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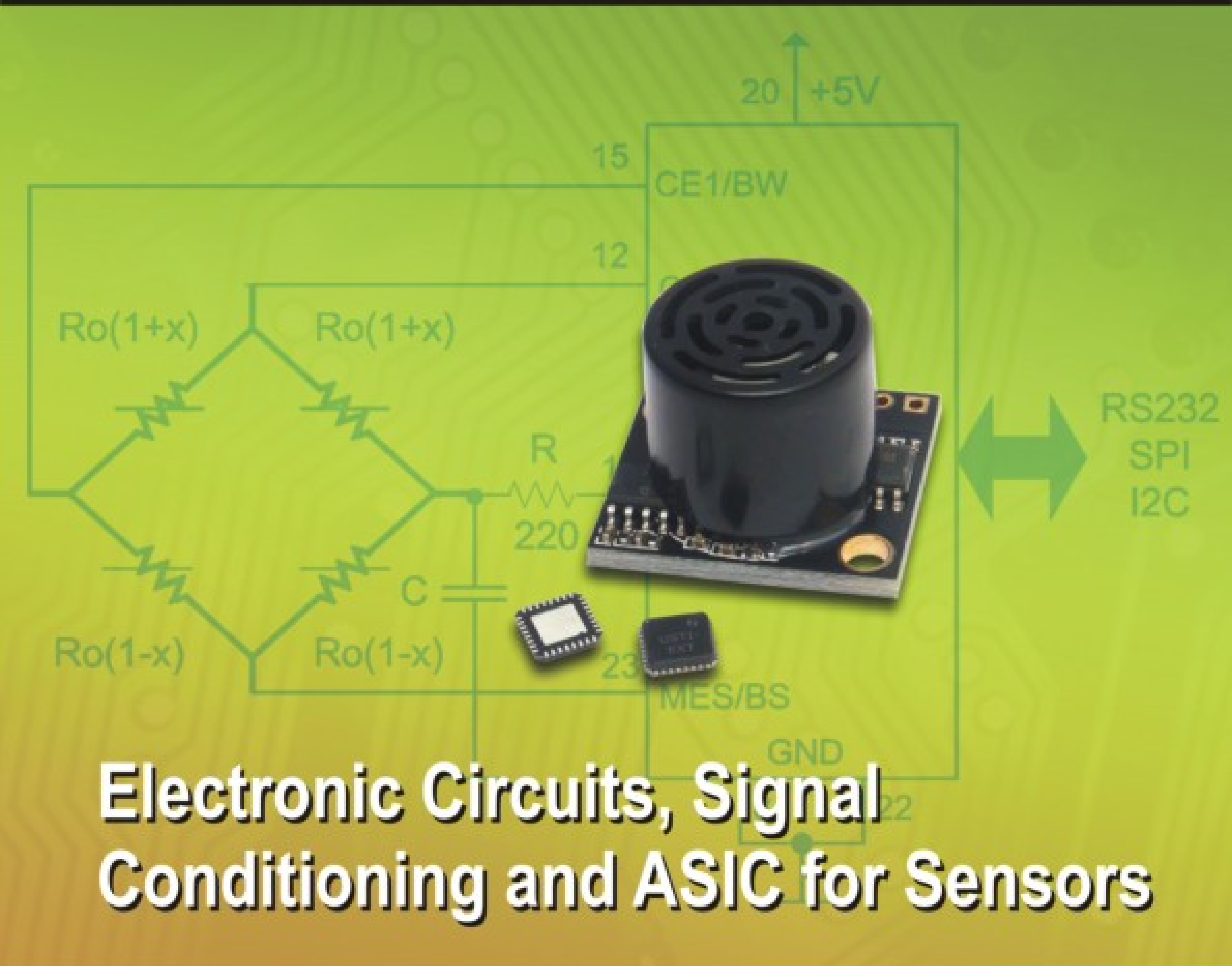

