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Multi-range sensors for the measurement of liquid film thickness distributions based on electrical conductance

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ABSTRACT

The paper presents an approach toward an enhancement of the measuring range of high-speed sensors for the measurement of liquid film thickness distributions based on electrical conductance. This type of sensors consists of electrodes mounted flush to the wall. The sampling of the current generated between a pair of neighboring electrode is used as a measure of the film thickness. Such sensors have a limited measuring range, which is proportional to the lateral distance between the electrodes. The range is therefore coupled to the spatial resolution. The proposed new design allows an extension of the film thickness range by combining electrode matrices of different resolution in one and the same sensor. In this way, a high spatial resolution is reached with a small thickness range, whereas a film thickness that exceeds the range of the high resolution measurement can still be acquired even though on the costs of a lower spatial resolution. A simultaneous signal acquisition with a sampling frequency of 3.2 kHz combines three measuring ranges for the characterization of a two-dimensional film thickness distribution: (1) thickness range 0–600 μm, lateral resolution 2×2 mm^2, (2) thickness range 400–1300 μm, lateral resolution 4×4 mm^2, and (3) thickness range 1000–3500 μm, lateral resolution 12×12 mm^2. The functionality of this concept sensor is demonstrated by tests in a horizontal wavy stratified air–water flow at ambient conditions. Using flexible printed circuit board technology to manufacture the sensor makes it possible to place the sensor at the inner surface of a circular pipe.

1. Introduction

Liquid films that are wetting surfaces are prominent in many technical applications, for instance on fuel rods of boiling water reactors, were the presence of the film is a necessary condition for a sufficient heat removal. They are found on cooled surfaces furthermore due to condensation or in numerous other fields of chemical and mechanical process engineering. The measurement of the liquid film thickness is therefore of interest in experiments aiming at an optimization of the related industrial processes, or, in certain cases, for their direct monitoring.

There are different methods which can be used for liquid film thickness measurements. The principles are based on extraction of the film by suction [1–3], on photons [4–6], on ultrasound [7] or on electrical impedance [8–13]. Most of these methods are used for the research on two-phase annular flow. Electrical methods have been widely applied for many years in the area of air–water annular pipe flow. They are mostly based on the relationship between conductance and liquid film thickness between a pair of electrodes. To apply this technique, the liquid must be electrically conductive. As a second option, capacitance can be used as primary measuring quantity in case of nonconductive liquids [14].

The electrical liquid film sensor used for the current work is based on the principles of the signal acquisition of wire-mesh sensors [15]. The first application of this signal acquisition method for the measurement of a liquid film thickness was presented by Belt et al. [16,17]. Electrodes are mounted flush to the wall of a flow channel. The sensor represents therefore essentially a non-intrusive technique. The receiver electrodes are circular conducting surfaces. The circumferential pitch between two receiver electrodes is 4.9 mm. The transmitter electrodes are ring shaped and placed in an axial distance from the receivers. A total of 10 rings of 32 measuring positions follow each other in axial direction. A second ring-shaped electrode separates the transmitter ring from the subsequent ring of receiver electrodes. The separation of measuring positions in axial direction is 19.5 mm. The spatial resolution of a sensor delivering a spatial distribution of the measured quantity is given by the dimensions of the smallest structure which is resolved. Since the conductance is averaged

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over the area of $4.9 \times 19.5\ mm^2$ given by the electrode spacing, the sensor averaged over smaller structures of the film thickness distribution, which defines the spatial resolution. The measuring frequency was set to 5 kHz.

The electrical current flowing between electrodes mounted flush to the wall reaches saturation at a certain liquid film thickness. This is a fundamental property of the electrical potential field. Since the field strength decreases with growing distance from the electrodes, the sensibility to a change of the film thickness decreases when the film becomes thicker. The current converges toward a value characteristic for an infinite coverage with the conducting liquid. The range at which the sensibility is still sufficient for a film thickness measurement is called "penetration depth". It depends on the geometry of the electrodes and scales with their size. This limits the measuring range. A similar behavior was found by Hu et al. [18] for capacitance measurements with electrodes flush to the surface. In case of the sensor presented by Belt et al. [16,17], the penetration depth at which 95% of the saturation is reached is 3.3 mm.

