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Development of impedance void meter for evaluation of flow symmetry

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ABSTRACT

Often it is useful or even necessary to know whether the void fraction is evenly distributed in two-phase flows. In industrial systems, unevenly distributed flows can be a factor in vibrations and other undesirable occurrences. In bubble column chemical reactors, uneven distribution of the void can result in reduced reaction efficiency. In experiments, it is often desirable to have symmetrically distributed void for local measurements since this allows for more rapid data collection. Current systems for determining the symmetry of the void distribution in distributed flows either suffer from very long measurement time requirements or cause significant disturbances to the flow. To address the need for approximate evaluation of flow symmetry without causing excessive disturbance to the flow, a new impedance void meter design has been developed and tested under a variety of conditions. The ability of the new design to evaluate the void distribution symmetry has been tested through comparison with conductivity probe measurements of local void fraction, and the accuracy of the impedance meter has been verified through comparison with the conductivity probe measurements and with typical impedance void meter measurements.

1. Introduction

The void distribution in two-phase flows can be of interest for many fields. Bubble column chemical reactors, nuclear reactor systems, and other industrial piping systems perform best when the void distribution is symmetrical, and symmetrical void distribution is generally assumed when analyzing these systems. This is an important assumption, as the void distribution can affect many facets of a flow system including production of turbulence, friction pressure losses or flow induced vibration. Uneven void distribution also affects the transport of void in the system.

In the nuclear industry, experiments are often required to evaluate the performance of cooling systems or of reactor components. In these experiments it is often necessary that the void profile be symmetric so that detailed local measurements can be made and the accuracy of these measurements be assured. Ensuring that these measurements are accurate and representative of the flow condition is essential, since the data from many of these experiments is used to develop models used to predict safety characteristics of reactors during the licensing process. This type of data is also used to evaluate code predictions and in developing new safety system designs.

Generally, uneven void distributions are caused by the hydrodynamics of the flow during changes to the flow direction such as occur in bends, elbows and tees. The difference in momentum between the gas and liquid phase, due to the difference in their densities, causes the liquid to more readily move to the outside of the bend while the gas moves toward the inside. This can result in significant secondary flows which, according to local measurement data, lead to vortex formation and uneven void distribution (Talley and Kim, 2010). Vortices can also form at pump inlets, leading to unevenly distributed void being drawn into the pump. The void distribution as the mixture enters the pump may affect not only the flow, but the performance of the pump and system safety as well.

Currently there are methods to measure the void distribution very accurately. Local conductivity or optical probes can be used to measure the void fraction at a given point in the flow field. These types of probes utilize differences in the properties of air and water to determine which phase the probe tip is surrounded by at a given time, and through time averaging obtain the local void fraction (Hibiki et al., 1998; Kim et al., 2000; Abauf et al., 1978). These measurements are very accurate and do not cause significant disturbance to the flow, however measurements must be taken for reasonably long periods on the order of 60 s or more. Further, these measurements must be taken at many locations in the flow field. This may require an hour or more of data acquisition for a given condition, and often this is not practical in industrial settings.

Another method for the measurement of the local void fraction distribution is the wire-mesh sensor (Prasser, 2007). This technique utilizes many wires placed within the flow field. The electrical conductance between each wire and all of the wires that cross it are measured very rapidly. This technique allows resolution on the

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Nomenclature

Latin characters

B	magnetic flux density
E	electric field strength
G	electrical impedance
g	gravitational acceleration
i	current
j	current density
P	pressure
q	current source
U	electric potential
v	velocity
V	voltage
z	axial position

Greek characters

α	void fraction
ρ	density
σ	fluid conductivity

Superscripts/Subscripts

0	value at void fraction of 0
1	value at void fraction of 1
CW	crossed-wire probe
g	value for gas
f	value for liquid
$*$	non-dimensional value

Operators

$\langle\cdot\rangle$	area-averaged value

order of 3 mm and can provide reasonable time-averaged void fraction measurements after only about one minute measurement time. The major drawback to this technique, however, is that the fine wire mesh causes large disruptions to the flow field. Especially at high mixture volumetric fluxes, wake regions may form behind the wire mesh causing bubble entrainment and other undesirable effects. Large bubbles are broken up and the void distribution may be altered, which while perhaps not of concern for some types of scientific measurements is generally undesirable in practical applications.