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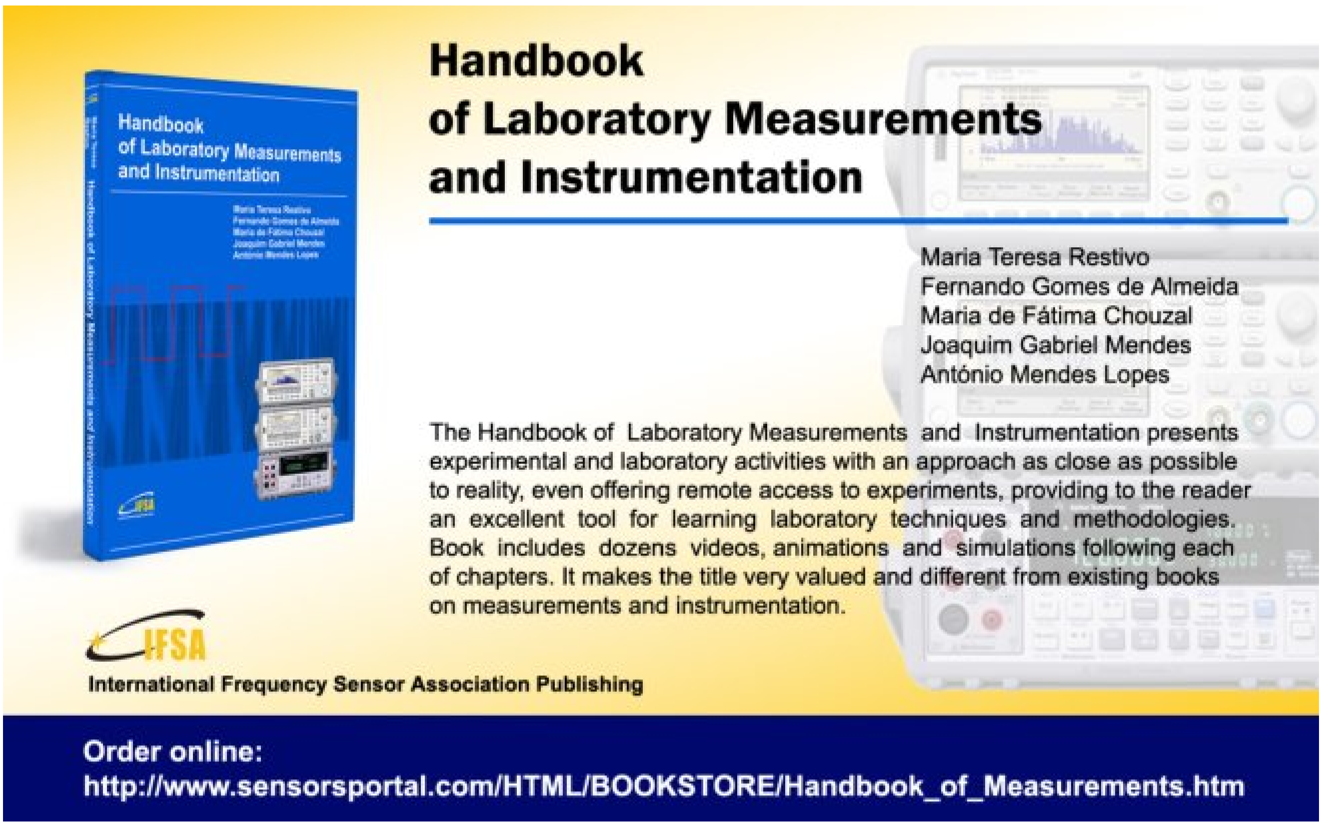

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Design, Development and Testing of a Semi Cylindrical Capacitive Sensor for Liquid Flow Rate Measurement in Process Industry

*** Sagarika PAL, * Sharmi GANGULY**
* Department of Electrical Engineering, National Institute of Technical Teachers' Training and Research, Kolkata [Under MHRD, Govt. of India],
Block-FC, Sector-III, Salt Lake City, Kolkata-700 106, India
E-mail: spal922@yahoo.co.in, s_ganguly07@yahoo.co.in

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Abstract: Flow rate through a pipe is an important process variable to be measured and controlled in any process industry. In the present paper, a low cost non contact semi cylindrical capacitive type liquid flow sensor has been designed, developed and tested. The semi cylindrical capacitive sensor consists of two large semi cylindrical thin copper plates separated by a gap distance and mounted along the outer wall of a non conducting horizontal flow pipe in a process. The capacitance of the sensor with variation of liquid flow rate has been measured and the relationship has been observed linear. The capacitance variation has been obtained in nano farad range which again has been converted into voltage by using proper signal conditioning circuit. For converting the sensor capacitance variation into voltage, capacitance to voltage converter (ICL 7660) has been used instead of conventional bridge circuit. The sensor is purely non contact type and does not create any problem due to contamination with corrosive, chemically reactive liquids flowing through a non conducting flow pipe. Experimental results are found to have good linearity and repeatability within acceptable limits. *Copyright © 2012 IFSA.*

Keywords: Liquid flow sensor, Semi cylindrical capacitive sensor, Non- contact sensor, Process industry, Signal conditioning circuit, Horizontal flow pipe.

1. Introduction

Flow rate through a pipe is one of the important variables that is required to be measured and controlled in any process industry. Capacitive types sensing techniques have been widely accepted due to its low cost, low power consumption, high linearity and simple to use. Various researchers [1-3] have used capacitive sensing technique for liquid level measurement. Jun Han, Feng Dong [4] studied a soft-measurement method for gas/water mass flow-rate, in which the V-cone differential pressure meter was used and the adaptive wavelet network was developed to achieve the soft-measurement of the mass flow-rate. The multi-input single output model was adopted to approximate the mass flow-rate of gas/liquid. The paper focused on the experimental measurement in horizontal pipe. Baoliang Wang, Yongfeng Fu, Zhiyao Huang, Haiqing Li [5] developed a capacitive electromagnetic flowmeter working in voltage sensing mode. These methods keep the noise to a minimum. The signal converter is designed to measure the signal from the sensor and get the flow rate. The prototype flowmeter is calibrated with water in a flow loop. Test results show that capacitive electromagnetic flowmeter has better performance than the electrode type flowmeter for oil-water two-phase volumetric flow. Mass flow rate using a vortex flow meter has been designed by Yongmei Huang, Hongjian Zhang and Zhiqiang Sun [6] which employs conventional mass flow rate which is derived from volumetric flow rate multiplied by fluid density. With this method mass flow rate is obtained directly and noise disturbance is reduced.

