometimes referred to as capacitance WMT, measure the capacitance of a space near the electrodes, which is proportional to the permittivity of the fluid, i.e., its ability to transmit electric fields. For the WMT to function in a mixture, the constituent fluids are required to have distinguishable values of the measured property. Moreover, conductivity WMT require at least one of the constituents to have a relatively large value of electrical conductivity (e.g., greater than 5 S/mm).

WMT may also be classified according to the technique used to reconstruct the cross–sectional phase distribution; different techniques are suitable for different sensor designs, particularly the arrangement of the electrode wires. The most widely used type of WMT comprises two arrays of parallel electrode wires separated by a small axial distance, such that the wires in each array are perpendicular to the wires in the other array (Fig. 1a). Thus, the two arrays may be projected into a mesh with nodes at the projected crossing points of the wires. The output of this sensor is temporally and spatially discrete measurements of conductivity or permittivity, which are nominally assigned to each individual node. Then, provided that the measurable property is sufficiently sensitive to the phase that is present in the vicinity of each node, one may reconstruct the cross–sectional phase distribution from the nodal conductivity or permittivity values. Consequently, one may identify such a device as a nodal WMT (NWMT), however, to avoid possible confusion, we will instead adopt the well–established label, wire–mesh sensor (WMS). The first device that can be classified as a WMS was described in a patent by Johnson [13] and was intended to measure the volume fraction of water in crude oil. It used a conductivity WMS design with the two wire arrays designated as the transmitter and receiver electrodes, respectively. The author described the design of a multiplexer that could be used to achieve relatively high cross–section sampling rates. Continuous application of DC current to the electrodes would possibly cause electrolysis, which would lead to unreliable measurements and even destruction of the sensor. Therefore, the conductivity measurements were acquired node by node, such that a voltage was applied to a particular transmitter wire for a short time interval. An improved conductivity WMS (Fig. 1a) was proposed by Prasser et al. [35,36], and it incorporated some important modifications to the data acquisition procedure (Fig. 1b). Most notably, to increase the data acquisition speed, measurements were done row by row, rather than node by node. For each transmitter wire, the current signal from each receiver wire was converted to a voltage by an operational amplifier and then sampled by an individual sample–and–hold circuit. To prevent electrolysis, a square–wave type pulsating voltage was applied to the transmitter wire. These authors achieved sampling rates of up to 1200 frames/s, which were later increased to 10,000 frames/s by an improvement of the digital components of the data acquisition system [40]. A similar device that was based on measurements of capacitance rather than conductivity was proposed by Da Silva et al. [8] for measurements in non–conducting fluids.

A second type of WMT was developed by Reinecke et al. [41] to measure the phase distribution in a gas–liquid flow. This device consisted of three arrays of 29 parallel electrode wires (Fig. 2), with the wires in each array rotated by an angle of 60° with respect to those in the adjacent array. With the device inserted in a pipe, the cross–section was discretised into 1000 equilateral–triangle–shaped pixels by the wire projections (Fig. 2b). This sensor measured sequentially the conductivity of the fluid between adjacent wires in each array, from which the cross–sectional phase distribution was determined with the use of analytical reconstruction algorithms at a sampling rate of up to 110 frames/s. Unlike WMS, which provide nodal phase measurements, this device reconstructs the cross–sectional phase distribution by processing the measurements of all pairs of wires simultaneously. To distinguish such devices from WMS, we shall refer to them as global wire–mesh tomographs (GWMT). It is noted that, in both WMS and GWMT, individual measurements of conductivity or permittivity are collected sequentially to eliminate electrical interference and/or electrolysis effects on the measurements; this necessarily results in a phase shift between the signals of different nodes in a WMS and those of different wire pairs in a GWMT. The GWMT has been far less popular than the WMS, presumably because of the dependence of the former on time–consuming reconstruction algorithms. The two devices will be discussed separately in the following sections, first with respect to their use in multiphase flows, then with respect to their few applications in multicomponent flows.

3. Wire–mesh sensors in multiphase flows

3.1. Extraction of flow properties from WMS signals

Wire–mesh sensors provide as output the cross–sectional distribution of conductivity or permittivity. In multiphase flows, one may post–process this output to obtain estimates of the cross–sectional phase distribution, the area–averaged phase fraction and the flow regime. Under certain flow conditions, one may also obtain estimates of the interfacial velocity, the individual bubble diameters and the interfacial area density (namely, the surface area of the interface between the two phases per unit volume).

A sequence of images of an air bubble as it crosses a WMS in water flow and the corresponding instantaneous void fraction maps, determined from the WMS output, are shown in Fig. 3 [39]. Each map was largely consistent with the corresponding image of the bubble. Consecutive maps were used to reconstruct an Eulerian side view of the bubble (sometimes referred to as a virtual– or pseudo–side view), by plotting the output of a single WMS row *vs.* an inverted time axis (Fig. 3). Although such a representation is useful for visualizing the flow inside channels, it must be noted that an Eulerian side view would not match any actual instantaneous volumetric phase distribution. When a slip velocity between the phases is present, as it is often the case in many multiphase flows, an accurate determination of the streamwise phase distribution would also require the phase velocities, which are not measured by a single WMS. Moreover, reconstruction of the streamwise variations of a property from time histories of the same property, which in turbulence research is known as Taylor's “frozen flow” approximation, requires that the distribution of the property remain “frozen” during the measurement time interval. In turbulent flows, this requirement would only be satisfied when the turbulence intensity were sufficiently low; even then, this approximation would gradually fail, if it were applied to “eddies” with progressively larger length scales. The accuracy of this approximation would be further reduced in gas–liquid flows, in which bubbles get distorted as they approach and cross the WMS. The reconstruction of the spatial phase distribution from WMS measurements is a challenging task that requires further study.