HIGH-PERFORMANCE DIFFERENTIAL PRESSURE MONITORING DEVICES USING PULSATING SENSORS FOR A SODIUM-COOLED FAST BREEDER REACTOR

NUCLEAR PLANT OPERATIONS AND CONTROL

KEYWORDS: *differential pressure monitoring instrument, pulsating sensor, prototype fast breeder reactor*

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We present an unconventional but high-performance differential pressure (DP) monitoring instrument constructed using a new class of sensor, i.e., a pulsating sensor developed in-house. This instrument of unique design is of industrial grade, and it is specially made for online monitoring of pressure in the Prototype Fast Breeder Reactor (PFBR), located in Kalpakkam, India. It measures pressure in two different ranges—0 to 25 mbars (0 to 2.5 kPa) and 0 to 60 mbars (0 to 6.0 kPa)—using two specially designed capacitance-based robust probes made of stainless steel (Type 304L). The performance of this innovative instrument using both probes was thoroughly investigated at ambient room temperature as well as at elevated temperatures (above 30°C to 60°C) in order to assess its suitability for reactor application. The precision, sensitivity, response time, and lowest detection limit of measurement using this pulsating DP monitoring instrument are <0.01 mbars (0.001 kPa), 423 Hz/mbar (4230 Hz/kPa), ~5 s, and 0.07 mbars (0.007 kPa), respectively. The influence of temperature up to 60°C on the measured parameters was found to be insignificant. A calibration technique has been evaluated to calibrate these pressure sensors.

I. INTRODUCTION

Experience gained in fast breeder reactor (FBR) technology from successful construction, commissioning, and operation of the Fast Breeder Test Reactor (FBTR) at Indira Gandhi Centre for Atomic Research (IGCAR), located in Kalpakkam, India, inspired enough confidence for us to commence the next phase of the FBR program, i.e., construction of the Prototype FBR (PFBR). PFBR is a 500-MW(electric) sodium-cooled pool-type, mixed oxide–fueled reactor.[1] All reactor internals including the core and primary coolant are contained in a single vessel called the main vessel (MV). Although unlikely, if a leak in the MV were to occur, to ensure the minimum sodium level for core cooling, a safety vessel (SV), that closely follows the shape of and surrounds the MV is provided. The load from the MV and SV is transferred to the surrounding cylindrical concrete structure known as the reactor vault (RV). The normal gap of 300 mm is provided between the MV and the SV to permit robotic and ultrasonic inspection of the MV (Ref. 2). The free space above the sodium is fully covered with argon as cover gas. During normal operation of the reactor, the pressure in the SV is maintained at 40 mbars g (4 kPa g) ± 5 mbars g (0.5 kPa g). The difference in pressure between the reactor cover gas in the MV and the SV is always monitored, and it is not allowed to fall below 20 mbars (2 kPa). Similarly, the difference in the pressure of the SV nitrogen and the RV is maintained at 25 mbars (2.5 kPa). However, during fuel-handling operation, the above parameters differ.[3] Appropriate precautions should be taken to maintain the external pressure of the MV and the SV

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within the prescribed limits in order to avoid their buckling. Hence, high-precision measurement of pressure in different reactor containments is essential for reactor safety. In order to achieve this objective, high-performance (high precision, high sensitivity with excellent resolution) differential pressure (DP) monitoring devices compatible with the reactor environment are needed. Moreover, these instruments must be dependable for round-the-clock use.

Many investigators[4–11] report various techniques to measure pressure at different ranges. The sensors mostly used in their work are a capacitive pressure sensor,[4] capacitance-type smart sensors with artificial neural networks for temperature compensation,[5] fiber Bragg grating,[6] a fiber optic sensor based on a single-mode Fabry-Perat cavity,[7] a piezoresistive sensor,[8] an integrated capacitive pressure sensor,[9] capacitive pressure sensors following a silicon-on-insulator process,[10] and a wireless batch sealed capacitive pressure sensor.[11] Some of these techniques are suitable for industrial applications, and others are recommended for certain specific applications. Most of these techniques are not suitable for low-range application, which is essential for reactor use. Moreover, none of these techniques are recommended for a nuclear reactor. Of course, based on reactor designers' specifications, some of manufacturers supply specific pressure monitoring instruments for reactor use. But, in order to use the most reliable and dependable DP monitoring devices in various containments of the PFBR, we decided to indigenously make our own DP sensing instruments with pulsating sensors.

In our laboratory we have successfully developed very high-precision pulsating-type level sensors for critical application, i.e., dash pot oil-level sensing in the PFBR control and safety rod drive mechanism to monitor the scram action of control rods.[12] This development inspired us to develop high-performance DP monitoring devices based on precise level sensing of a suitable nonconducting liquid of low vapor pressure within specially fabricated manometer housing of different types. These DP sensors are successfully used for accurate and high-precision measurement at a pressure differential of 0 to 60 mbars (0 to 6.0 kPa). With highly satisfactory performance from many in-house–built DP sensors, we fabricated dedicated DP sensing devices that would work successfully in reactors. Besides this crucial application, these sensors will be used in glove boxes (GBs) for handling sodium as well as radioactive materials and hot cells of nuclear facilities where accurate DP monitoring at levels of a few mbars is required.