Non-contact semi cylindrical capacitive type sensor was designed and described by Sagarika Pal, Rasmiprava Barik [7] for liquid level measurement in a tank.

Cheng-Ta Chiang and Yu-Chung Huang [8] and [9] used semi cylindrical capacitive sensor for flow rate and fluidic measurement. They used numerical analysis method to calculate the capacitance of the semi cylindrical capacitive sensor and the variation of capacitance has been converted to voltage by interface circuit.

A. Jaworek, and A. Krupa [10] proposed a radiofrequency resonance sensor with variable capacitance in the form of two semi cylindrical electrodes for gas/liquid volume measurement. Since a capacitive sensor has very weak output signal, proper signal conditioning is needed to convert the signal in useable form. Jian Qiu ZHANG and Yong YAN [11] described the blockage of the sensing lines of a differential-pressure (DP) flow sensor which is the main cause of malfunction of a flow measurement system in many industrial processes.

Since the capacitive sensor produces a very small change in capacitance, proper signal conditioning is needed to get the signal in useable form. D.M.G. Preethichandra, Katsunori Shida [12] proposed a simple interface circuit to measure very small capacitance changes. J. Dowd, A. Callanan, G. Banarie et al. [13] designed an interface circuit using sigma-delta technique that directly converts capacitance to a digital word. Satish Chandra Bera, Jayanta Kumar Ray, and Subrata Chattopadhyay [14] designed a low-cost non-contact capacitance type level sensor for a conducting liquid where the change in capacitance due to the change of liquid level has been measured by a modified linear operational amplifier based De' Sauty bridge network with adjustable bridge sensitivity.

In the present paper, a semi cylindrical capacitive sensor has been investigated for liquid flow rate measurement in a process flow line. The semi cylindrical capacitive sensor consists of two semi cylindrical copper plates which are separated by a gap distance. These two semi cylindrical plates are mounted horizontally around a polyvinyl chloride (PVC) type non conducting horizontal flow pipe. Water has been used as the liquid in the process flow pipe which acts as a dielectric medium between the capacitor plates. The variation in capacitance due to variation in water flow has been converted into voltage variation by using capacitance to voltage converter (ICL 7660s). The obtained voltage signal has been amplified to vary in the range 0-5 volt. The experimental results are found to have good repeatability, linearity and resolution.

2. Capacitive Sensing Technique for Semi Cylindrical Capacitive Sensor

The present semi-cylindrical capacitive sensor consists of two copper semi-cylindrical plates, which are separated by a gap distance. Fig. 1 shows mounting of the semi-cylindrical capacitive sensor around the flow pipe.

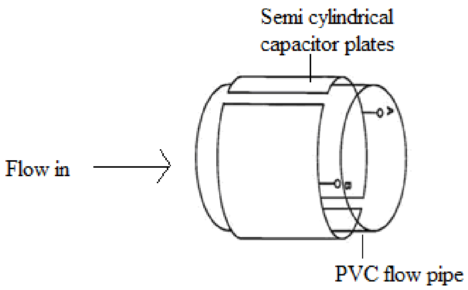

Fig. 1. Mounting of the semi-cylindrical capacitive sensor around the flow pipe.

Fig. 2 (a) displays the top view of the semi-cylindrical capacitive sensor and Fig. 2 (b) shows the approximate structure for numerical calculation of capacitance value of the sensor capacitor. The two semi-cylindrical copper plates have the radius R and a minimum gap distance d.

