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Flow Measurement Using Capacitance Technique

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Abstract: Precise and accurate measurement of liquid flow rate repeatedly has being a challenging and interesting area of research. Up till now, there is no singular flow metering device that could provide on-line mass flow rate of each component of industrial multi-component fluids that are conveyed in a confined environment. Capacitance sensor is one of the candidate devices under development for process tomography. However, its inherent dead zone in the central region of the plates somehow affects its precision and accuracy. This study reports on experimental investigations carried out on specific configurations of capacitance sensor using ≥3 electrode plates with the intention of determining a more optimal design configuration with improved accuracy and precision, bearing in mind the limitations of existing configurations. At this stage of the study, the configurations considered were mounted inside the pipe but with the full understanding of the inherent disadvantages of such arrangement (i.e., flow pattern distortion, fouling of the electrode surfaces by conveyed fluids, etc.). However, a marked improvement in the intensity of the developed electrostatic field was observed and the apparent dead zone in existing devices was removed by the inclusion of the third plate thus, improving the accuracy and precision of the device. For the investigation clean water was used.

Key words: Flow measurement, capacitance, tomography, multi-plate, accuracy, Nigeria

INTRODUCTION

Quantitative determination of flow rates of liquids is important in many fields of engineering, especially in industrial process control. The nature of the fluid and its properties are the major factors which prescribe the measurement technique most suitable for a given application. Flowmeters could be broadly divided into mechanical and electrical types. Most of these meters operate by obstructing the flow thus, producing measurable disturbance that can be related to the rate of flow of the fluid. Examples are the various differential pressure, variable area meters, vortex shedding and turbine flow meters (Anderson, 1980; Sydenham, 1992; Olatunbosun, 1991; Hayward, 1987).

The obvious drawback of these techniques is the energy loss in overcoming the obstruction caused by the sensing element in the path of fluid flowing in the pipe. The flow regimes in most cases are destroyed. In order to minimize this energy loss, some non-intrusive flowmeters have been developed. Examples are electromagnetic, nucleonic, capacitance and ultrasonic flowmeters, etc. However, none of these devices could directly measure the mass flow rate of fluid in pipes (Considine, 1993; Olatunbosun, 1991; Huang *et al*., 1989). Cross-correlation flowmeter has two identical sensors placed a known distance apart on the fluid carrying pipe. Their respective output is cross-correlated electronically to obtain the fluid flow velocity. The success of this development has led to wider applications of the capacitance technique in flow measurements and tomography. However, there is still the need for optimal configuration of the sensors. The earlier and subsisting configuration for the capacitance sensor has concave curvature because of its amicability and convenience in arranging them around the outside curvature of a fluid conveying pipe.

MATERIALS AND METHODS

The capacitance C of a parallel plate capacitor is dependent on the area A of the overlap of the plates, the distance d, separating the plates, the absolute and relative permittivity of the dielectric materials ϵ_o and ϵ_r between the plates (Morris, 1993; Hayward, 1987):

$$C = \frac{\epsilon_o \epsilon_r A}{d} \quad (1)$$

When an electrical voltage is applied across the plates, the dielectric material between the plates is electrically stressed. That is a form of elastic deprivation of the atomic structure has taken place as the electrons in

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the material strain towards the positive plate. The relative ease with which this phenomenon occurs determines to some extent the noticeable difference between dielectrics. For example if the material is readily stressed and permits a large amount of charge to be transferred, then such a material is said to have a high permittivity. Thus for a given configuration of electrodes with known dielectric permittivity ϵ_r and an applied voltage V, across the plates, charge Q is developed across the plates. The developed charge sets up an electric field between the opposing faces of the plates. The distortion or variation of this field causes changes in the capacitance of the electrodes. If this is due to fluid flow between the electrodes then the change in capacitance is an indication of the rate of flow of fluid between the electrode faces. This property is the basis of the capacitance flowmeters.

