



Recent Advances In Nano Science And Technology 2015 (RAINSAT2015)

## Design of Thin Film Capacitive Sensor for Flow Measurement

K J. Kumaresh, P. Deepak Raj, M. Sridharan\*

*Functional Nanomaterials & Devices Lab, Centre for Nanotechnology & Advanced Biomaterials and  
School of Electrical & Electronics Engineering, SASTRA University, Thanjavur - 613 401, India*

---

### Abstract

We report the design methodology of thin film capacitor (TFC) device using thermal evaporation technique for quality study or material differentiation application by testing with liquid (different concentration) and solid. A simple and special modification was incorporated in thermal evaporation setup for depositing semi cylindrical capacitor design on a capillary tube (CT). In order to avoid the disturbance due to electrostatic noise disturbance, TFC was covered with another glass tube, aluminum (Al) metal foil (as shield) and finally by plastic tube cover. Electrodes were taken from the film using silver paste and connected as input to the LCR-Z meter. The capacitance value of the thin film was varied up to 15-16 pF from the initial value (Al: 129 pF, Cu: 130 pF) when subjected to the static flow. A low cost embedded micro controller module with Liquid Crystal Display (LCD) was developed for the real time testing of TFC.

© 2015 Elsevier Ltd. All rights reserved.

Selection and Peer-review under responsibility of [Conference Committee Members of Recent Advances In Nano Science and Technology 2015].

*Keywords:* Thin films deposition; Semi cylindrical capacitor; Thermal evaporation; Capacitive sensor; Static flow measurement.

---

\* Corresponding author. Tel.: +91-4362-304000 Ext 2277; fax: +91-4362-264120.

*E-mail address:* [m.sridharan@ece.sastra.edu](mailto:m.sridharan@ece.sastra.edu)

## 1. Introduction

Flow measurement is an important aspect necessarily carried out in several areas like nuclear reactors, industrial applications, automobiles, biomedical application etc., for monitoring and or measurement or analyzing. Several flow measurement techniques had been reported for the measurement of void fraction, bubble distribution, bubble frequency, bubble size, velocity, growth rates etc., In all those measurement techniques the objective was to find one or more of the following parameters, bubble size distribution, void fraction profiles, phase fraction distribution, bubble velocity distribution, volume-averaged void fraction, flow regime characteristics, fluid temperature, bubble size, bubble velocity, bubble growth rate, level detection, flow pattern identification, time-averaged void fraction, concentration etc., This paper deals about concentration analysis of materials for material differentiation in static flow measurement. The application involving study of materials through concentration will be greatly useful for in situ analysis of oil quality in engines or machines or about study of biodegradable materials like milk or about analysis of liquid medium for contamination etc.

Flow measurement is carried out either intrusively or without flow objection. Intrusive methods include wire mesh sensors [1, 2], rod bundle [3] and optical probe [18]. Non-intrusive type measurements are carried out using different techniques like impedance method [4, 5], radiation method [6, 11], optical method [7], pressure [8], RF [9], induction [10] and capacitance [12-17]. Non-intrusive methods are generally preferred and out of those non-intrusive measurement techniques, capacitance is preferred because of its design simplicity and different interface possibilities for signal measurement. The reported works had employed one of the following metal electrodes for capacitor plates, such as copper [11,12,14,16,17,19] or aluminum [17,19] or brass [9,15] or stainless steel [5] over the one of the following dielectric tube such as glass [19,13,17] or plastic [6,7,9,12,14] or acrylic [4,11,15,16]. Abdullah et al. [19] tested different capacitor configurations and determined, strip and parallel plate capacitor [23] is more sensitive than other capacitor configurations. Thus, we have chosen strip type capacitor as it is more sensitive and suitable for semi cylindrical capacitor design.

The objective of this work is to design and develop thin film semi cylindrical capacitor structure over capillary tube (CT) using Aluminium (Al) or Copper (Cu) metal and to study the response of thin film capacitor (TFC) device with respect to different concentration of the material. The advantage of designing semi cylindrical capacitor structure over capillary tube is that the device can directly inserted in between or in parallel to the suitable liquid flow tube. The design was carried out using thermal evaporation technique with the help of a special setup designed using DC motor.