II. BASIC APPROACH TO SENSING DP

In our laboratory a new class of digital sensors has been developed, and they are deployed in many miscellaneous physical and physicochemical applications.[12–21] The primary consideration in developing such sensors is to generate the first electronic response in the digital domain, avoiding the intermediate signal processing that is normally used in conventional devices. Sensors are designed to respond very sensitively to shifts in one of the four electrical properties, namely, electrical conductance, dielectric permeability, inductance, and electromotive force of the physical or physicochemical systems to be probed. Any parameter that causes a change in any of the above properties, directly or indirectly, becomes measurable. In this type of digital sensor, the output is a train of digital pulses from which pulse frequency is determined. The pulse frequency is related to the sensing parameter. Hence, these new sensors are called pulsating sensors.

For highly sensitive pressure measurement, a specially designed U-shaped liquid dielectric manometer is used. A set of mirror polished stainless steel (SS) parallel plate electrodes with uniform gaps that acts as a parallel plate capacitor is fixed into one arm, called the sensing arm, of the manometer. The manometer is partially filled with a low-volatile mineral oil. The SS capacitor assembly constitutes the part of a specially designed tiny logic gate oscillator (LGO) operated by 5 V direct current (dc) at 0.5-A current. The capacitance of the sensor assembly is governed by two dielectric media: oil and air. For measurement of pressure in a confined containment, the sensing arm (A) is exposed to atmosphere whereas the other arm (B) is connected to the containment system. By applying a small positive pressure through B, the oil level in the sensing arm rises. With the increase in oil height, a minor increase in capacitance occurs due to a change in the overall dielectric permeability of the media following a change in the ratio of oil and air in the sensing arm. This results in an appreciable decrease in the output pulse frequency of the LGO. Thus, the pulse frequency decreases with an increase in the difference of oil heights of both arms or the difference of pressure between both arms. For high-precision measurement a relation between pulse frequency and pressure is established by appropriate sensor calibration, which is described in Sec. III.C. The working principle of the DP sensor is demonstrated in Fig. 1 using a laboratory-made DP monitoring assembly.

III. EXPERIMENT

III.A. Differential Pressure Sensor Assembly

The DP assembly consists of two arms made of two SS tubes widely differing in height and diameter. The tall and narrow tube is placed inside the short and wide tube with a common vertical axis. A special type of oil-level sensor consisting of a set of rectangular mirror finished SS electrodes fastened with nylon nuts and bolts with

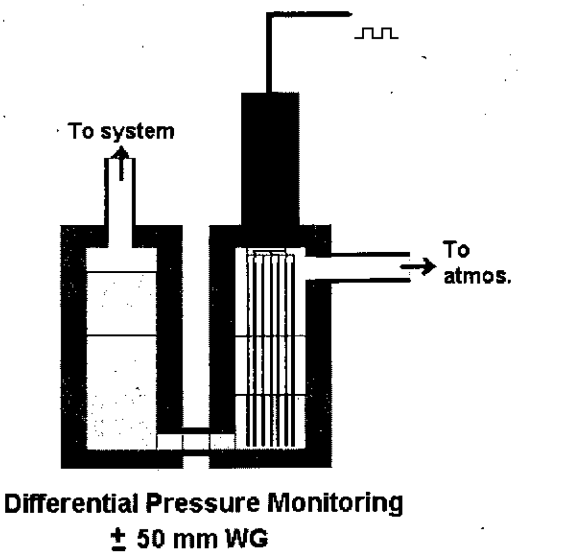

Fig. 1. Schematic demonstrating working principle of DP sensor.

uniform gaps maintained by Teflon spacers is placed in the narrow inner tube. These electrodes constitute a parallel plate capacitor assembly. The bottom of the electrode assembly is separated from the bottom of the wider tube with a gap of 10 mm using a Teflon washer in order to avoid electrode shorting during measurement. The sensor assembly is partially filled with a fixed volume of low-volatile mineral oil. The mirror finished SS electrodes have excellent wettability in oil, which is used as one of the dielectric media in the DP sensing assembly. It is also expected that the oil may undergo oxidation, which will lead to dielectric degradation. Hence, before choosing the oil for this specific application, we examined the effect of oxidation on the dielectric degradation of oil during long use. It was observed that even after keeping the same oil in the DP sensor assembly for 6 months, the dielectric degradation was <0.1%, which caused insignificant change in the measured parameter. Hence, the oil can be successfully used to monitor DP for a long duration. We have conducted a long-term performance study of the DP sensor (refer to Sec. IV.E) that clearly explains why this oil was selected for the sensing fluid. The volume of oil depends on the range of application. A small inlet tube is provided at the upper surface of the wider tube, which is connected to the containment during pressure measurement. A Perspex chamber with passive features is provided at the top portion of the assembly in order to hold oil in the event of accidental overpressurization. A resin embedded miniature pulse signal generator is mounted on top of the probe. Figures 2 and 3 are schematics of two types of DP sensing units to be used in PFBR.