Multiplate capacitor configuration: Having more than one plate in between the two end plates of a capacitor increases the electric field intensity within the end plates, when external voltage V is applied across them. Such arrangement shown in Fig. 1 is equivalent to having a set of capacitors in parallel. The capacitance of such a capacitor is given as:

$$C = \frac{(n-1)\epsilon_0 \epsilon_r A}{d} \quad (2)$$

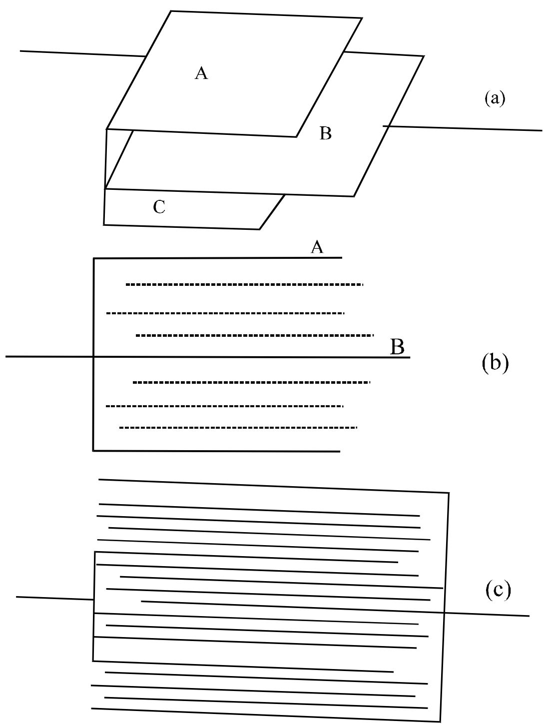

Fig. 1: Capacitance multi-plate configuration

Where, n is the number of plates and (n-1) is the number of capacitors in parallel. Admittedly, capacitance flowmeter based on this configuration will lose the traditional attraction of non-intrusiveness associated with the two-plate capacitance meter. However, two-plate capacitance meter has weak electric field intensity at and near the centre of a fluid-conveying pipe (Odejide, 1997). This weak electric intensity produces poor sensitivity and non-linear behavior of the change in capacitance to fluid flow rate. Fluid flow information at this region is very important in determining accurately and precisely the fluid flow rate, most especially at low flow. This is of more importance in having better definition of the fluid flow tomographic images from the capacitance measurement. Unfortunately, the elegance of non-intrusiveness has obscured this rather important requirement.

From the earlier study, the non-linearity mentioned above were corrected by the inclusion of a third electrode plate, mid-range of the two end plates. The third plate helps in reinforcing the electric field intensity at the centre of the pipe with the attendant improvement in sensitivity. The encouraging results obtained from the earlier research encouraged us to carry out further investigation on this configuration and modified forms of it.

Considered sensor configurations: In the investigations, varied dimensions of the multi-plate sensor was considered. In total five configurations of the capacitance sensor were considered with and without guard rings. The guard rings were introduced to correct for the end effects. All the sensor plates are internal to the pipe. The performance of these configurations was observed in both 1 and 2 inch diameter pipes. The considered configurations are shown in Fig. 2-6. Guard rings were incorporated in each configuration to correct for end effect.

