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Numerical Analysis for Conductance Probes, for the Measurement of Liquid Film Thickness in Two–Phase Flow

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Abstract

A three–dimensional numerical tool is developed to calculate the potential distribution, electric field, and conductance for any types of conductance probes immersed in the wavy liquid film with various shapes of its free surface. The tool is validated against various analytical solutions. It is applied to find out the characteristics of the wire–wire probe, the flush–wire probe and the flush–flush probe in terms of resolution, linearity, and sensitivity. The wire–wire probe shows high resolution and excellent linearity for various film thickness, but comparably low sensitivity for low film thickness fixed. The flush–wire probe shows good linearity and high sensitivity for varying film thickness, but resolution degrading with an increase in film thickness. In order to check the applicability of the three types of probes in the real situation, the Korteweg–de Vries(KdV) two–dimensional solitary wave is simulated. The wire–wire probe is strongly affected by the installation direction of the two wires; when the wires are installed perpendicularly to the flow direction, the wire–wire probe shows large distortion of the solitary wave. In order to measure the transverse profile of waves, the wire–wire probes and the flush–wire probes are required to be separately installed 2mm and 2mm, respectively.

1. Introduction

The wavy liquid films encountered in various types of process systems are known important role in their heat and mass transfer characteristics. Therefore, information on the localized wave characteristics of the liquid film is needed to predict their effects on the heat and mass transfer. In order to obtain the knowledge of the film and wave shape, a large number of conduction measurement techniques have been developed and analyzed to find out their characteristics.

The flush–flush probes of various designs have been used by different workers: Collier and Hewitt (1967) and Telles and Dukler (1970). Using a Schwartz–Christoffel transformation, Coney(1973) provided an analytical solution for prediction of the electrical conductance of the flush–flush probe as a function of the film thickness. He pointed out that the response of the flush–flush probe saturates for film thickness above the distance between electrodes.

The wire–wire probes have been widely used by several workers: Chu and Dukler(1974) and Karapantsios et. al. (1989). Brown et. al. (1978) derived an analytical form which enables us to predict the response of the wire–wire probe to the square wave. It is found out that its resolution heavily depends on the ratio of the diameter of the wire to their separation distance.

The flush–wire probe was suggested and analyzed by Kang and Kim (1992). For its analysis they developed a three dimensional numerical tool to solve potential distribution in the liquid film for several types of probes immersed in the liquid film with one square wave and applied it for their comparative analysis without its validation. If a 3–D numerical tools is validated, it becomes a powerful tool to find out the characteristics and applicability of several conductance probes.

Here, a three–dimensional analytical tool is validated and used to check the characteristics of several types of conduction probes such as flush–flush probes, wire–wire probes, and flush–wire probes. The 3–D tool has a capability of calculating potential distribution, electric field, and conductance. Its results for several types of probes are compared in terms of resolution, linearity, sensitivity, and hysteresis.

The first part describes the numerical tool and its validation. In the second part the characteristics of several types of conductance probes are investigated. Also, their responses to the KdV two–dimensional solitary wave are simulated to find out their applicability to the real situation.

2. Numerical tool and its validation

In the same way as described in Kang and Kim (1992) the three dimensional potential distribution is predicted using the following Laplace equation and boundary conditions for all the interfaces of the calculation domain of the liquid film:

$$\nabla^2\phi = 0, \tag{1}$$

$$\frac{\partial\phi}{\partial n} = 0. \tag{2}$$

The boundary conditions for the electrodes except the wire–wire probe can be written as follows:

$\phi = V$ for the source electrode,
$\phi = 0$ for the measuring electrode.

For the wire–wire probe in which the center plane between the wires represents zero potential for the following boundary conditions:

$\phi = +V/2$ for the source electrode,
$\phi = -V/2$ for the measuring electrode.

The power dissipation , p, in the liquid film divided by its conductivity, σ, becomes

$$Q = p/\sigma = \int_V |\nabla\phi|^2 \, dV. \tag{3}$$

For resolution the 95% region is defined as

$$0.95 = \frac{\int_{V_{95}} |\nabla\phi|^2 \, dV}{\int_{V_{total}} |\nabla\phi|^2 \, dV}, \tag{4}$$

where V_{95} :volume in which 95% of power dissipation occurs,
V_{total} :total volume of liquid film in the calculation domain.