## 2. Experimental details

### 2.1. Deposition technique

The major drawback of coating thin film over the CT in stationary mode was uneven deposition which affects the sensitivity/responsivity of the device. In order to overcome the drawback mentioned simple modification was made in deposition chamber setup by fitting dc motor to obtain even deposition. Glass substrates and capillary tubes used for deposition were cleaned with soap water & distilled water and ultrasonically agitated for 5 min in acetone and then dried in hot air oven. The cleaned substrates and CT (fixed on the motor shaft) were loaded inside the chamber. TFC over CT was made by depositing two semi cylindrical electrodes separated with 2 mm distance on both sides. The electrode separation was done by simple masking technique. The chamber was evacuated to the base pressure of  $5 \times 10^{-5}$  mbar and the source to substrate distance was maintained at 7 cm. Aluminum (Al) and copper (Cu) strips (99.99 % purity) was used as the source material and evaporated using the tungsten filament. Al and Cu thin films were deposited over the rotating CT (driven by 6 V, 60 rpm motor) using vacuum evaporation technique. The deposited films were annealed at 200 °C in vacuum for 1 hr to obtain increased adhesion with the substrate and to avoid the oxidation while exposed to ambient air. The schematic representation of thermal evaporation set up fitted with DC motor is shown in Fig. 1.

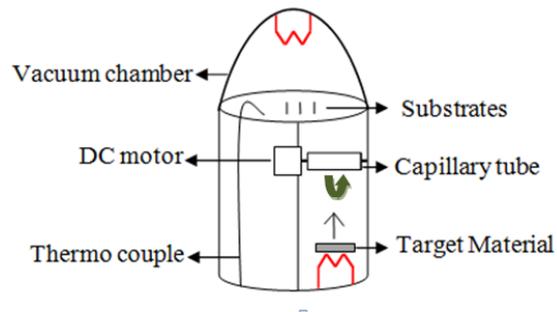


Fig. 1. Thermal evaporation setup with DC motor for CT deposition

As deposited films were characterized using the X-ray diffraction (XRD) (Rigaku Ultima III) which is operated with  $\text{CuK}_\alpha$  radiation ( $1.5406 \text{ \AA}$ ) and field emission scanning electron microscopy (FE-SEM) (JEOL JSM 670 1F) which is operated with an accelerating voltage of 3 kV and operating distance of  $\sim 4.8 \text{ nm}$  to study the structural and morphological properties respectively. The electrical studies (capacitance and resistance) of the deposited semi-cylindrical TFC were measured using the LCR/Z meter operated at different frequency (KOKUYO KC605).

## 2.2 Capacitor sensor fabrication

In the semi cylindrical TFC, metal contacts were taken using the silver paste is shown in Fig. 2(b). To avoid damage and interference (electrostatic interference) TFC with metal contacts was covered with glass tube and over which the aluminium shield was made and connected to the ground using shielded cable. Finally, the TFC device was covered with plastic tube and sealed using Teflon glue to avoid axial movements of TFC. The schematic and fabricated TFC device is shown in Fig. 2(a) and (b).

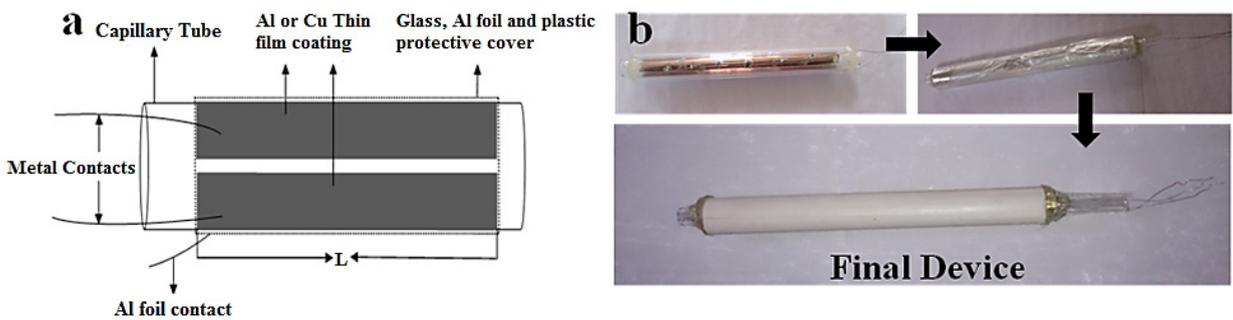


Fig. 2. (a) Schematic of fabricated TFC and (b) steps involved in TFC fabrication