III.B. Signal Generation and Processing

The DP sensor that comprises a set of rectangular SS plates (refer to Sec. III.A) is the capacitive component in

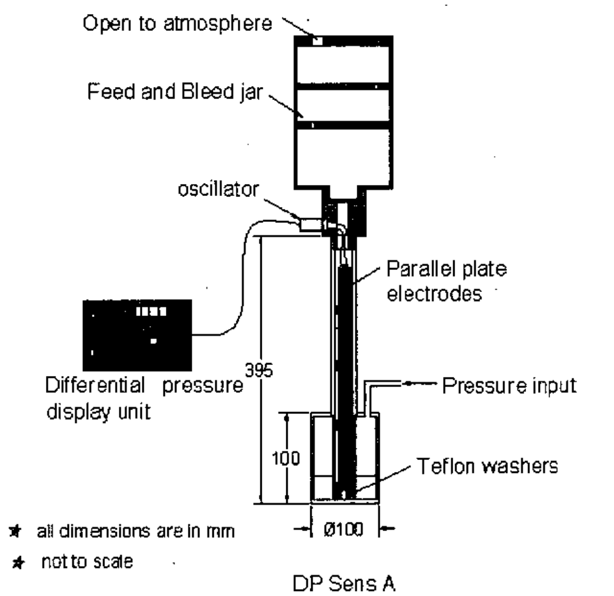

Fig. 2. Schematic of DP sensing instrument (DPSENS-A, 0- to 25-mbar range).

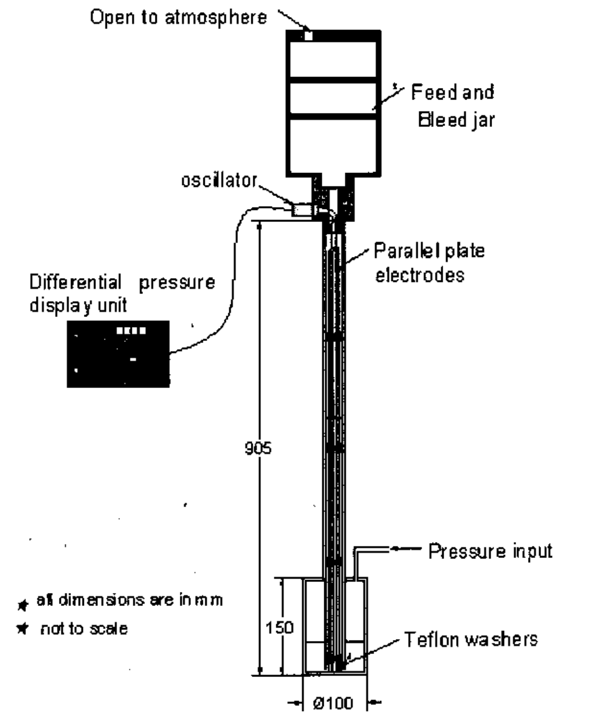

Fig. 3. Schematic of DP sensing instrument (DPSENS-B, 0- to 60-mbar range).

a specially designed low-power–consuming LGO circuit. The LGO circuit is embedded on the probe head and requires only 5 V dc supply from an external source. The train of rectangular pulses at the output of the pressure sensor from a given probe is processed by two independent signal processing and data acquisition systems such as a stand-alone embedded processor and a personal computer (PC)–based measurement with online graphic features.

III.B.1. Stand-Alone Embedded Processor

The DP sensor with LGO and the signal processing unit (SPU) are powered by a 5-V dual power supply. The signal from the sensor, i.e., the pulse train, is routed to the SPU via a five-core shielded cable. To avoid noise interference, the ground potential of the sensor circuit and the processing circuit are isolated using an optocoupler. The in-house–built embedded system (a) counts the number of input pulses for a fixed duration of time to determine the pulse frequency at the output of the pressure sensor, (b) evaluates the polynomial equation for conversion of pulse frequency to the parameter being sensed (here, pressure), (c) displays the parameter on a seven-segment light-emitting diode (LED) panel and sends it to a PC through a serial/Ethernet port, (d) operates the solenoid valves for pressure control and (e) stores the configuration values (coefficients of the polynomial equation, threshold values) in a nonvolatile memory and retrieves them during power reset. The SPU brain is an 8-bit microcontroller. The output from the optocoupler is counted by a programmable interval timer/counter (PIT) for a fixed duration set by the user during the configuration. A reference clock is used by the PIT to generate the fixed time interval. A microcontroller calculates the frequency of the sensor signal. A polynomial equation relates the frequency to the parameter, whose coefficients are provided by the user during the configuration. The controller displays the parameter in a four-digit seven-segment display and sends it to the serial/Ethernet port for remote data logging. A block diagram of instrumentation is shown in Fig. 4.