The smaller 95% region of the probe means its higher resolution. Since for given source voltage, the total current generated in the liquid film is proportional to Q defined in Eq.[3], sensitivity and linearity can be checked by calculating Q for various film thickness.

3. Validation

The present 3–D numerical tool is verified using the well–known analytical solutions. For the wire–wire probe with its separation distance, d, radius, r, and voltages, +V and -V for its electrodes, the following analytical function can be used for calculating a 3–D potential distribution:

$$\phi = \frac{V}{lnK} ln \frac{(x+a)^2 + y^2}{(x-a)^2 + y^2}, \tag{5}$$

where $a = \sqrt{h^2 - r^2}$,
$h = d + r$,
$K = ((h+a)/r)^2$.

Note that the above analytical solutions are derived with the assumptions of the negligible electrical resistance of the wire, its uniform surface, negligible conductivity of vapor, negligible three–dimensional effects at the interfaces, and being exactly parallel with each other and normal to the wall

As shown in figure 1 which represents the potential distribution at y=0 plane calculated analytically and numerically, there is in good agreement with each other, with 4.8% of the maximum error which is generated at the node closest to the wire. The reason why at the grid closest to the wire the maximum error mostly comes from representing the cylindrical wire by the rectangular grid in the numerical calculation. In the infinite medium with the flat film thickness, h, the capacitance between the source wire with its source, +V, and the zero potential plane is analytically derived as follows:

$$C = \frac{2\pi\epsilon h}{ln[1 + d/r + \sqrt{(1+d/r)^2 - 1}}, \tag{6}$$

where d: distance between the wire and the zero potential plane.
The zero potential plane is an anti–symmetrical plane for the wire–wire probe with its source and measuring electrodes charged with voltages,+V and -V, respectively. By using the following relationships among conductance, capacitance, current, and Q defined in Eq.[3],

$$G = C\sigma/\epsilon = I/V = Q\sigma/V^2, \tag{7}$$

Q is expressed in terms of h as follows:

$$Q = \frac{2\pi V^2 h}{ln[1 + d/r + \sqrt{(1+d/r)^2 - 1}}. \tag{8}$$

Since Q is proportional to I, the current flowing between the two wires linearly depends on the variations of the film thickness. Also, for given h, d, and r, the current depends on the square of the voltage difference between two electrodes. For the wire–wire probe with V=10V, d=0.5mm, and r=0.05mm, the analytical and the numerical simulations are performed for comparison. As shown in figure 2, the results from the numerical tool is higher by 7% than those from the analytical expression. Brown et. al. (1978) derived the following analytical solutions for the wire–wire probe with the wire distance, d, and the wire radius, r, immersed in the width of the film in the x direction, L:

$$Y = \frac{ln(d/r)}{ln[(d/r)\sqrt{\frac{\sin^2(\pi s/L) + \sinh^2(\pi d/(2L))}{\sin^2(\pi s/L) + \sinh^2(\pi r/(2L))}}]}, \tag{9}$$

where Y : ration of measured to effective wave height,

s : distance from the edge of the wave.

Note that the above analytical solutions are derived for no base film and the infinite width in the y direction in order to eliminate their dependence on the spatial variable, y. Then, the problem becomes two dimensional. For numerical calculation two cases are studied; without base film and with base film of which size is 1/4 of the maximum film thickness. As shown in figure 3, the numerical results without the base film are in good agreement with the analytical ones while those with the base film are higher over the film width than the analytical ones. The case with the base film shows the three dimensional effect. Therefore, Brown's analytical solutions are only valid for the liquid film with the very thin base film compared with the maximum film thickness and the relatively large width in the y direction.

4. Comparison of the characteristics of several types of probes

Resolution indicates how fine waves can be detected and is quantified through the definition to the 95% resolution region. The 95% resolution region represents the size of rectangular region in which 95% of electric dissipation takes place in the liquid film. As shown in Fig.4, the 95% resolution region of the wire–wire probe is kept constant for varying film thicknesses, while they increase in the film thickness for the flush-wire probe and the flush-flush probe. Below 2mm of the film thickness, the flush-wire probe has the lower 95% resolution region than the wire-wire probe does.