## 3. Results and discussion

### 3.1 Structural and morphological analysis

XRD patterns of the Al and Cu thin films are shown in Figs. 3 (a) and (b) respectively. XRD pattern of the Al films has no significant peak corresponding to the reflections of Al which confirms that the deposited Al film was amorphous in nature. XRD pattern of the Cu has a preferential orientation peak at  $2\theta$  angle of  $43.6^\circ$  corresponding to the reflection plane (111) with cubic crystal structure which was also observed by Habibi *et.al.*[20].

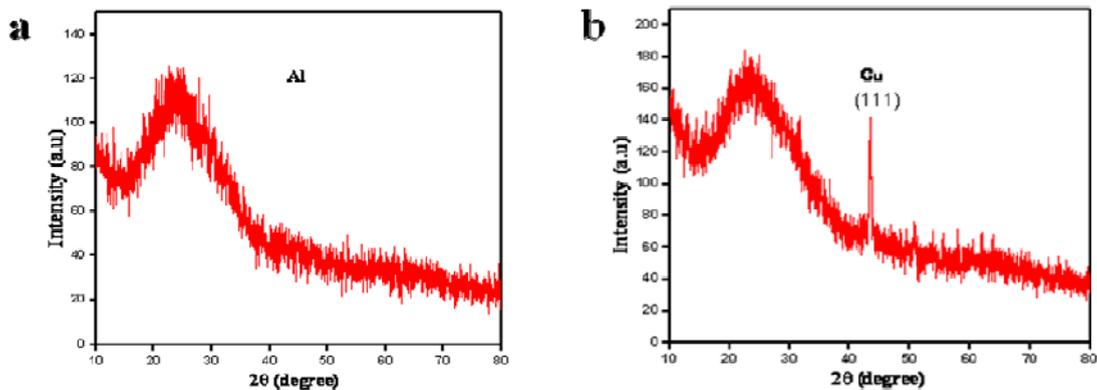


Fig. 3. XRD patterns of (a) Al and (b) Cu thin films.

FE-SEM micrograph of Al and Cu thin films are shown in Figs.4 (a) and (b) respectively. FE-SEM micrograph of Al films shows grains of different size and presence of defects. FE-SEM micrograph of Cu thin film shows flakes like morphology which is due to the agglomeration.

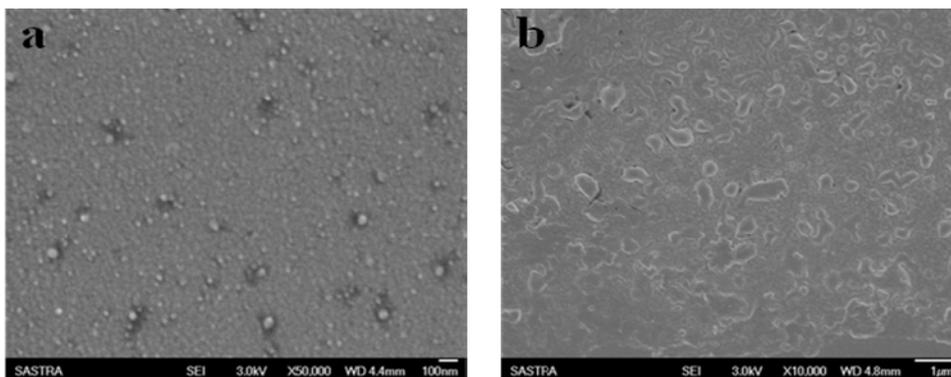


Fig. 4. FE-SEM micrographs of (a) Al and (b) Cu thin film.