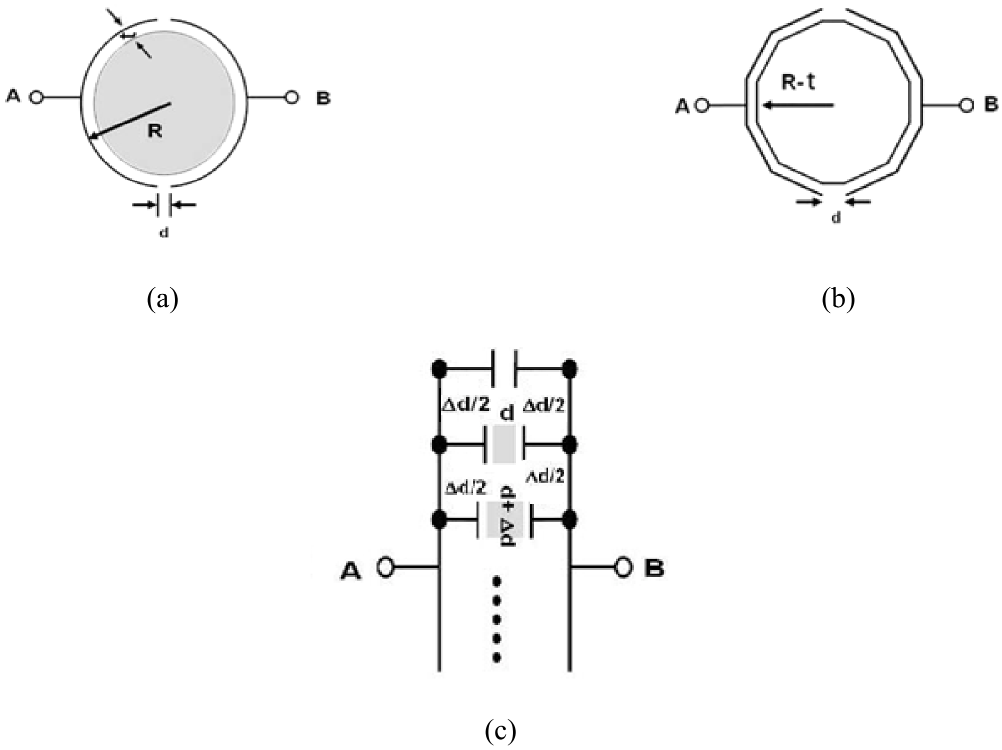

Fig. 2. (a) The top view of the semi-cylindrical capacitive sensor with dielectric fluid; (b) The approximate structure of the semi-cylindrical capacitive sensor with dielectric for numerical calculation; (c) Equivalent capacitors between A and B terminals.

The capacitance can be approximated as each pairs of two unit plates with an increment Δd distance as shown in Fig. 2 (c). So capacitance of the semi-cylindrical capacitor without dielectric fluid can be expressed as

$$C_0 = \varepsilon_0\, \varepsilon_1\, 2\, A \left[\frac{1}{d} + \frac{1}{d+\Delta d} + \frac{1}{d+2\Delta d} + ... + \frac{1}{d+(n-1)\Delta d}\right] + \frac{\varepsilon_0 \varepsilon_1 A}{2R}\,, \tag{1}$$

where ε_0 is the permittivity of free space of magnitude 8.85 (pF/m), ε_1 is the dielectric constant of air, n the cutting number for numerical calculation, A is the unit area of semi-cylindrical plates.

In the present work two thin semi cylindrical copper plates have been fixed with adhesives on the wall of a thin PVC flow pipe where liquid flow rate measurement have been performed. The PVC flow pipe has wall thickness t.

So the approximate capacitance between the semi cylindrical plates embracing the PVC flow pipe when it is fully filled with water during maximum flow rate, can be given by equation 2.

$$C_1 = \varepsilon_0 2A \left[\frac{1}{\frac{d}{\varepsilon_2}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d}{\varepsilon_3}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+\Delta d}{\varepsilon_3}} + ... + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+\Delta d\,(n-1)}{\varepsilon_3}}\right] + \frac{\varepsilon_0 A}{\frac{2t}{\varepsilon_2} + \frac{2R-2t}{\varepsilon_3}}\,, \tag{2}$$

where ε_2 is the dielectric constant of the PVC flow pipe material, ε_3 is the dielectric constant of the water, t is the wall thickness of the PVC flow pipe.

If the semi-cylindrical capacitor plates have height h, equation 2 can be modified as expressed in equation 3.

$$C_1 = \varepsilon_0 2(\pi Rh) \left[\frac{1}{\frac{d}{\varepsilon_2}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d}{\varepsilon_3}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+\Delta d}{\varepsilon_3}} + ... + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+\Delta d\,(n-1)}{\varepsilon_3}}\right] + \frac{\varepsilon_0 (\pi Rh)}{\frac{2t}{\varepsilon_2} + \frac{2R-2t}{\varepsilon_3}} \tag{3}$$

In the present flow rate measurement system, during maximum of water flow rate through the pipe, the dielectric liquid (water) fills the full cross-sectional area of the flow pipe and during no flow, air as dielectric fills the flow pipe completely.

