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To cite this article: H N Nagendra et al 2020 IOP Conf. Ser.: Mater. Sci. Eng. 755 012079

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Design optimization and calibration of a void fraction measurement capacitance sensor for LN2 flow

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Abstract. Cryogenic fluids are used for wide range of industrial and laboratory applications. Vacuum or super-insulated transfer lines are efficiently used to transfer these fluids from the storage Dewars to the end applications. As the heat transfer to the cryogens flowing through the transfer line cannot be completely eliminated, many a times two-phase flow occurs during the transfer process. It is necessary to estimate the quality of the flow (void fraction) and the amount of cryogen being evaporated in the transfer process. Many techniques are available to measure the void fraction, but implementing these techniques to cryogenic fluid flow is sometimes difficult and expensive. Capacitance measurement is easy and simple method to find the liquid level and void fraction. Towards this, an attempt has been made to design void fraction measurement sensor based on capacitance measurement. Most of the capacitance sensors are made with inner glass tube, which needs special attention in handling the device and also it is difficult to make the end connections for the glass tubes. The present work deals with the design optimization of Hylam™ (Bakelite) and fibre-reinforced plastic (FRP) inner tube concave plate capacitance sensors for liquid nitrogen level measurement. 3-D modelling and thermo structural analysis of the developed sensors has been carried out in ANSYS workbench and electrostatic analysis has been carried out using ANSYS Maxwell software. The results obtained by the analysis have been validated with experimental results.

1. Introduction

Many a times two-phase flow occurs during transfer of liquid cryogens. Hence, it is very important to measure the void fraction during the transfer process. Different techniques such as quick-closing valve method, electrical impedance method, capacitance method, constant electrical current method and nuclear magnetic resonance method etc. are available to measure the void fraction [1]. However, most of these techniques are not suitable for cryogenic fluids because of nonconductive and very low temperature nature of these cryogens. Some of the techniques suitable for cryogen flows are gamma ray attenuation method, microwave method, radio frequency technique and capacitance method etc. [2]. Capacitance method is simple, less expensive, easy to construct and more importantly has quick response [3].
Capacitance method works on the principle of different dielectric constant of the gas and liquid phase of the cryogen in between the electrodes, the electrodes being placed on nonconductive tube. Many investigators have used glass or FRP tubes to mount the electrodes for capacitance measurements, though varieties of insulating materials are available.

The present work is based on the study of different insulating tube materials for concave capacitance void fraction sensors, studies on tube thickness and calibration of the developed sensors in horizontal and vertical mounting conditions for different two-phase conditions.

### 2. Selection of insulating tube

In most of the cases the electrodes are mounted on glass tube. Handling of the glass tube and making leak tight end connections are difficult for cryogenic flow. Hence, other insulating materials such as Bakelite, Poly Tetra Fluoro Ethylene (PTFE/Teflon), FRP and nylon tubes are considered and the thermo structural analysis of these materials have been carried out to find the structural stability at 77 K. ANSYS 17 work bench is used for modeling and analysis. Co-efficient of thermal expansion (\(\alpha\)) and poison’s ratio (\(\gamma\)) for different materials are taken from the table 1. An insulating tube (without copper electrode) of 19 mm inner diameter (ID) and variable outer diameter (OD) is modelled with ANSYS software. Initial temperature of 300 K was applied on the tube and 77 K was applied on the inner wall of the tube. ANSYS thermal analysis was done to obtain the temperature distribution throughout the tube. Then ANSYS structural analysis was carried out by importing the thermal boundary conditions from the previous analysis. Structural deformation of the tube was obtained by applying the fixed boundary condition on both ends of the tube. The results from these analyses are plotted in figure 1 and 2.

| Sl. No. | Capacitor No. | \(\alpha (10^{-6} \text{ m/mK})\) | \(\gamma\) |
|--------|---------------|-----------------|---------|
| 1      | Glass         | 4               | 0.22    |
| 2      | Bakelite      | 27              | 0.24    |
| 3      | Teflon        | 125             | 0.46    |
| 4      | FRP           | 70              | 0.14    |
| 5      | Nylon 66      | 80              | 0.41    |

**Table 1.** Material properties [4-8].

![Figure 1. Deformation on outer diameter.](image1)

![Figure 2. Deformation on inner diameter.](image2)

It can be seen from the above figures that the deformation on outer and inner diameters for the glass tube is least compared to other materials like Bakelite, FRP, Nylon and Teflon. As mentioned earlier, making the end connections and leak tight with glass tubes for cryogenic applications is rather difficult. In view of the above, we have considered the next least deformed tube material i.e. Bakelite for the developed capacitance sensor. The studies on Bakelite as insulating material for capacitance...
type level/void fraction sensors will be very useful as there is not much data available in this regard in open literature.