Da Silva et al. [19] proposed a sensor with higher spatial resolution. Individual sensitive positions were designed as an interdigital structure of a pair of electrodes arranged in a two-dimensional measuring matrix. The current generated between a pair of interdigital electrode is sampled and used as a measure of the film thickness. The lateral period of measuring positions is 7.8 mm in the first and 9.7 mm in the second direction; the measuring frequency is 2500 Hz for a matrix with the dimensions of 64×64. Transmitter electrodes have three fingers ranging into gaps between the fingers of the opposite receiver electrode. The interlaced structure has a spatial wavelength of 2.6 mm. The described structure leads to a penetration depth of 0.69 mm given by the authors for 97% of saturation. This is a quite small measuring range compared to the lateral resolution given by the spatial period of electrode pairs of about 8–9 mm. The small relative penetration depth which corresponds to only about 10% of the lateral resolution is a clear disadvantage. The benefit of the interdigital geometry lays in a higher signal strength and with it in a better sensibility for very thin films of a liquid with low conductivity. This was not important neither in the application to gravity driven mixing processes in a pool [19] nor in the experiments in the hydraulic coupling [20]. Both cases would have benefitted from a higher penetration depth providing more information from beyond the boundary layer.

The first step to increase relative penetration depth is the abandonment of the interdigital structures, which is accompanied by a reduction of the signal strength. This can be compensated by a higher amplification of the input cascades of the signal acquisition system. A second step consists of an optimization of the electrode geometry. Li et al. [21] have shown that the relative penetration depth of a single permittivity sensor with electrodes flush to the wall can be increased by grounded shield electrodes put between the measuring electrodes. Since sensors for permittivity and for conductivity behave essentially similar, this concept can be applied to conductivity sensors as well. Damsohn and Prasser [22] succeeded in applying the approach of using shield electrodes to increase the penetration depth relative to the lateral electrode pitch in two-dimensional sensor arrays. Also there, the lateral resolution can be increased by arranging grounded surfaces between transmitter and receiver electrodes. In [22] a number of periodic electrode structures were identified that are compatible with the concept of the two-dimensional measuring array of their liquid film sensor. This is novel compared to the solution of Da Silva at al. [19], which used grounded surfaces only to reduce cross-talk by shielding the second neighbors of receiver lines from the potential of the activated transmitters. A sensor based on electrodes and ground pitches with a circular shape represents a good compromise of resolution, penetration depth, signal quality and easy manufacturing is described in [23]. This sensor geometry was taken as the basis for the multi-range sensor described below.

2. Sensor design

The sensor consists of a matrix of electrical conducting pads arranged flush on an insulating surface which is representing the wall of the flow duct in the same time. The conducting areas serve as electrodes for establishing a contact with the fluid. There are three different types of electrodes, namely transmitter, receiver and ground electrodes. The basic idea for the fast acquisition of time sequences of two dimensional film thickness distributions is the measurement of the electrical current flowing from a transmitter pad to a neighboring receiver pad due to potential difference between both electrodes. The current depends on the thickness of the electrically conducting liquid film covering both electrodes. The two-dimensional array is arranged in such a way that the transmitting electrodes are connected in one direction (transmitter lines), while the receiver electrodes are coupled perpendicular (receiver lines) to this direction (Fig. 1). The voltage pulses are supplied to the transmitter lines in successive order. During the excitation of each transmitter line, all currents arriving at the receiver lines are sampled in parallel. After the excitation of the last transmitter electrode, a complete matrix of primary measuring values is recorded. These values represent the conductance distribution in the liquid film on the sensor surface, which is the measure of the film thickness.

The signal acquisition method used for this sensor is equivalent to the one of the wire-mesh sensors, which is described in detail in [15]. A special feature of the wire-mesh electronic circuitry is the low impedance of transmitter driver and receiver pre-amplifier cascades, which guarantees that the potential at all non-activated transmitter electrodes and all receiver electrodes remains very close to ground potential. This is an important feature to suppress cross-talk to far located receiver electrodes, as discussed in [15]. The low impedance guarantees that all receives and the not activated transmitter electrodes stay on ground potential during the activation of one set of transmitter electrodes. Consequently, parasitic currents traveling from not activated transmitters to receivers as well as from a receiver electrode to a neighboring one are not induced and cannot affect the measurement.

The sensor introduced in this work is a modification of the sensor presented in [23]. The diameter of receiver and transmitter electrodes was set to 0.5 mm, whereas the ground electrodes had a diameter of 0.9 mm (Fig. 2). The distance between the centers of

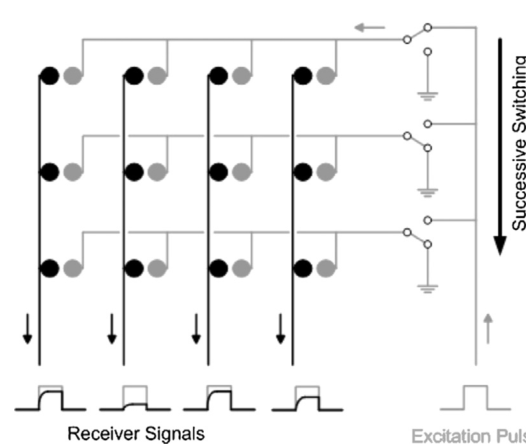

Fig. 1. Connection of electrode pads forming the sensor matrix [23].