So at any rate of flow of liquid through the PVC flow pipe, its cross-sectional area is partially filled with liquid (of dielectric constant of ε_3), and partially filled with air (of dielectric constant ε_1). Thus during the flow when the pipe cross-section is half filled with the dielectric liquid and half with air, the overall sensor capacitance C will be given by equation 4.

$$C = C'_1 + C'_2\,, \tag{4}$$

where

$$C'_1 = \varepsilon_0 (\pi Rh) \left[\frac{1}{\frac{d}{\varepsilon_2}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d}{\varepsilon_3}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+\Delta d}{\varepsilon_3}} + ... + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+\Delta d\,(n-1)}{\varepsilon_3}}\right] + \frac{\varepsilon_0 (\pi Rh)}{\frac{2t}{\varepsilon_2} + \frac{2R-2t}{\varepsilon_3}}$$

and

$$C'_2 = \varepsilon_0(\pi Rh)\left[\frac{1}{\frac{d}{\varepsilon_2}} + \frac{1}{\frac{\Delta d}{\varepsilon_2}+\frac{d}{\varepsilon_1}} + \frac{1}{\frac{\Delta d}{\varepsilon_2}+\frac{d+\Delta d}{\varepsilon_1}} + \ldots + \frac{1}{\frac{\Delta d}{\varepsilon_2}+\frac{d+\Delta d\,(n-1)}{\varepsilon_1}}\right] + \frac{\varepsilon_0(\pi Rh)}{\frac{2t}{\varepsilon_2}+\frac{2R-2t}{\varepsilon_1}}$$

So if the liquid flow rate within the horizontal flow pipe varies, capacitance between the semi cylindrical plates will also vary because of the variation of the cross-sectional area of the flow pipe filled by the dielectric liquid. Thus liquid flow rate measurement in terms of the capacitance of the semi cylindrical plates can be possible.

3. Design of the Semi Cylindrical Capacitive Sensor

The semi cylindrical capacitive sensor has been designed and constructed from two Copper plates of thickness 0.2 mm, length 200 mm and width 32 mm. Each plate has been bent to form a semi cylindrical shape. These two semi cylindrical plates are mounted horizontally around a PVC type liquid flow pipe using adhesives, separated by a gap distance of 3.0 mm. Care has been taken to avoid any air gap between the capacitor plates and the outer wall of the flow pipe. The gap distance between the semi-cylindrical plates has been kept at the two diametrically opposite sides of the horizontal flow pipe with one gap at the top and other at the bottom, as shown in the Fig. 3. The outer and inner radiuses of the PVC flow pipe are 11.13 mm and 10.81 mm respectively.

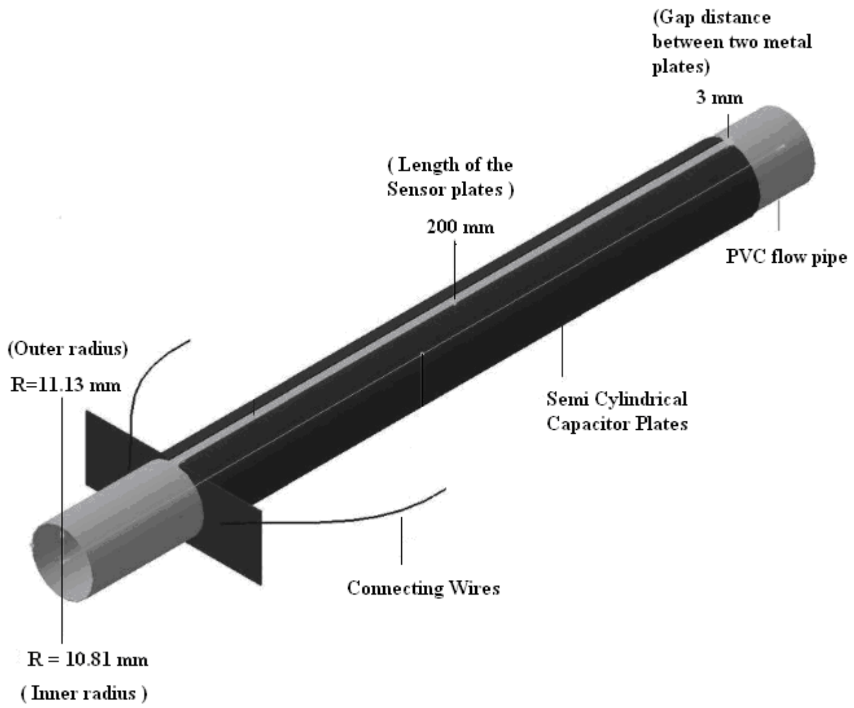

Fig. 3. Isometric view of the semi cylindrical capacitive flow sensor on the PVC flow pipe (All dimensions are in mm).

4. Signal Conditioning Circuit for Semi-cylindrical Capacitive Sensor

The variation of sensor capacitance due to variation of flow rate in the pipe has been converted into voltage variation with the help of ICL7660 as shown in the Fig. 4.

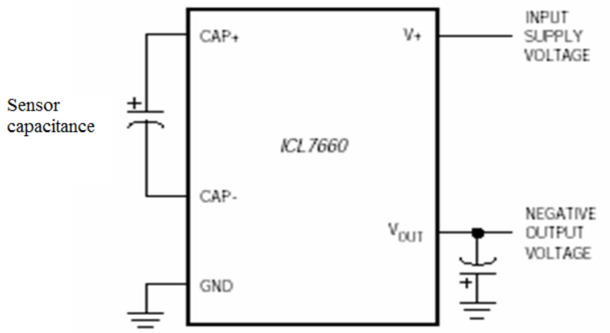

Fig. 4. Signal conditioning circuit for semi cylindrical capacitive sensor.