![Figure 3. Total deformation on 19 mm ID and 25 mm OD Bakelite tube.](image)

A similar analysis procedure was followed for obtaining the total deformation of the capacitance sensor with copper electrode and Bakelite inner tube. The total deformation for a 19 mm ID and 25 mm OD capacitance sensor assembly with liquid nitrogen flowing through it is shown in figure 3. Maximum deformation on the outer tube is 0.1024 mm as compared to the inner tube. As shrinkage to inner diameter is 0.0338 mm, it can be neglected in simulation of capacitance sensors.

3. Measurement of dielectric constant of Bakelite

Bakelite is chosen as the insulating tube of the developed capacitance sensor. As the developed sensor will be used for measuring the level/void fraction of liquid nitrogen, it is necessary to find the dielectric constant of Bakelite at liquid nitrogen temperature (77 K).

![Figure 4. (a) Sample Chamber. (b) Experimental setup.](image)

The dielectric constant of Bakelite is measured by the following method. The parallel plate capacitor electrodes are used to find the dielectric constant of Bakelite. Dielectric constant of the unknown material can be found by placing the sample in between the parallel plates. Figure 4 (a) shows the top and front views of the sample chamber. Sample chamber is of box shaped and made up of copper sheets. This copper box also acts as an active shield.

Two copper electrodes of 38 mm × 38 mm are used as parallel electrodes. The sample is placed in between these parallel electrodes and held tightly by electrically insulated clamps. The sample chamber along with the sample is immersed in a liquid nitrogen bath. The electrodes are connected to
the 1 KHz capacitance bridge with the help of Teflon shielded wires for measuring the capacitance across the electrodes as shown in figure 4 (b).

Initial experiments were conducted by immersing the sample chamber (without Bakelite sample in between the electrodes) in a liquid nitrogen bath. This capacitance value of the sample chamber is known as $C_0$. Again, the capacitance value of the sample chamber along with the Bakelite sample is measured by immersing the whole sample chamber in a liquid nitrogen bath. This value of capacitance is known as $C_b$.

The capacitance $C$, is defined as,

$$ C = (\varepsilon_0 \times \varepsilon_r) (A/d) \tag{1} $$

Where $\varepsilon_0$ is the permittivity of free space $= 8.84 \times 10^{-12} \text{ F/m}$, $\varepsilon_r$ is the relative permittivity, $A$ is the Area of electrode in $\text{m}^2$ and $d$ is the distance between the electrodes in $\text{m}$.

Equation 1 can be written as,

$$ C_0 = (\varepsilon_0 \times \varepsilon_r) (A/d) \tag{2} $$
$$ (A/d) = C_0 / (\varepsilon_0 \times \varepsilon_r) \tag{3} $$
$$ C_b = (\varepsilon_0 \times \varepsilon_r) (A/d) \tag{4} $$

Substituting equation 3 in equation 4 we get,

$$ C_b = (\varepsilon_0 \times \varepsilon_r) (C_0 / (\varepsilon_0 \times \varepsilon_r)) \tag{5} $$

Where $(\varepsilon_0 \times \varepsilon_r) = 1.4 \ [9]$, by measurement, we get $C_0 = 5.3 \text{ pF}$ and $C_b = 10.9 \text{ pF}$. Substituting these values in equation (5), the dielectric constant of Bakelite is found to be 2.06.