### 3.2 Electrical studies

The sheet resistance of thin films was studied using 4 probe measurement technique, an average resistance of  $0.49 \Omega$  and  $0.25 \Omega$  was obtained respectively for Al and Cu thin films, which indicated that the deposited metal films were good conductors. Capacitance measurement of Al and Cu TFC is done using LCR meter in which, capacitance of 29 and 130 pF is obtained respectively.

### 3.3 Capacitance measurement

The theoretical prediction of capacitance of semi cylindrical capacitor was discussed by Sagarika PAL et al. [21] and Subir Das PAL et al. [22]. In general, the capacitance of a capacitor is given by the formula,

$$C = \epsilon \times \frac{A}{D} \quad (1)$$

where,  $A$  (area of the electrode) and  $D$  (distance between the electrode) is constant, which is the thickness specification of the designed TFC as given in section 1 and  $\epsilon$  is called dielectric constant of the material. The

capacitance of the device is purely determined by the dielectric constant  $\epsilon$  of the capacitor. The dielectric constant is given by

$$\epsilon = \epsilon_0 + \epsilon_1 + \epsilon_2 \quad (2)$$

where,  $\epsilon_0 = 8.854 \times 10^{-12}$  F/m,  $\epsilon_1$  = dielectric constant of the glass tube and  $\epsilon_2$  = dielectric constant of the material inside the capillary tube. Thus the capacitance of the designed TFC device is mainly based on dielectric constant of the material inside the CT and varies according to its quality or concentration.

The fabricated TFC device was tested for capacitance using LCR-Z meter and an embedded controller device. The embedded controller device was designed using PIC 16F628 a low cost micro controller. It is an 8 bit micro controller with inbuilt analog comparator. With an external 10 k resistor and TFC, a RC oscillator is formed around inbuilt analog comparator. The output of the RC oscillator is a square wave and its frequency is determined by the connected resistor and capacitor. The external resistance value is constant therefore the generated frequency is directly proportional to TFC device capacitance. Thus depending on the material, capacitance changes which in turn is measured in terms of frequency. In addition to RC oscillator the micro controller was programmed as a frequency counter. The RC oscillator output was given as input to the frequency counter and displayed with the help of LCD. The output waveform of RC oscillator and TFC charging and discharging cycle studied using 'FALCON DSO-100C1G' oscilloscope. The conversion of frequency to capacitance is explained in section 3.2. Other than LCR [4] meter, Data acquisition (DAQ) system [12-14] and other signal conditioning [5, 7, 10, 16] system where reported to be used for signal study.

### 3.4 Device testing materials and methods

The designed TFC device was tested with following materials to study its capacitance response with respect to different material concentration. The TFC device was tested with one solid (wooden stick) material and different concentration of liquid materials. Only static flow measurements were carried out because our intention was to test the response of TFC for different concentration of materials. In order to use the designed TFC device in different application areas different testing methods were adopted. For all the test methods the TFC device will be interfaced to the micro controller and the response of the device is measured in terms of frequency. The difference between initial and final value can be used to determine the material based on its concentration. Capacitance deviation of 3 to 4 pF for wooden stick, 2 pF for oil and up to 16 pF for distilled water was noted from the initial value. A minute reduction in capacitance deviation was seen if the distilled water concentration is increased by mixing salt gradually. In addition to LCR [4] meter, TFC was tested in real time by interfacing it with the measurement circuit. The capacitance of the TFC device is measured in terms of frequency and the equivalent capacitance can be found from the RC oscillator formula,

$$C = 0.72 / (R \times F) \quad (3)$$

where, R = 10000 ohms resistor and F is measured frequency. The equivalent initial value capacitance is of 168 and 169 pF for Al and Cu TFC device respectively. A very small capacitance difference of 39 pF was found between the LCR meter and controller based measurement which may be due to the very small change in resistance and supplied voltage was possible from its standard value in embedded controller module and this error doesn't influence the deviation difference between the capacitance.