Water has been taken as the dielectric fluid to flow through the pipe line. As the flow in the flow pipe has been gradually increased, the semi cylindrical sensor capacitance C_1 has increased and accordingly voltage output also has increased. Output voltage is further amplified by two stage amplifiers and after zero and span adjustment final output has been recorded with the liquid flow rate in the flow pipe. The detail circuit diagram for signal conditioning is shown in Fig. 5.

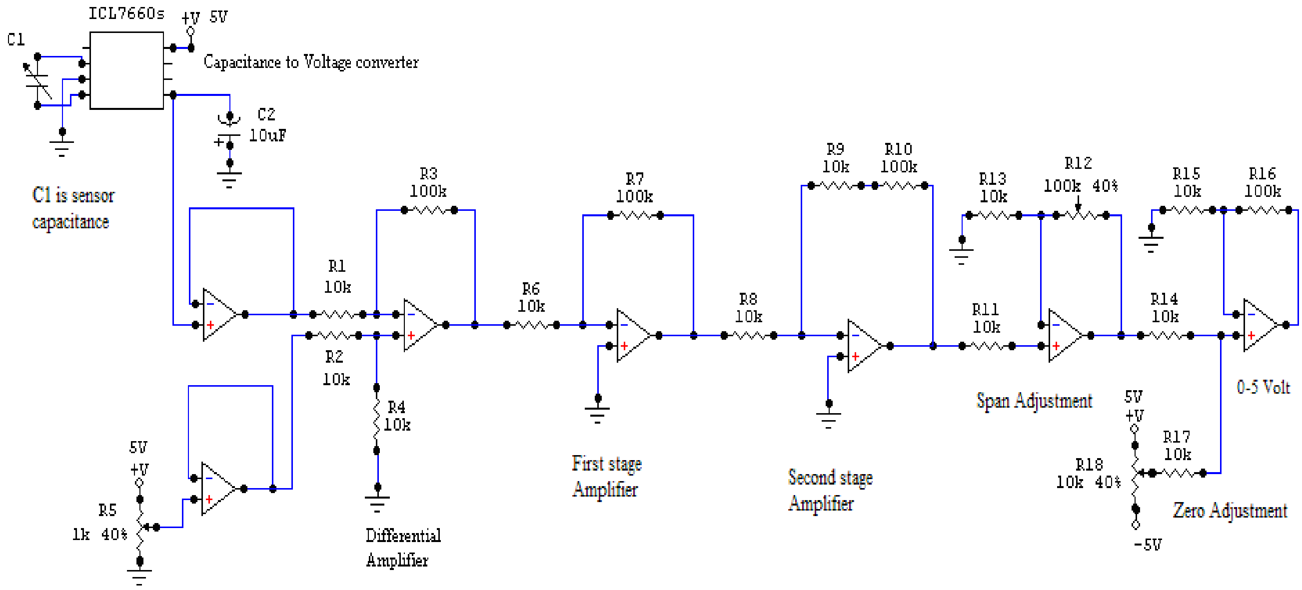

Fig. 5. Signal conditioning Circuit after the semi cylindrical capacitive sensor for flow rate measurement

5. Experimental Result

In the present setup water has been used as the dielectric medium within the PVC flow pipe and the sensor capacitor has been calibrated against a rotameter mounted in the same flow line of the process system. The inlet flow rate has been varied from 50 LPH to 170 LPH which corresponds to the sensor capacitance variation of 0.045 nF to 0.061 nF. After proper signal conditioning the variation corresponds to voltage in the range 0-5 V.

In the experiment it has been observed that the semi cylindrical capacitance variation with the variation of water flow rate through the pipe is linear and is shown in Fig. 6. The % Error from linearity is shown in Fig. 7. The error from linearity lies within +0.9051 % to -0.6813 %, which is in the tolerable limit.

