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Microprocessor based flow meter for measuring flow rate of cryogenic liquids

S K Ray*, L K Bandopadhyay, R P Singh, N Sahay, I Ahmad, A Narayan and B C Bhowmick

Central Mining Research Institute, Barwa Road, Dhanbad 826 001

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This paper presents the design of a microprocessor-based flow meter to optimize the flow rate of liquid nitrogen required to control fire in underground coalmines. The salient features of the device and its set-up procedure with the liquid nitrogen tanker are illustrated with suitable schematic diagram. The program logic of the proposed device is illustrated in the form of a flow chart.

Keywords: Control of fire, Drag force, Flow meter, Liquid nitrogen, Microprocessor, Repulsive force
IPC Code: G06F1/20

Introduction

Liquid nitrogen (LN_2) is widely used for control of fire in underground coalmines. Generally, it is infused through boreholes. For the purpose, the cryogenic liquid from tankers is flushed to underground mines direct through boreholes or through super insulated tubes laid along boreholes. For best results, it is essential to measure the flow rate of LN_2 accurately. A number of flow meters viz., Orifice meter, Venturimeter, Turbine flow meter, Kent Vortex meter is available for measurement of flow rate of cryogenic liquid. They have several disadvantages. In the Orifice meter, a few components create resistance to the flow of the liquid and it produces a relatively large permanent pressure drop, which is undesirable when measuring flow of cryogenic liquid under saturated condition[1]. Venturimeter suffers from problem of cavitations[2,3]. Turbine flow meter should be protected during cool down of a cryogenic fluid transfer line in which the meter is placed, because severe flow oscillations and surges may destroy meter[4]. As regards Kent Vortex meter, accuracy of the instrument deteriorates at lower Reynolds number[5]. Apart from the known devices, there are two US Patents US 5,765,602 dated June 16, 1998[6] and US 3,958,443 dated May 25, 1976[7] relating to metering and transfer of cryogenic liquid, and apparatus for proving and calibrating cryogenic flow meters respectively. In the Japanese Patent JP60213070 dated October 25, 1985[8] entitled “Monitor device for liquid level in cryostat”, the level difference of the liquid is measured with Electric type gas flow meter. Therefore, the flow rate is measured in gaseous state only, whereas in the proposed device flow rate of the cryogenic liquid is measured in liquid state while the liquid is flowing through a tube/pipe.

Proposed Device

The proposed device is capable of measuring flow rate of inert cryogenic liquid without offering any additional resistance to the flow[9] (Figs 1-3). The device essentially consists of two coaxial tubes integrated with plugs at both ends. The space between the coaxial tubes being air-free is filled with insulating material. A small segment at the bottom of the coaxial tubes is cut, removed to accommodate a hollow cylinder having a matching inner surface profile as that of inner surface of coaxial tubes. A metal strip rounded off at the bottom is welded with the outer surface of the hollow cylinder. The metal strip being rotatably fixed at its middle portion by means such as a hinge, support and fixed frame in such a manner that the inner surface of the cylinder flushes with the inner wall of the tube and allows lateral movement of the cylinder due to drag force of cryogenic liquid flow. The metal strip supported on a metal flat, is fitted with a smaller coil mounted at its lower portion, which is electrically insulated from the upper portion by an insulator. Metal flat is fitted in such a way that metal strip can slide on a stretched potentiometer wire and the said wire and free end of metal strip make contact to form the junction of two arms of a Wheatstone bridge. Metal flat is supported