### 3.5 Measurement result analysis

#### 3.5.1 Concentration test

The concentration test helps in identifying the sensitivity of the designed TFC device with respect to different test materials. The concentration test was carried out with liquid materials like distilled water, tap water (ground water), hair oil and distilled water mixed with different quantity (0.5, 1.5 and 3 g) of table salt. The designed Al and Cu

TFC sensor can hold up to 4.7 and 3.7 ml of liquid respectively. For concentration test, initial frequency was noted down i.e. without any test material. Then the TFC device was completely filled with liquid test materials and the change in frequency was noted. The frequency deviation decreases with increase in concentration. Fig. 5 (a) and (b) shows the result of concentration test for Al and Cu TFC device respectively. From graph it is evident that as the concentration of the salt increases the frequency deviation was less. The reason for the lower frequency deviation may be stated as follows: on the addition of solute hydration may happen such that an appreciable amount of water molecules may froze around solute ions due to the exceeded interaction energy of water molecule dipole than that of the hydrogen bond between species and solvent. Due to the hydration the hydrated salt ion will become bulkier than non-hydrated ion.

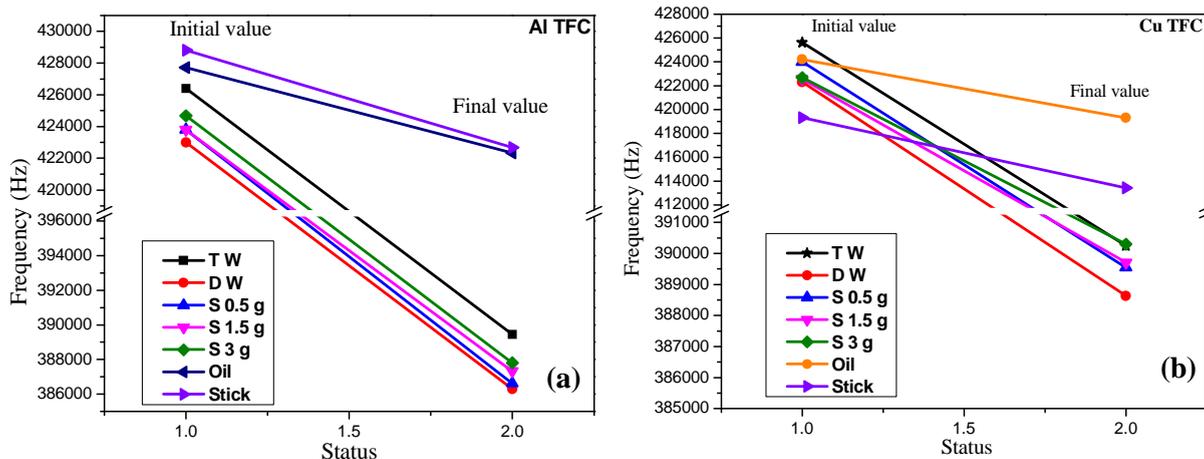


Fig. 5. Plot of concentration test using different material for (a) Al TFC and (b) Cu TFC device.

The hydrate sheath around the dipoles prevents them from orienting themselves with the changing electric field. As a result of this the permittivity was decreased with increase in salt concentration which directly has the impact on the capacitance. The oil has very low frequency deviation than distilled water. The tap water was having higher concentration than the distilled water hence it shows lower frequency deviation. Wooden stick is having a better deviation than the oil material but lesser than the water. A maximum capacitance deviation of 16 and 2 pF from initial value is obtained for distilled water and oil respectively. Initial value for each test is varied because of the device sensitivity to temperature and humidity. Subir das *et al.* [22] designed a semi cylindrical capacitive sensor with signal conditioning and tested it for soil moisture measurement.

### 3.5.2 Length test: Stick

Length test is a solid material test that is testing the response of TFC device using the wooden stick. Wooden stick of length 17 cm and with a diameter of 0.5 cm. This test is used to find the linearity response of the designed TFC device. Initially in level test, the wooden stick will be fully inserted first (corresponding frequency will be measured as initial value) and the stick will be removed in the order of 1 cm and corresponding frequency is noted. Fig. 6. Shows the graph of length test performed using wooden stick in Al and Cu TFC. The graph clearly shows a linear variation of capacitance with respect to stick movement and the variation stabilizes at the removal of stick from the sensor. A capacitance deviation of 3 to 4 pF is noted from the initial value. The test is carried out by fully inserting the wooden stick first and then removing it in the order of 1cm. Subir das *et al.* [22] reported linear change in capacitance in the nano farad range with the variation of soil moisture.