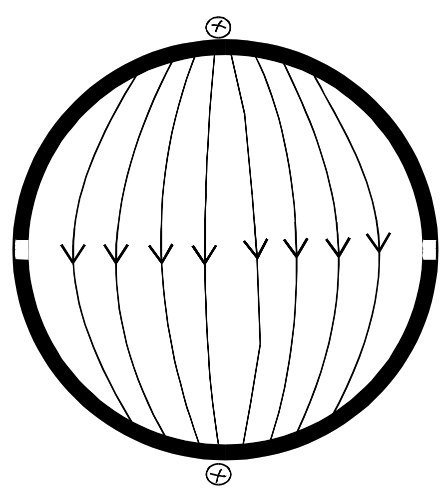

Fig. 2: Sensor configuration A

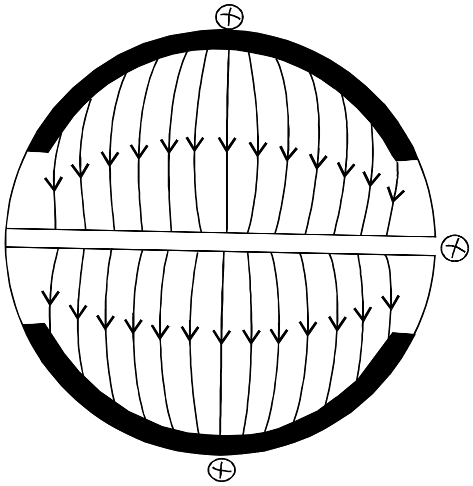

Fig. 3: Sensor configuration B

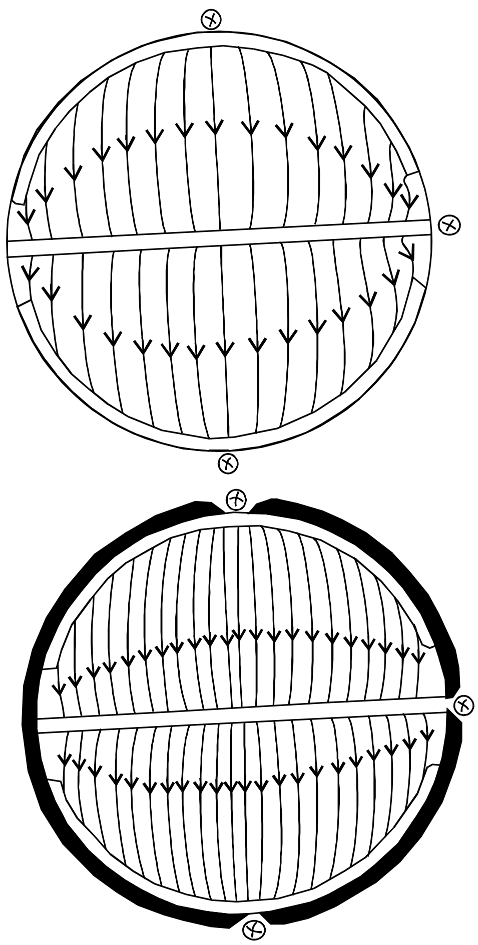

Fig. 4 : Sensor configuration C1 and C2

Capacitance measuring device: The capacitance electrodes mounted within the pipe wall are excited by a saw tooth (ramp) a.c. signal. The generated electrostatic field produces a known standing capacitance C_0 when the pipe is empty. A change in capacitance occurs when the field is perturbed by fluid flow inside the pipe. This change in capacitance is related to the volumetric fluid flow rate.

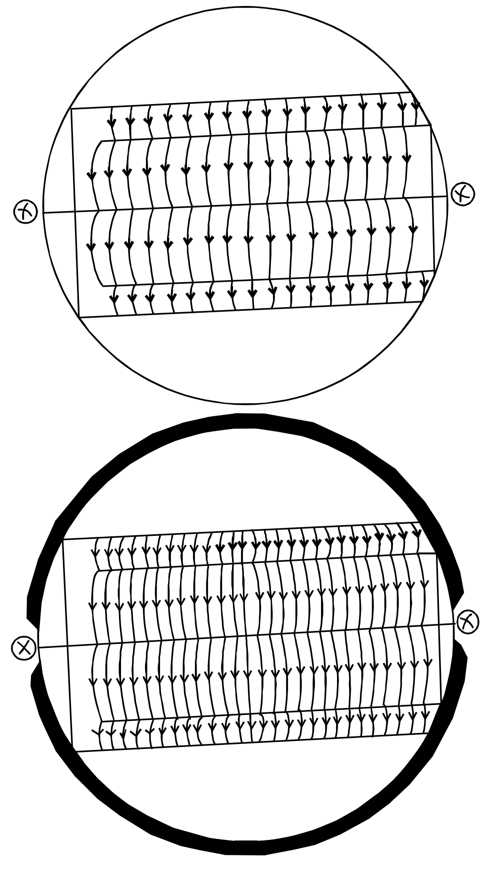

Fig. 5: Sensor configuration D1 and D2

Figure 7 shows the developed electronic circuit for processing the signal generated by this change in capacitance and relating it to volumetric flow rate of conveyed fluid. The third stage of the circuitry consists of a differential amplifier.