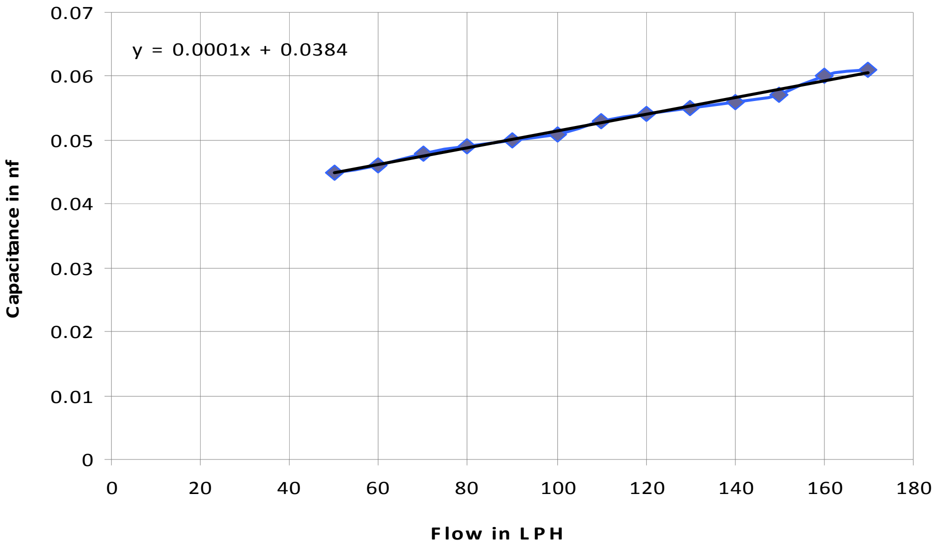

Fig. 6. Semi cylindrical Capacitance variation with liquid flow rate through the pipe.

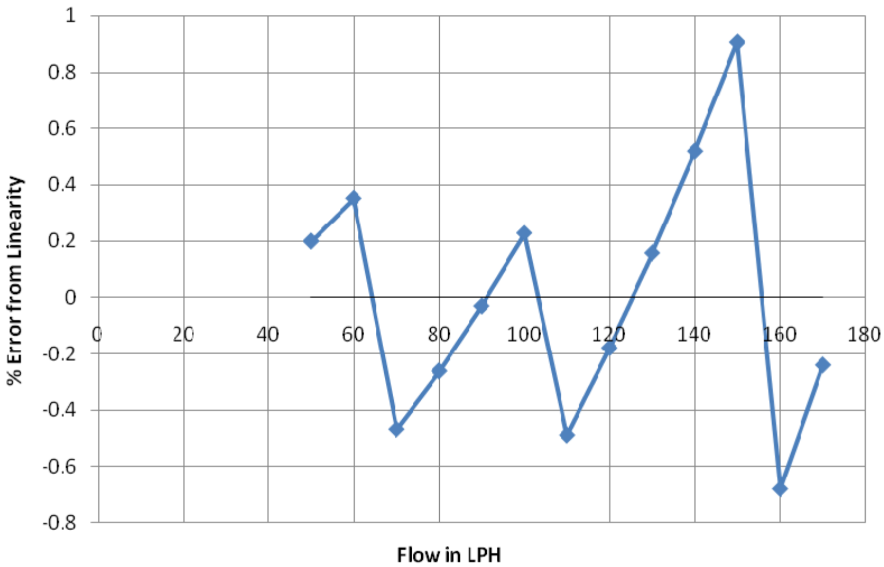

Fig. 7. Flow rate Vs. % Error from linearity.

By using the signal conditioning circuit shown in Fig. 5, the capacitance variation of the sensor has been converted in to voltage variation, followed by two stage amplification, the span and zero adjustment which brings the circuit output within the voltage range of 0-5 V for liquid flow rate variation of 50 LPH to 170 LPH. The final voltage output after signal conditioning with respect to flow rate is also linear as shown in Fig. 8. The percentage error from linearity is within the range +0.27 % to -0.302 % and is shown in Fig. 9.

Finally MATLAB software has been used to calculate theoretically the capacitance between the two semi cylindrical plates using equation (2) for air as dielectric and equation (3) for water as dielectric. The calculated value of capacitance has been obtained in the nano farad range i.e. same as that of the experimental value.

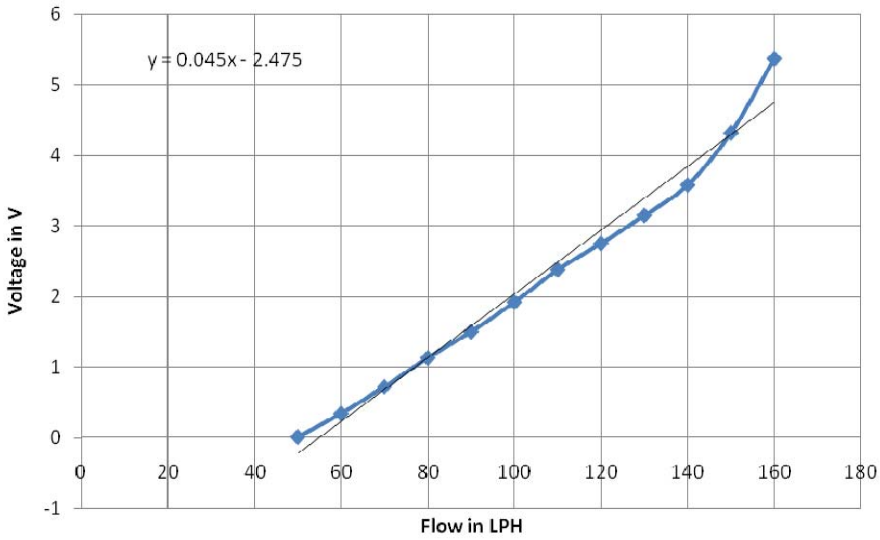

Fig. 8. Voltage variation after signal conditioning with respect to flow rate.