III.B.2. Personal Computer–Based Measurement with Online Graphic Features

The pulse generating unit positioned very close to the probe is powered by 5 V dc. A train of pulses generated from the LGO is directly transmitted to the PC through its parallel port along with a reference frequency. Since the output is TTL (transistor-transistor logic) pulses, no other pulse conditioning circuits are required. The indigenously developed software processes the train of pulses and calculates the frequency. It further converts frequency to pressure using a predetermined mathematical relation obtained during instrument calibration. The dedicated application software enables graphic presentation of data as a function of time, storage of data, quick review and analysis, cursor navigation features, and quick computation of simple statistics.

III.C. Calibration

Unlike commercially available DP monitoring instruments, a simple calibration procedure based on the first principle is followed to calibrate these pulsating-type DP monitoring devices. Hence, whenever they need to, users can check calibration independently in a more convenient way without depending upon any other devices. A typical

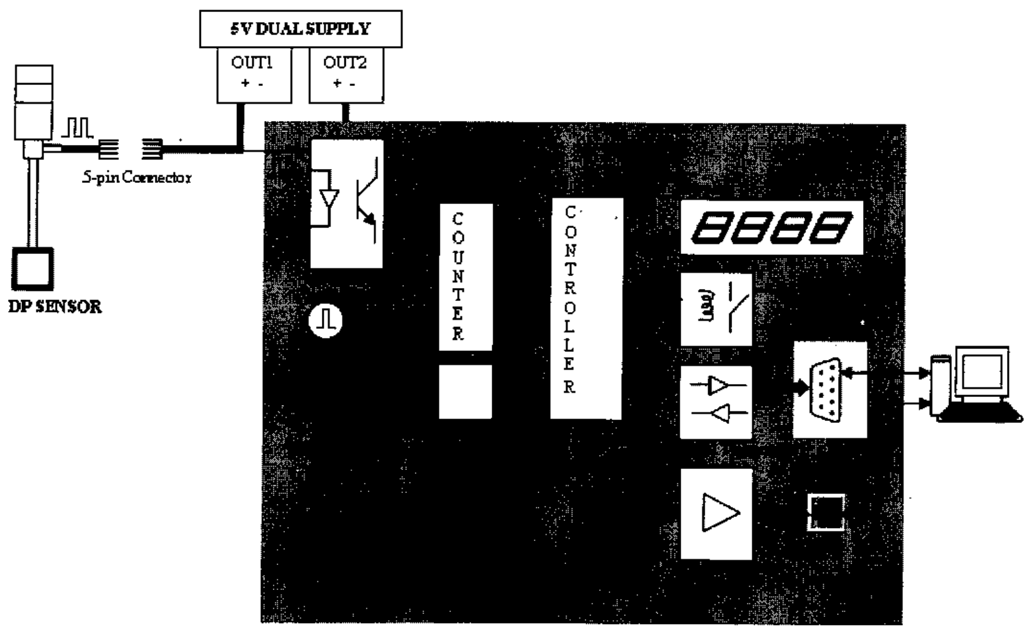

Fig. 4. Block diagram of instrumentation for DP sensing device.

calibration utility as shown in Fig. 5 based on the principle of manometer is made in-house. It is a U-shaped oil manometer constructed using a transparent Perspex tube partially filled with a fixed volume of oil. It is also provided with a Y-shaped connector. One side of the connector is connected to a specially designed injection port, a hollow tubular-type Perspex container fixed with a silicone rubber septum. Two other sides are connected to the inlets of the manometer and the DP sensing assembly using the appropriate rubber tube. During calibration a fixed volume of air is injected into the injection port. The volume of air injected into the closed system creates equal pressure in both the DP monitoring system and the calibrator. The difference in oil height between both arms of the oil manometer used as the calibrator is measured using either a scale or a height gauge. From the difference in oil height, the pressure difference between both arms in the required working pressure unit (in millibars) is computed. The corresponding frequency due to the change in the oil level in the sensing arm is measured. This process is repeated several times in order to cover the entire measurement range.

A calibration plot is prepared using frequency versus pressure difference in millibars. Using a least-squares-fitting technique, an appropriate polynomial relation in the second or third degree between the frequency and the pressure is generated. This mathematical relation is used in the system software in order to give a pressure reading directly in millibars. The calibration plots for both DP monitoring instruments are shown in Fig. 6. The sensor is also used in case of an inverse DP measurement, i.e., negative DP up to a limited negative value (−7.5 mbars) as per the requirement of PFBR designers. In such case the sensor is calibrated by stepwise removal of a fixed volume of air through the injection port. The DP sensors DPSENS-A and DPSENS-B are exclusively constructed with a view to meeting the reactor requirement. However, we have constructed DP sensors in the range −10 to +10 mbars (−1.0 to +1.0 kPa) by slightly modifying the design in order to use them in GBs and hot cells used in IGCAR.