The capacitance electrodes are connected to the input stage of the differentiator circuit. This circuit converts the rate of change of capacitance to a measurable electrical voltage. That is:

$$e_0 = -RC\frac{der}{dt} \quad (3)$$

Where:

e_r = The saw tooth excitation voltage

R and C = They are passive components around the differentiator circuit

The resulting differentiator output e_0 is related to the capacitance being measured by the expression:

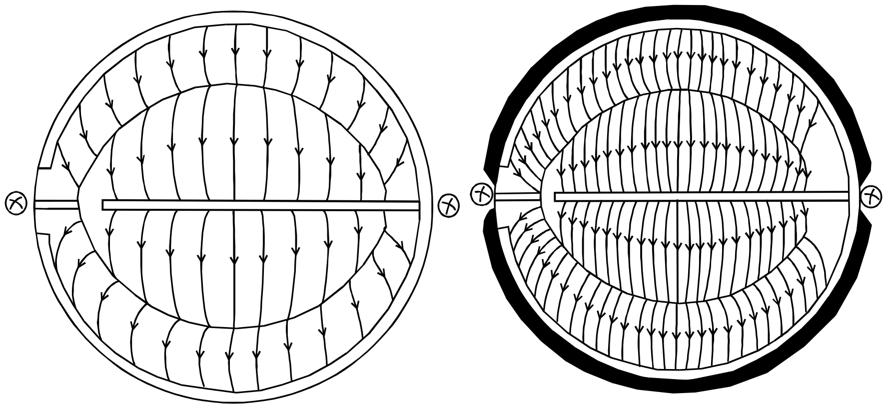

Fig. 6: Sensor configuration E1 and E2

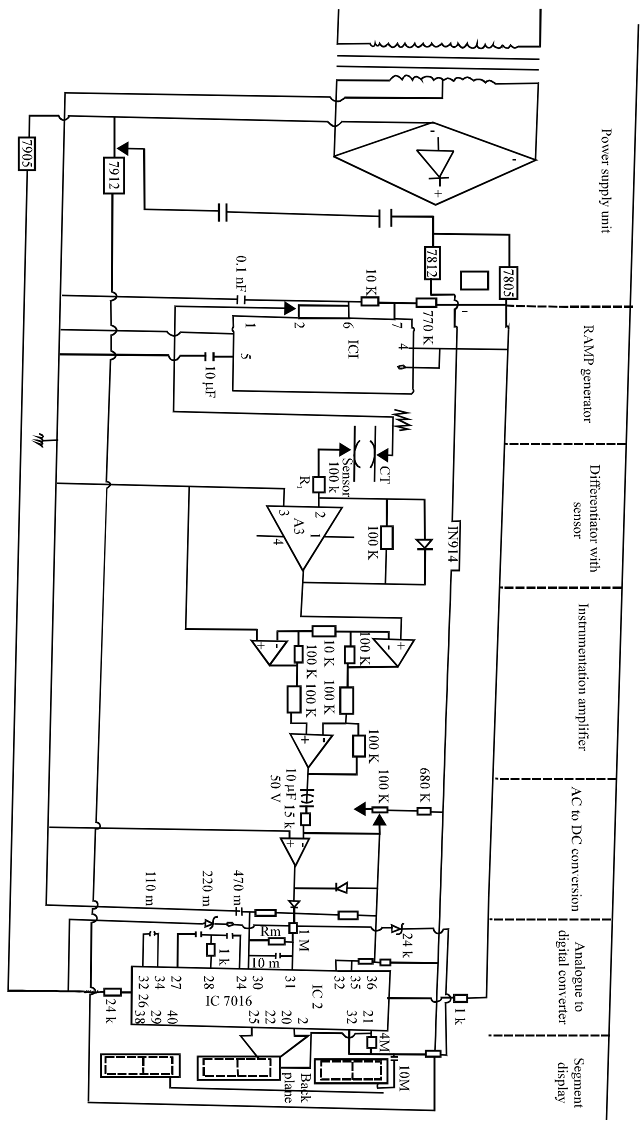

Fig. 7: Overall circuit diagram

$$C_x = Ke_0 \quad (4)$$

K is a constant determined by the values of the passive components around the ramp generator circuit (IC1). The measured C capacitance value is compensated for the standing capacitance value C_0 and the result obtained related to the fluid volumetric flow rate (Idowu, 1998). The differentiator circuit has a gain-limiting resistor which ensures frequency stability and a damping diode which limits the negative output swing produced by the ramp-train reset swing. The damping makes the average e_0 value to approximate a dc equivalent. Subsequent stages of the overall circuitry (Fig. 7) processed the output of the differentiator circuit and finally displayed it as volumetric flow rate using a 3½, digit LED display (Wobschall, 1987).