*Author for correspondence
E-mail: santoshkray@yahoo.com

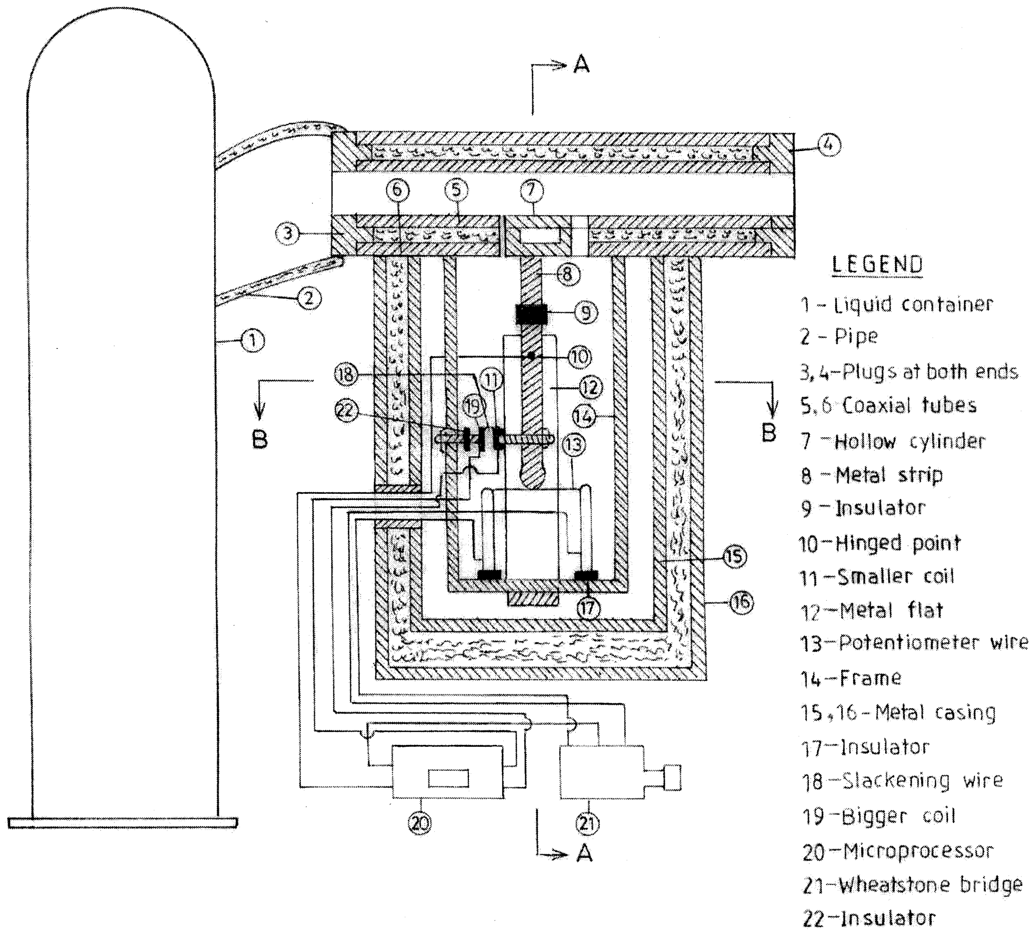

Fig. 1—Sectional elevation of the proposed device

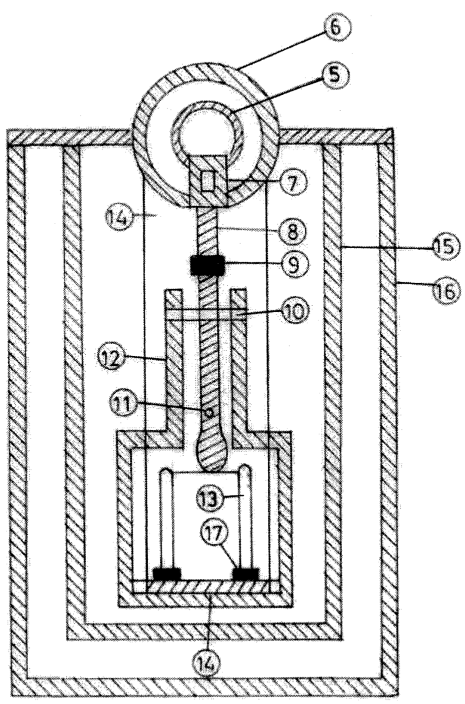

Fig. 2—Sectional side view at A A

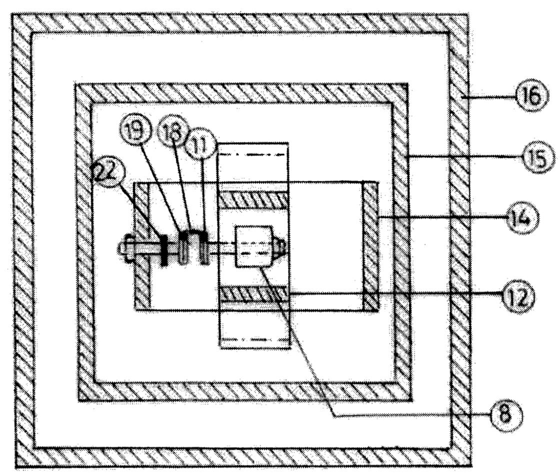

Fig. 3—Sectional plan at BB

on a frame; two ends of which are welded with the tube. Horizontal segment of the frame accommodates part of Wheatstone bridge circuit. Potentiometer wire is mounted on two insulators, which are based on the frame. Bigger coil is fixed at one side of the frame but electrically insulated by an insulator while the smaller coil moves with the metal strip and a slackening wire connects both the coil. The whole system is enclosed in two parallel metal casing maintaining an air free space between them, which is filled up with insulating material. Two ends of the coils and a connection from the hinge of the metal strip are brought out of the casing and connected to a microprocessor unit. Two ends of the potentiometer wire are connected with Wheatstone bridge at the outside of the casing.