We have realized that the calibration holds for a longer period, even more than 2 months. However, for field application we strongly recommend checking calibration in the field. In order to do that, the unit has to be connected to the calibration utility. Differential pressure is created in the system by injecting a fixed volume of air through the injection port as described above. With a single-point calibration, the sensor can be tested immediately in the field. If the reading in the display unit differs from the calibration utility manometer value above 2%, it is advised that a fresh calibration be done, incorporating the fresh coefficients in the system software.

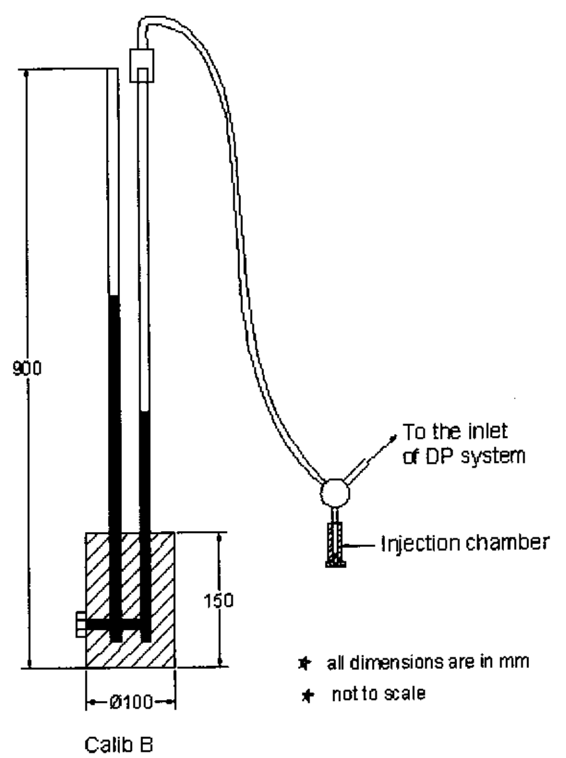

Fig. 5. Schematic representation of calibration utility used for calibration of pulsating DP sensor.

IV. RESULTS AND DISCUSSION

IV.A. Initial Studies Using a Typical Laboratory-Made DP Sensor (LABMOD-B)

Many measurement campaigns were conducted using different types of laboratory-made DP sensors using Perspex as the construction material of the oil manometer

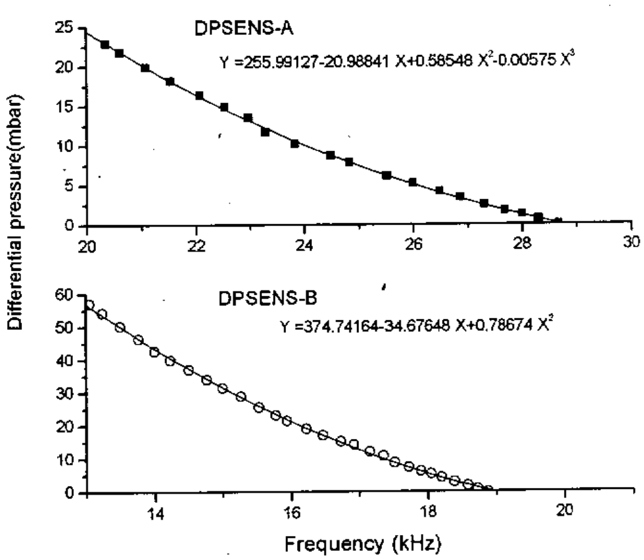

Fig. 6. Calibration plot to show the relation between frequency and pressure in DPSENS-A and DPSENS-B.

and a series of SS parallel plate capacitors, described in Sec. III.A, as the oil-level sensor. Mineral oil (fresh transformer oil) of very low volatility was used as the sensing fluid. The results of the performance test of one such DP monitoring device are given in Table I. Excellent reproducibility in background frequency over a period of 1 month, high precision in pressure measurement, rapid response, and high sensitivity inspired us to make a device suitable for reactor use. Hence, we made compact SS DP sensors of two different ranges: 0 to 25 mbars (0 to 2.5 kPa) and 0 to 60 mbars (0 to 6.0 kPa) with associated instrumentation. The performance of two prototype units is described below.