4. Design of capacitance sensor

Two concave electrodes capacitance sensor is chosen to acquire the local capacitance. Figure 5 shows the cross-sectional view of the sensor with two concave electrodes, one of which acts as the source electrode and the other as the detector electrode. The opening angle, $\beta$ plays an important role for concave electrode capacitance sensors. Lesser the opening angle less is the change in the capacitance. In our studies we have taken the open angle $\beta$ as 160º since this is the optimum value for these types of sensors [10]. The inner diameter, $D_1 = 19 \text{ mm}$ and length, $L = 50 \text{ mm}$ of the electrode is kept constant for all the designed sensors. The dielectric layer is varied by varying the outer diameter, $D_2$. Table 2 shows the dimensional details of the designed sensors.

![Figure 5. Cross-sectional view of a concave capacitance sensor.](image)
Table 2. Dimensional details of the capacitance sensors.

| Sl. No. | Capacitor No. | D1 in mm | D2 in mm | L in mm |
|---------|---------------|----------|----------|---------|
| 1       | C1            | 19       | 26.2     | 50      |
| 2       | C2            | 19       | 31.6     | 50      |
| 3       | C3            | 19       | 38.0     | 50      |

The simulations of the capacitance values for designed sensors were carried out with the help of ANSYS Maxwell software. 1 Volt input is given to source electrode and $\varepsilon_r$ value is 2.06. Liquid nitrogen dielectric constant is taken as 1.4 [9, 11]. The simulation results for the stratified flow condition are plotted in the figure 6.

Figure 6. Simulation results of capacitance for different level of LN2.

From the simulation results it is clear that, increasing the outer diameter of insulating material increases the area of the electrode that increases the capacitance. After a certain value of the outer diameter, the increase in outer diameter decreases the capacitance. The variation of capacitance for the developed sensors C1, C2 and C3 at different frequencies for 0 % and 100 % LN2 level is shown in figure 7, 8 and 9 respectively. It can be seen from the above mentioned figures that the variation of capacitance with frequency is more for sensor C3 compared to sensors C1 and C2. The variation of capacitance at 100 kHz frequency for all the 3 types of sensors is given in table 3.

Figure 7. Capacitance v/s Frequency for C1.  
Figure 8. Capacitance v/s Frequency for C2.
Figure 9. Capacitance v/s Frequency for C3.

Table 3. \(C_{\text{max}}, C_{\text{min}}\) and \(\Delta C\) for the developed sensors.

| Sl. No. | Capacitor No. | \(C_{\text{max}}, \text{pF} \) Expt. | \(C_{\text{min}}, \text{pF} \) Expt. | \(\Delta C, \text{pF} \) Expt. | \(C_{\text{max}}, \text{pF} \) Simulation | \(C_{\text{min}}, \text{pF} \) Simulation | \(\Delta C, \text{pF} \) Simulation |
|---------|----------------|-----------------|-----------------|----------------|-----------------|-----------------|----------------|
| 1       | C1             | 5.1             | 4.84            | 0.26           | 4.66            | 4.43            | 0.23           |
| 2       | C2             | 6.26            | 5.93            | 0.33           | 5.64            | 5.33            | 0.31           |
| 3       | C3             | 4.17            | 3.99            | 0.18           | 3.92            | 3.76            | 0.16           |

From table 3 it can be seen that the simulated results are in good agreement with the experimental results.

5. Calibration of capacitance sensors

We have developed 4 nos. of capacitance sensors C1, C2, C3 and C4. C1, C2 and C3 are capacitance sensors with Bakelite as the insulating material and the detailed dimensions are given in table 2. C4 is the capacitance sensor with FRP as the insulating material. It is of 16.6 mm ID, 17.6 mm OD and 100 mm in length. The developed capacitance sensors are calibrated against a standard sensor [12] and the capacitance value is measured at different void fractions (liquid holdup) for liquid nitrogen flow. An experimental setup consisting of a vacuum insulated liquid nitrogen cryostat and data acquisition system is developed for this purpose. The schematic of the experimental setup is shown in figure 10.

Figure 10. Schematic of experimental setup for calibration of capacitance sensors.
As shown in the figure, the developed capacitance sensors are mounted in the cryostat one below the other with the help of support stand. The standard capacitance sensor of 700 mm length is mounted vertically by the side of the developed sensors. After assembling the sensor in the cryostat, LN2 is filled to the outer LN2 vessel of the cryostat and allowed for about 30 minutes to cool down the system. After stabilizing the system, LN2 is filled into the inner vessel/sample chamber of the cryostat, so that all the sensors are completely submerged in LN2 bath and maintained at 77 K. Now the gas vent 2 of the sample chamber is connected to high pressure GN2 cylinder. By pressurizing LN2 in the sample chamber, the LN2 level in the sample chamber is maintained as required. The LN2 level in the sample chamber is reduced 1 mm in steps by opening and closing the GN2 vent valve and removing the LN2 from the sample chamber.