Functioning of the Device

Cryogenic liquid, which is passed through the pipe connected with liquid container into the device, produces a drag force, which makes the hollow cylinder slide horizontally in the direction of flow. When there is no flow of liquid through the pipe, the contact point is at the middle of the potentiometer wire and a small amount of unbalanced voltage is available between junctions of the bridge. During the movement of rectangular cylinder due to drag force of liquid in the right hand direction, opposite end of the metal strip will move towards the left hand direction on the hinge. Arrangement of the bridge is such that as the free end of the metal strip moves towards left, the unbalanced voltage increases. Output of this is fed to a microprocessor unit, which will now produce a DC current proportional to the bridge output and fed to the larger as well as smaller coil. The current in the coils will produce a repulsive force because the coils are connected with a thin slack wire so that same current flows through both the coils but in opposite direction. This repulsive force will move the metal strip back till a balance position is attained, reducing the bridge output below a prefixed small value. Under such condition, microprocessor unit will stop further increase in the value of current supplied to the coil. The value of this current is calibrated against the flow rate of cryogenic liquid through the device and displayed in a liquid crystal display panel. Any change in the flow rate of cryogenic liquid will produce change in the drag force on the hollow cylinder and the microprocessor unit will effect change in the current flowing through the coils to keep the metal strip in the central position.

Principle of Operation

When cryogenic liquid is passed through a pipe, it exerts a drag force at wall of the pipe along the direction of flow. This drag force is proportional to the square of velocity of fluid, roughness of pipe wall, and density and viscosity of the fluid. For a particular fluid and pipe system, all parameters are constant, only velocity changes with the quantity of flow. Therefore, drag force on a small segment of the pipe wall is proportional to square of the velocity and hence square of flow rate of liquid[10].

$$\tau = 0.034\, \rho\, U_m^{\,2}\, (\nu / U_r)^{0.25} \qquad \ldots(1)$$

where, τ is drag stress on pipe wall, Nm^{-2}; ρ is the density of the fluid, kg/m^3; ν is the viscosity, m^2/s; U_m is the velocity of the fluid in the pipe, m/s and r is the radius of the pipe, m.

The flow criterion in the pipe may be regarded as a boundary layer on a flat plate, which has been wrapped round an axis at a distance δ from the plate equal to radius of the pipe. The axial velocity (U_m) is equivalent to the undisturbed stream velocity (U) of the flat surface boundary layer. The drag force is the product of τ and the surface area of the walls over the length (δx) that is $\tau P \delta x$ where P is the perimeter of the pipe. Therefore, drag force is proportional to the square of the velocity of fluid flow and hence proportional to square of the volume flow rate. However, for the volume flow rate of LN_2 and pipe diam normally used in infusion of LN_2 in mines, the drag force would be small and therefore the system must have a device to measure small force accurately.

A small segment of the pipe wall is cut and removed to accommodate a hollow cylinder having inner surface profile same as that of the pipe (Fig. 1). A thin metal strip is hinged at around its middle portion such that inner surface of the cylinder flushes with the inner wall of the pipe and the cylinder can easily move due to drag force on it. The gap between the cylinder and the pipe is however kept small. The material of the hollow cylinder, the metal strip and the volume of the cylinder are so fixed that overall density of entire set-up is same as that of LN_2. Therefore, when the system is immersed in LN_2, no downward or upward force is experienced by the set-up due to gravity or buoyancy.

The current in the coils produces a repulsive force, which is derived from the following expression:

$$F = 1.5\, \mu\, \pi.\, i_a.\, i_b\, a^2 b^2\, x / (a^2 + x^2)^{3/2} - \qquad \ldots(2)$$

where, x is distance between coils along their axis; a, b are radius of the coils; i_a, i_b are current through the coils a and b respectively; μ is magnetic permeability of the medium.

In this case, $i_a = i_b = i$, a and b are fixed, and x is also constant for central position of the metal strip. Therefore, $F = ki^2$ ...(3)

where $k = 1.5\, \mu\, \pi a^2 b^2\, x/(a^2 + x^2)^{3/2}$
For the equilibrium of the hollow cylinder

$$A.\tau.\, l_1 = k.\, i^2.l_2 \qquad ...(4)$$

where, l_1 and l_2 are distances of the cylinder and the coil from hinge of the metal strip. A is area of the cylinder surface exposed to the liquid flow.

