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Research of non-contact measurement for high viscous fluid falling film thickness on spherical series surface

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In the heat exchange system, the thickness of viscous liquid film on the surface of corrugated tube formed by fluid is an important parameter to control the performance of heat exchange. Because the surface of corrugated tube is a spherical series surface, it makes it difficult for measuring the thickness of liquid film. Based on the measuring object of liquid film formed by fluid on the surface of the corrugated tube, we specially designed a capacitive sensor for this kind of abnormity surface in the paper. We detailedly introduced the structure and operational principle of capacitive sensor, the circuit design and software system analysis, finally we displayed the waveform chart formed from the field data. Experimental results showed that the measuring system realized high precise and non-contact measurement for the liquid film thickness on the surface of the corrugated tube.

1. Introduction

When we use non-contact capacitive sensor to measure the thickness of liquid film on corrugated tube surface, the sensor head and the external surface of the corrugated tube constitutes two electrode plates respectively, which can be equivalent to a parallel plate capacitor [1]. Under the condition of position between sensor and measuring surface being fixed, the liquid film thickness on the surface of corrugated tube determines the effective distance between the two measuring plates and dielectric constant [2]. Literature [3] introduced a method to measure thickness of a dielectric water film coating with a capacitance sensor. Literature [4] successfully applied the capacitance online thickness measurement technology in lithium batteries industry. The common point is that the water film coating and lithium battery coating are both flat surface. In this article, the liquid film we are testing has high viscosity and is non-conductive, we regard the film as medium of capacitive sensor. In the whole measuring process, we keep enough and a constant space between the sensor and film surface to ensure the sensor and the liquid film surface without contact, it will not cause any impact on the physical form of liquid film and measurement results. Due to the special shape of corrugated tube, considering the factors such as precision of capacitive detection method and installation convenience, we only measure in two locations of wave peaks and wave hollows of the corrugated tube [5]. Because the surface of corrugated tube is a curved surface, not a ideal flat, we must revise error in the final measurement results [6].

2. Fundamental principle

2.1. The operating principle of capacitive sensor

The working principle of capacitive sensor is to transform the physical quantity variation into capacitance variation. According to the formula $C = \varepsilon S/d$, there are three parameters namely dielectric constant ε, overlap area S and the electrode distance d, whichever can result in the corresponding change of capacitance.

In our system, both the dielectric constant and electrode distance is changeable. There are non-conductive medium polytetrafluoroethylene (PTFE) protecting cap, air and liquid film between the two electrode plates, the dielectric constant ε depends on the different proportion of the three medium. Here, the sensor head is one electrode plate, and the surface of corrugated tube is another electrode plate, the equivalent distance between two

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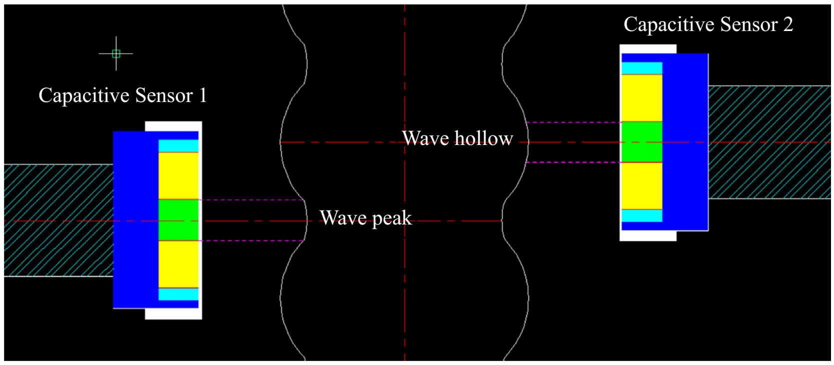

Fig. 1. Equivalent longitudinal cross-section diagram for measuring sensor.