The capacitance values of the developed sensors are recorded for every 1 mm decrease in LN2 level in the sample chamber. Relay switches are used to switch on the developed sensors one by one. Ultra precision capacitance bridge is used to display the capacitance values measured from the developed sensors. ‘Nation instruments’ (NI) low power DXI, NI SCC-68 and NI cDAQ 9178 is used for data acquisition. The calibration curves obtained for different capacitance sensors C1, C2, C3 and C4 are shown in figures 11, 12, 13 and 14 respectively.

**Figure 11.** Capacitance v/s Level for capacitor C1. **Figure 12.** Capacitance v/s Level for capacitor C2.

**Figure 13.** Capacitance v/s Level for capacitor C3. **Figure 14.** Capacitance v/s Level for capacitor C4.

As shown in above figures, the calibration curve for sensor C4 is very stable and almost linear. Similar behavior is also noticed in the calibration curve of sensor C1. The calibration curves for sensors C2 and C3 are not linear. It is observed that the capacitance sensors with thin walled insulating
tubes suits very well for developing capacitance sensors for liquid level / void fraction measurements for LN2 flow.

6. Conclusion
An attempt has been made to develop simple capacitance sensors to measure the liquid level / void fraction for LN2 flow. Thermo-structural analysis has been carried out for different insulating materials like Bakelite, Poly Tetra Fluoro Ethylene (PTFE/ Teflon), FRP and Nylon. Bakelite has been selected for the same because of its less deformation at LN2 temperature. Experimental setups have been developed to measure the dielectric constant of insulating materials and capacitance of the developed sensors at 77 K. The simulations of the capacitance values for designed sensors were carried out with the help of ANSYS Maxwell software. The simulation results are in good agreement with the experimental results. The developed sensors are calibrated against a standard capacitance sensor and found that the capacitance behavior is linear over wide range of LN2 level with decreased insulating tube thickness of the sensor. The studies show that the developed simple capacitance sensors will be useful for measuring liquid nitrogen level accurately. These studies will be very useful for developing capacitance sensors for two-phase flow void fraction measurements for LN2 flow.

7. References
[1] Chen J, Wang Y, Zhang W, Qiu L and Zhang X 2017 Cryogenics 84 69
[2] Sakamoto Y, Peveroni L, Kobayashi H, Sato T, Steelant J and Vetran M R 2018 Cryogenics 94 36
[3] Lim L G and Tang T B 2016 ICITEE Yogyakarta, Indonesia
[4] Glass material properties https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html and https://www.engineeringtoolbox.com/poissons-ratio-d_1224.html
[5] Bakelite material properties https://www.misumi-techcentral.com/tt/en/mold/2010/05/040-linear-expansion-coefficients-of-materials.html
[6] Teflon material properties page 23 table 10 http://www.rjchase.com/ptfe_handbook.pdf
[7] FRP material properties https://en.wikipedia.org/wiki/FR-4
[8] Nylon 66 material properties https://www.engineeringtoolbox.com/young-modulus-d_417.html and http://www.goodfellow.com/E/Polyamide-Nylon-6-6-Polymer.html
[9] SAKAMOTO Y, SATO T and KOBAYASHI H 2016 Journal of fluid science and technology 11 1
[10] Caniere H, Jone C T’, Willockx A, Paepe M De, Christians M, Rooyen E, et al. 2007 Measurement science and technology 18 2898
[11] Maeno N, Okada W, Kitakogo S, Sumi Y, Sato T and Kobayashi H 2014 Trans. JSSASS Aerospace Tech. Japan 12 Pa_101
[12] Gour A S, Sagar P, Karunannithi R 2017 Cryogenics 84 76

Acknowledgments
The authors thank the staff of Centre for Cryogenic Technology for their help in developing the experimental setups and the financial support from the Board of Research in Nuclear Science (BRNS) for the project.