Substituting the value of τ in Eq. (4) the above expression may be written as:

$$A[0.034\, \rho\, U_m^{\,2}\, (\nu / U_r)^{0.25}]\, l_1 = k.\, i^2 .\, l_2$$
or $U_m^{\,2} = ki^2$
or U_m is proportional to I

Since the flow rate of liquid through the pipe is proportional to velocity of the liquid, flow rate through the pipe is directly proportional to current flow through the coil.

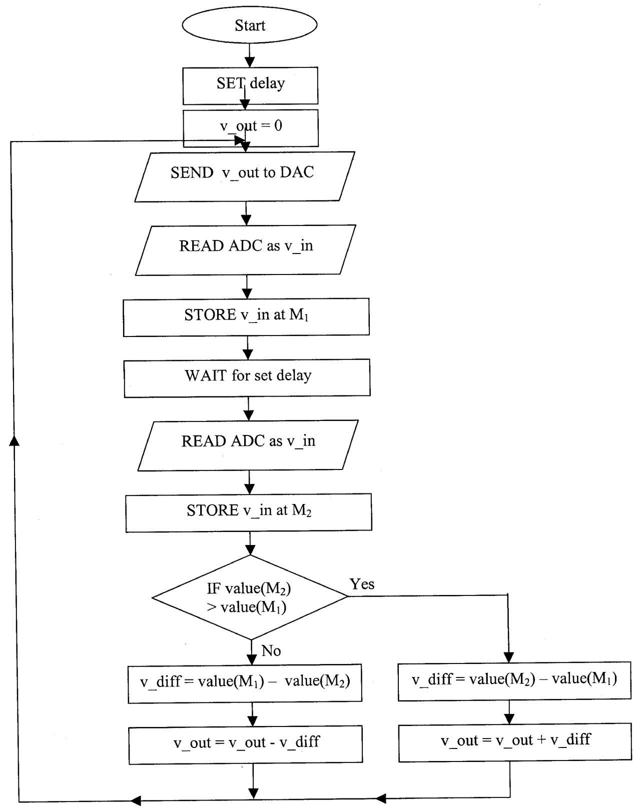

Fig. 4—Flowchart for the program logic of the proposed device

Program Logic

According to the program logic of the proposed device (Fig. 4), the unbalanced voltage is fed to ADC (analogue to digital converter) port of a microprocessor-based unit and the converted digital data is stored in the memory location M_1 of the microprocessor unit. At this moment, no force is required to keep the metal strip to its central position. As the fluid flows through the pipe, metal strip is pushed towards left and the unbalance voltage increases. The new unbalanced voltage is read after a prefixed delay from ADC port and the corresponding digital value is stored in some other memory location M_2. The processor then compares values stored in M_1 and M_2, and depending upon the difference of values, the processor correspondingly gives an output analogue signal through DAC (digital to analogue) port by adding difference with the existing DAC port input (initially zero). This analogue voltage is fed as the input to the two coils which in turn enables flow of current through them till the repulsive force produced between them tries to push metal strip back to its central position. This is confirmed by the microprocessor as it gets an input value same as stored in memory location M_1 during the next round of ADC port scanning. Microprocessor again controls analogue output voltage by adding existing DAC port input with the new difference of M_1 and M_2. At this stage, current through the coil ceases to increase and remains constant because the further iterations of ADC port scanning and processing result in zero difference between M_1 and M_2. Under the circumstances, value of the current flowing through the coils becomes a measure of the applied force to the metal strip and hence the flow rate of the liquid. This value is calibrated and displayed in terms of the flow rate (l/min). When the flow starts decreasing and the processor still supplies the constant current to the coils, due to which the metal strip slides to the right direction and at this moment, ADC value becomes less than the value stored at M_1, the microprocessor calculates difference and the existing constant DAC output is decreased by the same amount which causes flow of less current through the coils indicating less flow through the tube. As the liquid flow reduces further, current through the coil also reduces and if the flow becomes zero, microprocessor's DAC port output also becomes zero and stops generating analogue voltage. Thus current through the coil is also zero.

Conclusions

Microprocessor based flow meter, which would avoid rough estimation of flow of liquid nitrogen (LN_2) from a tanker at a particular time is designed to optimize rate of flushing of LN_2. Thus combating of fire is possible in minimum time and precise measurement of flow of inert cryogenic liquid at any time is assured. The proposed device is simple, straight forward, cost effective, based on fundamental principle, and does not introduce any resistance to the flow of the liquid being measured. Since the sensing element is such that its average density is same as that of liquid whose flow is to be measured, there is no alignment problem in the device.

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