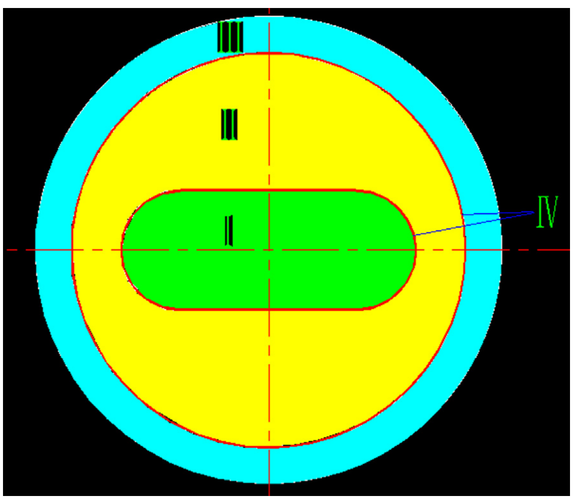

Fig. 2. The external lateral view of capacitive sensor.

plates is the electrode distance d. Two independent sensors are distributed on both sides of the corrugated tube with an angle of 180° to measure film thickness in wave peak and wave hollow respectively [7]. During the measuring process, the central axis of the two sensors and the central axis of the corrugated tube are required to be coplanar, and the horizontal axis of effective measuring electrode and the horizontal axis of wave peak or wave hollow of the corrugated tube are coplanar. Fig. 1 shows the schematic diagram of measuring principle.

2.2. Design of capacitive sensor

Fig. 2 shows the external view of capacitive sensor. There are four areas: I (green[1] area) represents the effective measuring electrode, II (yellow area) represents equipotential ring, III (cyan area) represents outside shielding layer, and IV (red area) represents the insulating layer. Specially, the outside shielding layer III needs to connect to ground together with corrugated tube. Electrode I, electrode II and electrode III are insulated each other through insulating layer IV [8]. In measuring process, the capacitance is produced between the electrode I and the surface of corrugated tube, which is called the main measuring area. Electrode II is used to effectively amend the electric field line emitted from electrode I, and guarantee as many as possible electric field lines to emit in the direction of corrugated tube [9], consequently, the edge effect between electrode I and III reduces in a large extent.

The shape of effective measuring electrode is composed of two semicircle and a rectangle. This structure is to make the effective measuring electrode facing the corrugated tube in a narrow longitudinal width, to minimize the longitudinal curved surface error caused by the surface of corrugated tube, and correspond to the maximum film thickness in wave peak or wave hollow [10]. The sensor is required to install an external protecting cap. The protecting cap is made from polytetrafluoroethylene (PTFE) with the characteristics of acid resistance, alkali resistance, all kinds of organic solvent resistance and high temperature resistance, so it can effectively protect sensor's end face in measuring environment, and will not influence the accuracy of measurement greatly. For the convenience of calculation, the effective measuring electrode is equivalent as Fig. 3.

In Fig. 3a, l is maximum width of sensor's effective measuring electrode, r is radius of semicircle, b is height, $b = 2r$. Then the sensor's shape can be equivalent to a rectangle with width l' and height b shown in Fig. 3b, the l' is equivalent to a constant:

$$l' = \frac{\pi r^2 + b\cdot(l-2r)}{b} = l + b\cdot\left(\frac{\pi}{4} - 1\right) \tag{1}$$

2.3. Mathematical model of capacitive sensor

Based on the average effect of capacitive sensor, when the longitudinal width of sensor's effective measuring electrode is small enough, the longitudinal curved surface error in the overlap area of sensor head and corrugated tube can be ignored, then corrugated tube in wave peak and wave hollow can be equivalent to two uniform cylinders with different diameters. Then we focus on sensor's effective measuring electrode to do local analysis [11,12]. Fig. 4 shows the cross-section vertical view of effective measuring electrode and corrugated tube.

In Fig. 4, the meaning of parameters is listed as follow:

- R-radius in the position of wave peak or wave hollow of corrugated tube,
- α-angle between the vertical center axis and circular sector formed when the sensor's effective measuring electrode is projected onto the corrugated tube,
- a-thickness of polytetrafluoroethylene (PTFE) protecting cap,
- l'-width of sensor's effective measuring electrode after being equivalent,
- d-minimum distance from corrugated tube to sensor's external face,
- δ-thickness of liquid film to be tested,

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.