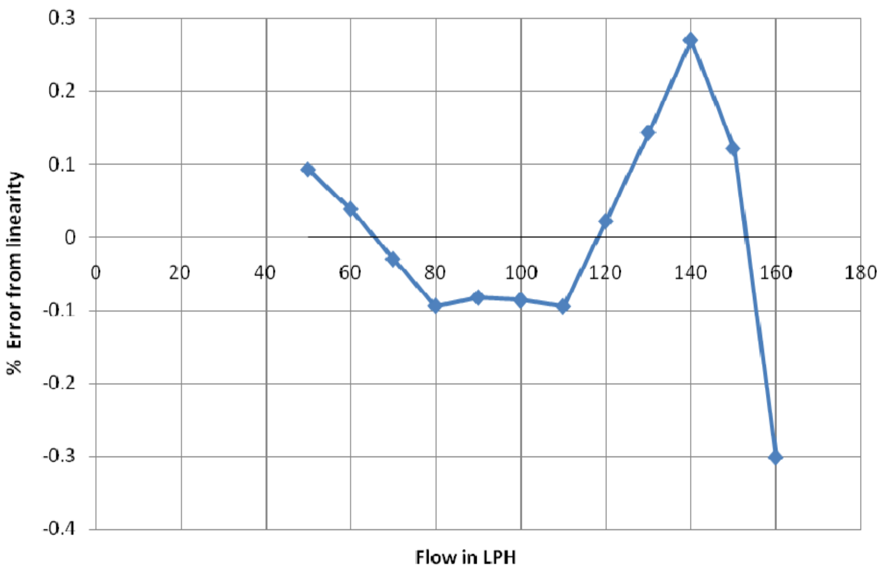

Fig. 9. Flow rate Vs. % Error from linearity (after signal conditioning).

6. Conclusions

In the experiment, the semi cylindrical capacitance has been observed to vary in the range 0.045 – 0.061 nano farad for flow rate variation of 50-170 LPH.

From the Fig. 6 the variation of capacitance with the variation of liquid flow rate is linear. Theoretically computed value of the capacitance from equation (2) and (3) matches with the experimental value.

It has been observed that the semi cylindrical capacitance type flow sensor has good linearity and repeatability in the measured range.

Since it is a non contact type of liquid flow rate measurement, it can be used for both conducting and non conducting type of liquid contained within a non conducting flow pipe.

In the present scheme the capacitance variation has been converted in to voltage variation by using the capacitance to voltage converter ICL 7660s instead of conventional bridge circuit for simplicity.

Closed loop flow rate control in the process system can be achieved by using the output of the semi-cylindrical flow sensor developed in the present scheme. This is the future scope of work.

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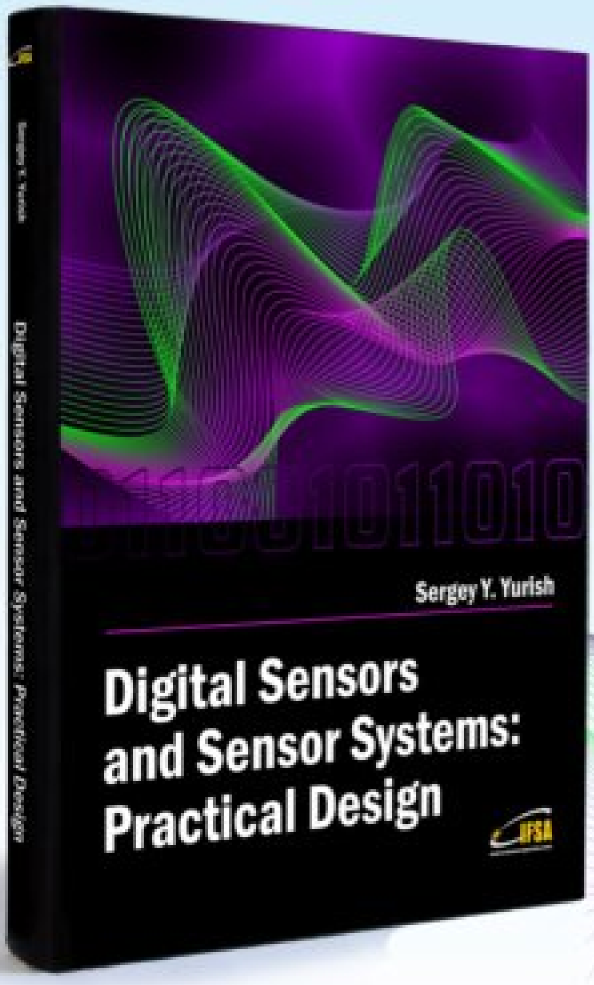

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