Sensitivity denotes how sensitively conductance can be changed with respect to the variation of the thickness of liquid film and high sensitivity means the high amplitude of electric current between the electrodes of a conduction probe for given liquid depth because the electric current is zero for the zero thickness of liquid film. Linearity represents how linearly the electric current can be changed with respect to the liquid depth. As shown in Fig.5 the wire-wire probe shows the linearity over the whole simulated film thickness while the flush-wire probe over the region higher than 4mm of the film thickness does. The sensitivity of the flush-wire probe is higher than that of the wire-wire probe for the film thickness lower than 4mm because of the use of the plate electrode in the flush-wire probe instead of the thin wire used in the wire-wire probe.

Hysteresis is related to how much the liquid film remaining on the wire after a decrease in the liquid depth affects the signal of the conductance. The hysteresis of the wire-wire probe is simulated by increasing the size of the square ring of the liquid film remaining on the wire. The axial thickness of the liquid film remaining on the wire is assumed to be equal to the base film thickness. It turns out that the hysteresis effect with even 0.4mm of liquid film remaining on the wire is negligible small; lower than 1% of the variation of the current in comparison with the case of no film remaining on the wire.

5. Application to a Korteweg-de Vries type(KdV) solitary wave

In order to see the performance of several types of conductance probes in a real situation, a following moving two–dimensional KdV solitary wave is simulated:

$$\delta(\xi) = \delta_o + h_o sech^2(k\xi) \tag{10}$$

where δ_o : thickness of the substrate,
h_o : wave height at the center of the wave,
ξ : the axial distance from the center of the wave,
k : wave number.

For simulation it is assumed that the wave number of the roll wave is equal to k which is the wave number of the most fast growing wave at the marginal stability of Helmholtz instability defined as

$$k = \sqrt{\frac{(\rho_l - \rho_g)g}{\sigma}}, \qquad (11)$$

and that the ratio of h_o to δ_o is equal to 3.
Two cases, 2mm and 10mm of the maximum film thickness are simulated for the three types of conductance probes. For the latter case, only the wire–wire probe exactly represents the KdV solitary wave while the flush–wire probe and the flush–flush probe seriously distort it in the region within $\pm 2mm$ of the axial distance from the wave center as shown in Fig.6. However, as shown in Fig.7, for the 2mm case, the flush–wire probe well represents the solitary wave. As shown in Fig.4 , the 95% resolution regions of the wire–wire probe and the flush–wire probe are almost the same, being equal to 1.2mm. In order to well represent a solitary wave, we need a probe at least with 1.2mm of the 95% resolution region.

When the wire–wire probe in which the two wires are installed perpendicularly to the flow direction is used for the KdV solitary wave, it turns out that the solitary waves are severely distorted as shown in Fig.8.

6. Conclusions

A three–dimensional numerical tool is applied to find out the characteristics of the wire–wire probe, the flush–wire probe and the flush–flush probe. The wire–wire probe shows high resolution and linearity, but low sensitivity. The flush–wire probe shows high sensitivity but resolution degrading with an increase in film thickness.

When the KdV solitary wave is simulated, the wire–wire probe is strongly affected by the installation direction of the two wires. It is shown that the wire–wire probe installed perpendicularly to the flow direction and the flush–wire probe well represent the KdV solitary wave up to 10mm and 2mm of the peak height of the liquid film, respectively.