IV.B. Background Frequency Measurement

At the outset the background frequency measurements in both DP sensors—DPSENS-A, range of 0 to 25 mbars (0 to 2.5 kPa), and DPSENS-B, range of 0 to 60 mbars (0 to 6.0 kPa)—were carried out. At equilibrium, i.e., when the oil heights in both arms of the DP sensors were equal and the pressure difference of both arms was zero, background pulse frequency measurements were taken for 1 h. Figure 7 shows the real-time measurement of the background frequency in DPSENS-A and DPSENS-B. In each case, three sets of measurements taken at 1-month intervals for a period of 3 months are displayed. From these data it is observed that the relative standard deviation (RSD) in background frequency measurement in each campaign is <0.1%. Hence, it is quite obvious that the background values do not change since the dielectric degradation of oil used in both manometers is practically negligible. Of course, after a long period, i.e., after 6 months, a small change in background frequency is expected due to minor dielectric degradation of oil, which may be possible with the access of polar molecules such as moisture and oxygen during storage of oil in the manometer. In such a case, fresh calibration of the DP sensor is recommended prior to its deployment in a specific application.

TABLE I

Performance of a Laboratory-Made DP Sensor (LABMOD-B)*

Background frequency (Hz)	36017 ± 16.6 (n = 3288) 36046 ± 12.3 (n = 3244) 35989 ± 15.2 (n = 3260) 36029 ± 16.2 (n = 3275)
Precision in pressure measurement	4.2 ± 0.04 mbars (n = 10)
Response time (s)	3.2
Sensitivity	439 Hz/mbar

*Background measurement was taken every week for 1 month. In each measurement campaign the background reading was taken for 1 h. The term n refers to the number of measurements.

IV.C. Precision, Response, Sensitivity, and Detection Limit of DP Sensors

In order to determine the measurement precision throughout the entire working range, the following procedure was followed. The DP sensor was pressurized by injecting a small volume of air into the inlet provided at the wide arm of the probe through the injection port. This resulted in an increase in the height of the oil in the narrow arm (the sensing arm). The process was repeated several times in order to cover the entire measurement range. The change in oil height between both arms of the manometer in each step caused a change in the pulse frequency because of a sudden change in the dielectric ratio of two media in the sensing arm: air and oil. Using frequency and pressure relation as loaded in the software package, pressure in millibars at each step was monitored online. Figure 8 shows a stepwise increase in pressure with the respective RSD in one of the prototype sensors. The RSD in the above measurements lies between 0.03% and 0.22%. The measurement sensitivity is found to be 423 Hz/mbar (4230 Hz/kPa).

The response time of one of the pulsating DP sensors is demonstrated in Fig. 9. In this case, the response time, which is defined as the time required for the instrument to register 63% of a sudden change in DP, has been evaluated in both increasing and decreasing pressure directions. In the increasing pressure direction, the response time is 4 s whereas in the decreasing direction it is slightly higher (4.5 s). Viscous drag along the walls of electrodes during gravity fall of oil from an upper to a lower level introduces some delay, which results in a marginally higher value of response time. The value for the lowest detection limit defined as the pressure corresponding to three times of uncertainty in background frequency (three times the standard deviation in background) of both sensors is <0.1 mbar (<0.01 kPa).

IV.D. Influence of Temperature

Minor temperature influence on DP sensor output arises because of influence of temperature on dielectric permittivity, minor volume expansion of oil, slight structural change in the sensing region due to differential thermal expansion of structural material, and temperature sensitivities of the electronic components in the pulse generating circuit mounted over the probe head. As these effects are reversible, the overall effect on DP sensor output needs to be considered. In PFBR these pressure sensors will be used in containments where temperatures will never exceed 60°C. Hence, before introducing any preventive measure for temperature compensation, we thoroughly investigated the performance