RESULTS AND DISCUSSION

Each sensor configuration was inserted into the flow line of the laboratory flow rig and measurement of flow rate obtained using the developed electronic circuitry. The meter was calibrated using the time interval weighing method. Some of the experimental results are shown in Fig. 8-12. A somewhat linear relationship between fluid flow rate and changes in capacitance was obtained for a reasonable range of flow rates and establishing the fact that the capacitance technique could be used directly to measure flow rates. The poor sensitivity and non-linear behavior of the two-plate capacitance meter has been improved upon by the developed configurations which have enhanced the intensities of the electric field at and near the center of a fluid-conveying pipe.

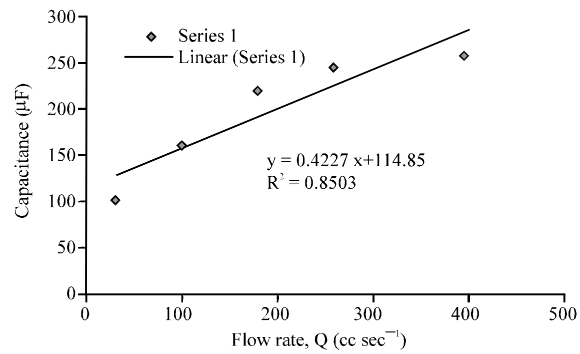

Fig. 8: Sensor A capacitance change against flow rate in cc sec^{-1}

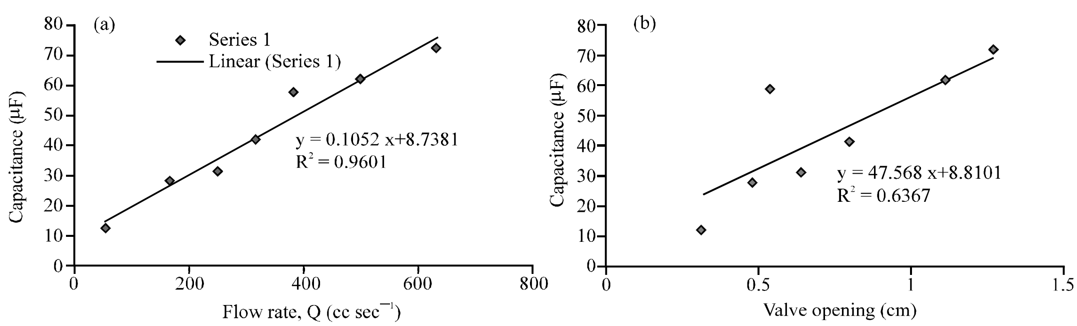

Fig. 9: Sensor B, capacitance change against flow rate and valve opening

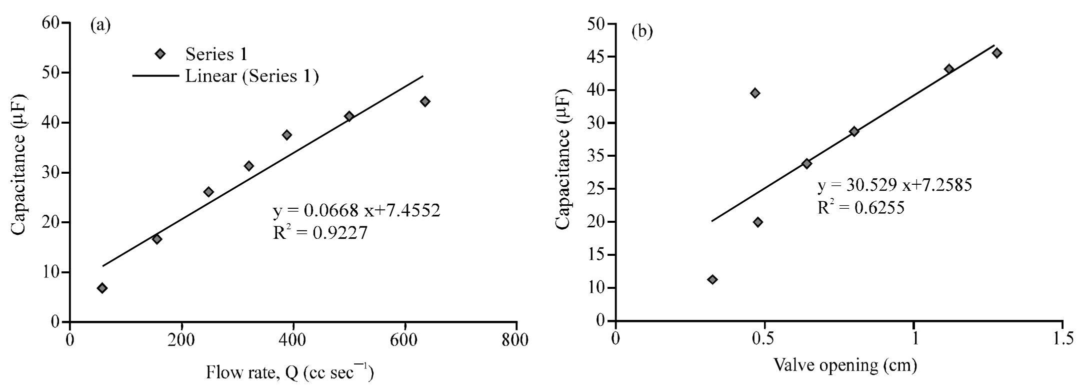