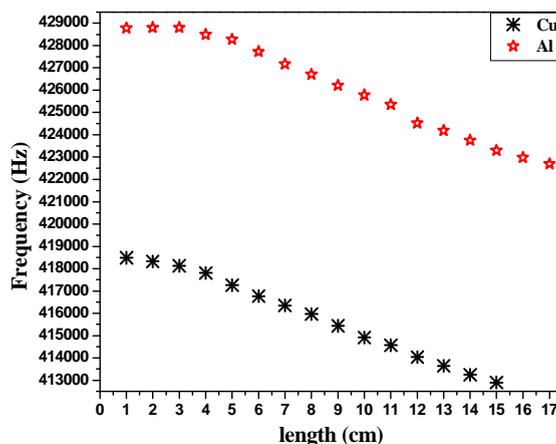


Fig. 6. Graph of length test using stick in Al and Cu TFC device.

### 3.6 Device sensitivity

The designed TFC was very much sensitive to temperature [8, 9, and 21]. Hence, the initial value of each measurements was somewhat differ from one test to other. Whatever may be the initial value the level of deviation to final value from initial value is almost constant for all material, but changes only depending on the test material. Testing of solid material like wooden stick doesn't affect the initial value whereas liquid material like water highly affects successive readings. Hence before each measurement the tube is thoroughly cleaned. The above sensitivity issue has very little effect on the concentration test in room temperature. The entire tests were carried out several times to confirm the sensitivity of the device. Future work should be aimed in designing small sized TFC device with very low or no response to temperature and the same should be used for material analyse under dynamical flow condition.

## 4. Conclusion

Thus in the present work Al and Cu TFC device were successfully designed and developed. The designed device has initial capacitance of 129 and 130 pF for Al and Cu TFC device respectively. The device was tested with different materials and the response to their concentration, level was studied. Increase in capacitance that is deviation of 2 pF for oil and up to 4 pF for wooden stick from the initial value was observed. With increase in the concentration the capacitance of the film decreases which is due to the unchanged dipoles with change in electrical field because of hydrated sheath. From the results it is clear that the device has good linearity and repeatability. The device is designed to be insensitive to electrostatic interference. Presently the device is sensitive to temperature changes because of glass capillary tube and may be avoided by using acrylic or plastic tubes. Out of the two device, Al and Cu, Al is preferred because it is easier to design and its sensitivity is better than copper. The device can be employed in engines or machines to study the quality of the coolant oil.

## ACKNOWLEDGEMENTS

Authors sincerely thank SASTRA University for providing necessary experimental facilities.