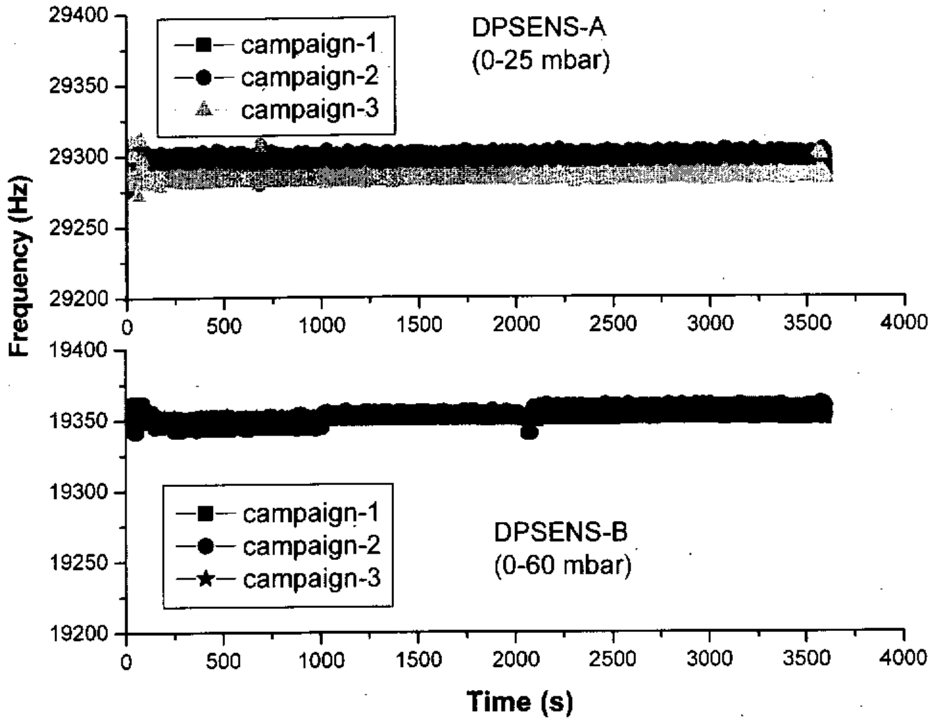

Fig. 7. Real-time measurement of background frequency using prototype DP sensors (DPSENS-A and DPSENS-B).

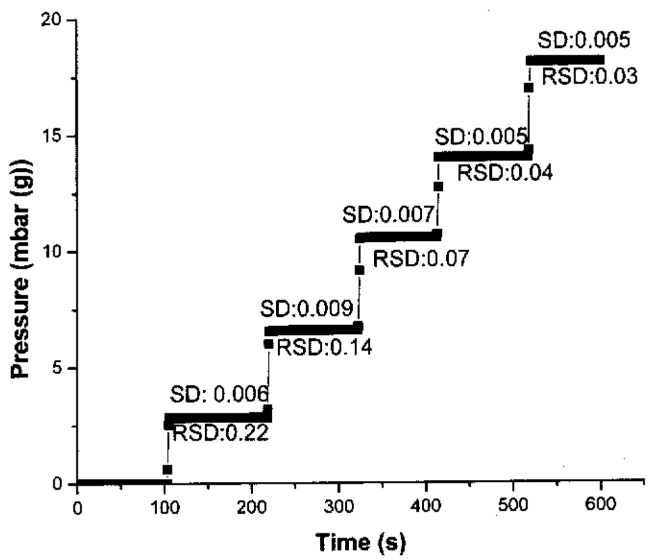

Fig. 8. Precision check in a typical DP sensor with stepwise increase in pressure.

of two prototype units at different temperatures. A typical vertical-type top-loading oven was used to maintain the desired temperature with a precision of ±1°C. The DP sensing device was kept inside the oven at a constant temperature. The frequency output, which is a function of pressure, was monitored. Table II shows the effect of temperature on the DP sensor output measured at different constant temperatures. From these data it is quite obvious that a change in temperature from 30°C to 60°C results in a change in frequency up to a maximum value of 119 Hz, which is equivalent to <0.3-mbar (0.03-kPa) pressure. Hence, for application in PFBR the change seems to be insignificant.[3]

IV.E. Long-Term Performance Study

One of the prototype DP sensors was maintained at a constant DP at ambient room temperature. The frequency output corresponding to the DP was measured every week for a total of 2 months. The results of uncertainty in frequency measurement are shown in Table III. From these data the measurement reproducibility even for a long period (~2 months) is found to be extremely satisfactory (RSD: <0.1%). Since the sensing fluid was kept inside the manometer without any disturbance, it did not show any degradation in its dielectric property. However, it is advised that calibration be checked periodically to avoid any error in measurement.

IV.F. Validation of the Present Measurement Technique

We validated the present DP measurement technique by comparing the results with those obtained from an independent technique using a commercially available

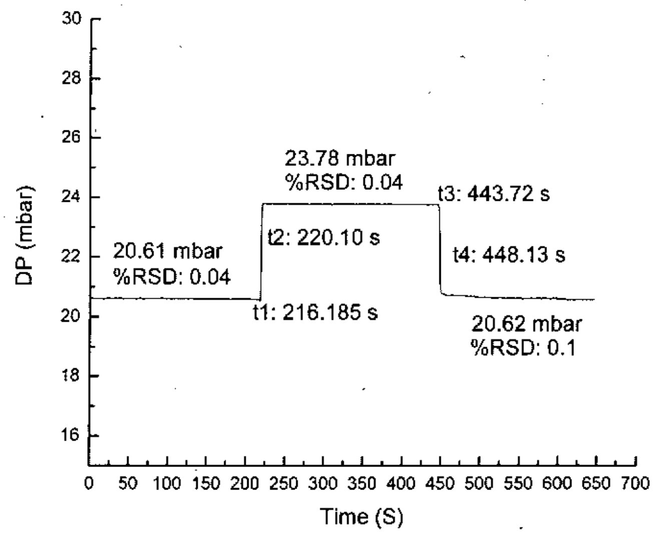

Fig. 9. Demonstration of response time in a prototype DP sensor [t1 = time (in seconds) corresponding to the sudden increase in DP; t2 = time (in seconds) corresponding to 63% of increase in signal; t3 = time (in seconds) corresponding to sudden decrease in DP; t4 = time (in seconds) corresponding to 63% of decrease in signal].