Fig. 10: Sensor C, capacitance change against flow rate and valve opening

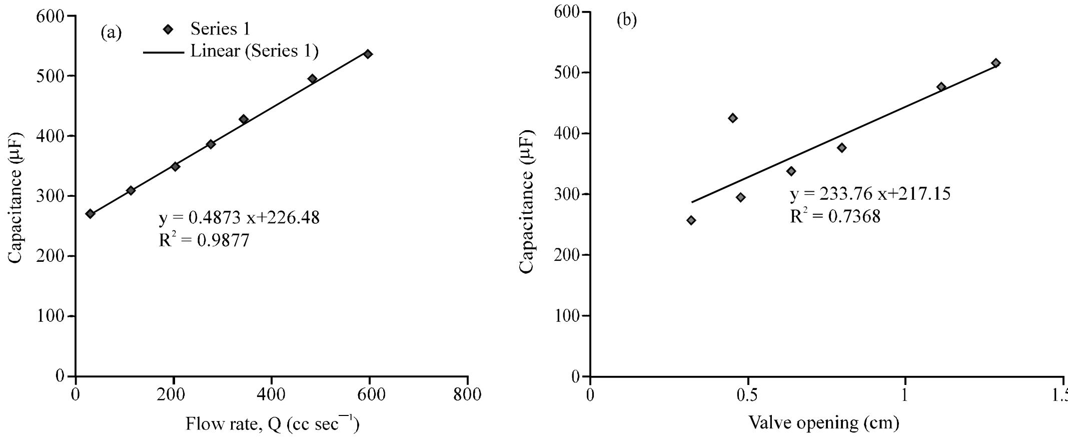

Fig. 11: Sensor D, capacitance change against flow rate and valve opening

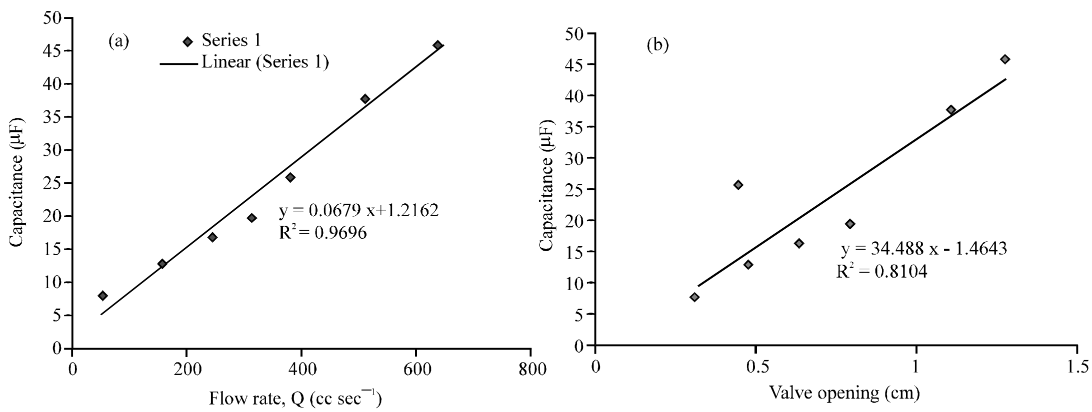

Fig. 12: Sensor E, capacitance change against flow rate and valve opening

CONCLUSION

Researchers have developed an innovative approach for measuring liquid now rate using capacitance technique. From the obtained graphs, the sensitivities of the sensor configurations are:

Sensor A = 40 μF cc^{-1}
Sensor B = 6.1329 μF cc^{-1}
Sensor C = 6.23 μF cc^{-1}
Sensor D = 44.84 μF cc^{-1}
Sensor E = 9.75 μF cc^{-1}

Hence, the sensor with the best linearity is D followed by sensor E then B. The approach has substantially improved the inherent dead zone associated with central region of conventional two plate capacitance technique. This approach ensures a linear relationship between the fluid flow rate and changes in capacitance. The electronic circuitry is low-cost and can be readily actualized.

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