## References

- [1] H.M. Prasser, D. Scholz, C. Zippe, Bubble size measurement using wire-mesh sensors, *Flow Measurement and Instrumentation*. 12 (2001) 299–312.
- [2] Marco Jose da Silva, Uwe Hampel, Capacitance wire-mesh sensor applied for the visualization of three-phase gas–liquid–liquid flows, *Flow Measurement and Instrumentation*. 34 (2013) 113–117.
- [3] Takahiro Arai, Masahiro Furuya, Taizo Kanai, Kenetsu Shirakawa, Development of a sub channel void sensor and two-phase flow measurement in 10 X10 rod bundle, *International Journal of Multiphase Flow*. 47 (2012) 183–192.
- [4] H.C. Yang, D.K. Kim, M.H. Kim, Void fraction measurement using impedance method, *Flow Measurement and Instrumentation*. 14 (2003) 151–160.
- [5] Sidharth Paranjape, Susan N. Ritchey, Suresh V. Garimella, Electrical impedance-based void fraction measurement and flow regime identification in microchannel flows under adiabatic conditions, *International Journal of Multiphase Flow*. 42 (2012) 175–183.
- [6] Abdullah Abbas Kendoush, Zareh Azat Sarkis, Void fraction measurement by X-ray absorption, *Experimental Thermal and Fluid Science*. 25 (2002) 615–621.
- [7] David Fogg, Milnes David, Kenneth Goodson, Non-invasive measurement of void fraction and liquid Temperature in microchannel flow boiling, *Exp Fluids*. 46 (2009) 725–736.
- [8] K. H. Chien, T. T. Chen, B. S. Pei, W. K. Lin, Void fraction measurement by using the side tube method, *Flow Measurement and Instrumentation*. 8 (1997) 103–112.
- [9] Jaworek A, Krupa A, Trela M, Capacitance sensor for void fraction measurement in water/steam flows, *Flow Measurement and Instrumentation*. 15 (2004) 317–324.
- [10] Tiemei Yang, Guang Chen, Wuliang Yin, Peipei Hu, Qian Zhao, A high frequency digital induction system for conductive flow level measurements, *Flow Measurement and Instrumentation*. 37 (2014) 83–91.
- [11] Ronghua Zhang, Qi Wang, Huaxiang Wang, Mu Zhang, Hongli Li, Data fusion in dual-mode tomography for imaging oil–gas two-phase flow, *Flow Measurement and Instrumentation*. 37 (2014) 1–11.
- [12] H Canière, CT Joen, A Willockx, M De Paepe, M Christians, E van Rooyen, L Liebenberg, J P Meyer, Horizontal two-phase flow characterization for small diameter tubes with a capacitance sensor, *Meas. Sci. Technol.* 18 (2007) 2898–2906.
- [13] Marco Demoria., Vittorio Ferrari, Domenico Strazza, Pietro Poesio, A capacitive sensor system for the analysis of two-phase flows of oil and conductive water, *Sensors and Actuators A*. 163 (2010) 172–179.
- [14] Kathleen De Kerpe, Bernd Ameel, Sven De Schampheleire, Christophe T’Joen, Hugo Canière, Michel De Paepe, Calibration of a capacitive void fraction sensor for small diameter tubes based on capacitive signal features, *Applied Thermal Engineering*. 63 (2014) 77–83.
- [15] LIU Yi-ping, NIU Gang, WANG Jing, Design of capacitance sensor system for void fraction measurement, *J Zhejiang Univ SCI*. 12 (2005) 1424–1429.
- [16] J.J. M. GERAETS, J.C. BORST, A capacitance sensor for two-phase void fraction measurement and flow pattern identification, *International Journal of Multiphase Flow*. 14 (1988) 305–320.
- [17] MOON-HYUN CHUN, CHANG-KYUNG SUNG, Parametric effects on the void fraction measurement by capacitance transducers, *International Journal of Multiphase Flow*. 12 (1986) 627–640.
- [18] Masahiro Yamada, Takayuki Saito, A newly developed photoelectric optical fiber probe for simultaneous measurements of a CO<sub>2</sub> bubble chord length, velocity, and void fraction and the local CO<sub>2</sub> concentration in the surrounding liquid, *Flow Measurement and Instrumentation*. 27 (2012) 8–19.
- [19] Abdullah A. Kendoush, Zareh A. Sarkis, Improving the Accuracy of the Capacitance Method for Void Fraction Measurement, *Experimental Thermal and Fluid Science*. 11 (1995) 321–326.
- [20] Mohammad Hossein Habibi, Reza Kamrani, Reza Mokhtari, Fabrication and characterization of copper nanoparticles using thermal reduction: The effect of nonionic surfactants on size and yield of nanoparticles, *Microchim Acta*. 171 (2010) 91–95.
- [21] Sagarika PAL, Rasmiprava BARIK, Design, Development and Testing of a Semi Cylindrical Capacitive Sensor for Liquid Level Measurement, *Sensors & Transducers Journal*, 116 (2010) 13–20.
- [22] Subir Das, Tuhin Subhra Sarkar, Badal Chakraborty, A Semi-Cylindrical Capacitive Sensor Used for Soil Moisture Measurement, *World Academy of Science, Engineering and Technology International Journal of Electrical, Electronic Science and Engineering* 8 (2014) 1.
- [23] B.Pranav, B. Arunkumar, T. Vetrichelvan, P. Deepak Raj, M. Venkatesan, M. Sridhran, Thin Film Capacitor for Void Fraction Measurement in a Two-Phase System. *IEEE Xplore – Proceedings ICANMEET 1 (2013) 625–627*.