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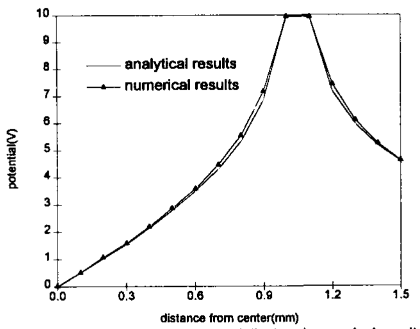

Fig.1 Comparison between analytical and numerical results for wire-wire probe

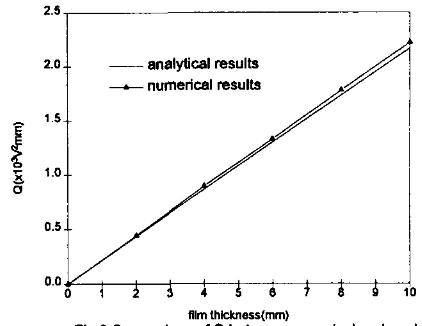

Fig.2 Comparison of Q between numerical and analytical

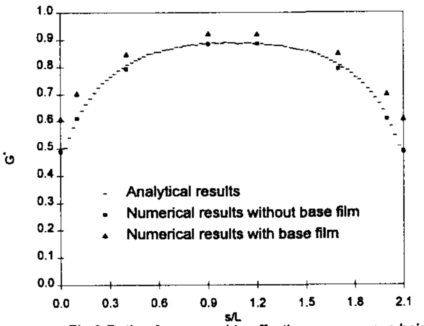

Fig.3 Ratio of measured to effective square wave height

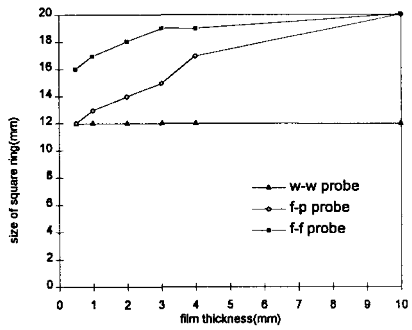

Fig.4 Comparison of resolution of several types of probes

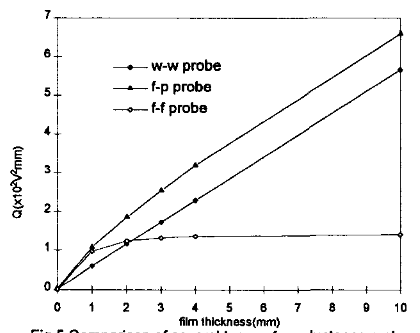

Fig.5 Comparison of several types of conductance probes in terms of sensitivity and linearity

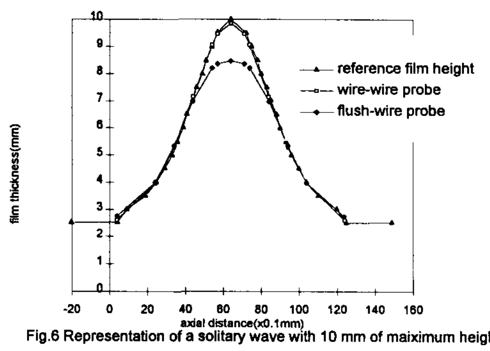

Fig.6 Representation of a solitary wave with 10 mm of maiximum height by wire-wire probe and flush-wire probe

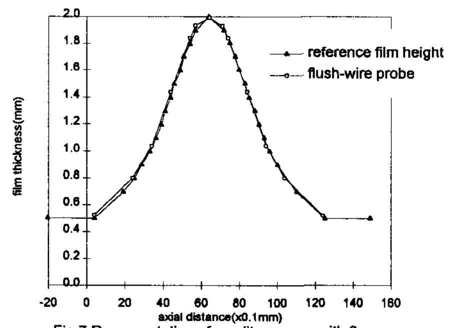

Fig.7 Representation of a solitary wave with 2mm of the maiximum height by a flush-wire probe

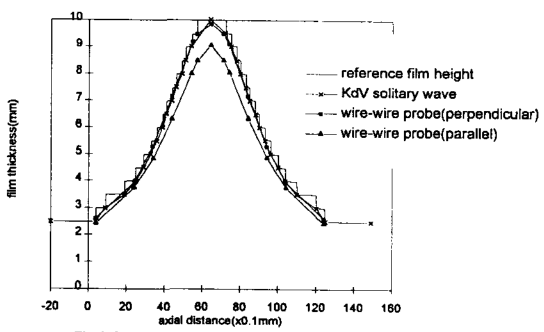

Fig.8 Comparison between wire-wire probes perpendicular to and parallel with flow direction