Various types of tomography, including gamma densitometry (Shollenberger et al., 1997), magnetic resonance imaging, positron emission tomography, and electrical impedance tomography (George et al., 2000), can be used to measure void fraction distributions and avoid intrusive effects on the flow. While these technologies are very capable, they are also very expensive and data processing is very complex.

Because of the drawbacks to these methods, a relatively simple method has been developed based on the electrical impedance void meter to approximately evaluate the symmetry of the void fraction in two-phase flow situations. The electrical impedance void meter is a simplified version of an electrical impedance tomography device that uses only two electrodes. The new design has been tested and shown to perform reasonably well in evaluating the magnitude and symmetry of the void fraction. Such a device is able to provide real-time evaluation of the symmetry of the void profile and can be used as a maintenance or diagnostic tool for pump inlets, bubble column reactors, and detailed two-phase flow experiments as well as other applications where real-time symmetry information is desirable.

2. Impedance void meter theory

The impedance void meter is a very simplified version of electrical impedance tomography which typically consists of two electrodes positioned on the surface of the flow channel. A typical impedance meter with arch-type electrodes is shown in Fig. 1. The electrodes act to convert ion currents within the fluid to an electrical current. This is then used to measure the electrical impedance of the two-phase mixture. The most significant task in developing the impedance meter system is then to find the relationship between impedance and void fraction.

For air–water experiments, the conductivity of the liquid phase is generally very large while the gas phase is nearly an ideal insulator. In this case, the current density in the two-phase mixture is proportional to the electric field intensity. This is Ohm's law,

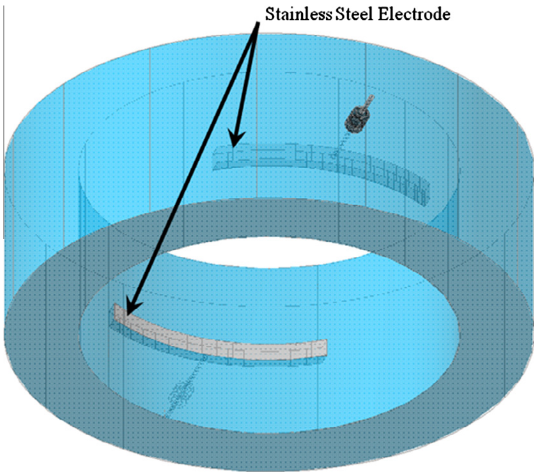

Fig. 1. Electrical impedance void meter.

$$\bar{j} = \sigma(\vec{E} + \vec{v} \times \vec{B}) \tag{1}$$

where σ is the fluid conductivity, E is the electric field, v is the fluid velocity and B is the magnetic flux density. In the electrical impedance void meter, the magnetic flux density is 0. The electric field can also be assumed to be irrotational, and thus can be described as the gradient of the electric potential U. Then the impedance between electrodes is essentially the ratio between the current passing through the two-phase mixture and the potential between the electrodes (Mi, 1998).

Because the interest is on area-averaged measurements, we use a two-dimensional assumption in developing the equations for the impedance. Therefore the total current can be expressed as

$$i = \int_l \vec{j} \cdot d\vec{l} \tag{2}$$

where l is the curve describing the interface between the electrode and the mixture. Substituting Eq. (1) and describing the electric field as the gradient of the electric potential gives

$$G = \frac{\sigma}{V} \int_l \frac{\partial U}{\partial n} dl \tag{3}$$