instrument: a photohelic pressure gauge[a] used to monitor DP in the range of 1 to 5 in. of water gauge (WG) (0.249 to 1.245 kPa) with ±2.0% accuracy as against ±0.5% in our DP sensor in the range of 1 to 60 mbars (0.1 to 6.0 kPa) determined by using a primary sensor (water manometer). The photohelic pressure gauge is not the primary standard sensor. The calibration of such a type of sensor is done by the manufacturer, and it has to be checked periodically using a primary sensor. In our research center such instruments are being used in all sodium and radioactive facilities where reliable measurement at a very low DP level is required, i.e., in GBs handling radioactive materials, GBs handling sodium, hot cells used for handling highly radioactive materials, etc. Our DP sensor and photohelic pressure gauge were connected to a sodium-handling GB available at the IGCAR Safety Engineering Division. The GB was maintained at a slightly more positive pressure (~2 to 8 mm WG). In situ measurement of DP by both instruments simultaneously was recorded time to time. Results obtained from both instruments, as shown in Table IV, agreed well. Because of the fast response of our instrument, it not only measured the pressure but also provided information on a sudden change in pressure in the GB during recirculation of Ar gas for purification. We also connected one of our DP sensors in the GB for continuous online measurement. For the last year the sensor has been working satisfactorily.

In addition, two prototype pulsating sensors have been tested for environmental qualification for the PFBR instrumentation and control systems based on International Organization for Standardization ISO 9000 as mentioned in one of our internal reports.[22] Both sensors passed all the tests stipulated in the report. Based on these tests they are classified as Safety Class-II instruments. Hence, we are confident that this novel technique using a pulsating sensor can be successfully used in high-precision measurement of DP in the GB, hot cell, and reactor containments of nuclear facilities where high-precision measurement at relatively low pressure is required.

IV.G. Influence of Radiation

The DP sensor presented in this work is mainly constructed for monitoring DP in various PFBR containments mainly in the inner space between the MV and the SV and in the RV. In such locations the radioactivity level is expected to be much less. However, in the case of leakage of cover gas from the MV to the SV, a small amount of radioactivity may be expected in the inner space region. When this radioactive gas is continuously passed through the oil, which acts as the sensing fluid of the DP sensor, the oil may degrade to some extent in the long run, which will affect the measurement. To address this problem, we put a fixed volume of oil in a ^{60}Co gamma chamber for irradiation. The influence of absorbed dose on frequency output corresponding to a fixed oil height was studied systematically. It was observed that at an absorbed dose of 200 Gy, there was a difference of frequency of ~120 Hz, which corresponds to ~0.3-mbar (0.03-kPa) pressure. Hence, our DP sensor can be comfortably used in reactor containments for long duration without replacing the oil.

IV.H. Effect of Signal Transmission over a Long Distance

Since the primary signal obtained from the sensor head is directly in digital form, i.e., a train of rectangular pulses, the signal shows excellent noise immunity. Hence, the signal can be transmitted a long distance without any loss. In order to ensure this, we carried out an experimental campaign as described below. One of our DP sensors was maintained at a constant DP. The in situ DP measurement was carried out in the laboratory by connecting the sensor to the measurement unit using a 5-m cable. The same procedure was repeated by replacing the 5-m cable with a 100-m cable. The results obtained in both operations agreed well. This inspires confidence that our DP sensing instrument is perfectly suitable for field application.

IV.I. Differential Pressure Control

The DP sensing device with pulsating sensors presented in this paper has also been used to control a small shift in DP besides its deployment in precise measurement of DP down to a few millibars, which is required for

[a]Photohelic pressure gauge: Dwyer, Model A3005.

TABLE II

Effect of Temperature on DP Sensor Output*

Temperature (°C)	Frequency (Hz) Campaign 1	Frequency (Hz) Campaign 2	Frequency (Hz) Campaign 3	Frequency (Hz) Campaign 4	Probe Used
30 ± 1	19297 ± 6	19325 ± 5	19300 ± 4	19310 ± 9	DPSENS-B
40 ± 1	19282 ± 8	19298 ± 5	19279 ± 5	19283 ± 7	DPSENS-B
50 ± 1	19275 ± 5	19270 ± 8	19267 ± 7	19269 ± 6	DPSENS-B
60 ± 1	19269 ± 6	19253 ± 5	19255 ± 5	19257 ± 5	DPSENS-B
30 ± 1	29385 ± 6	29379 ± 7	29389 ± 4	29397 ± 5	DPSENS-A
40 ± 1	29340 ± 4	29345 ± 8	29355 ± 8	29353 ± 9	DPSENS-A
50 ± 1	29310 ± 6	29318 ± 6	29322 ± 7	29326 ± 4	DPSENS-A
60 ± 1	29278 ± 7	29284 ± 5	29281 ± 4	29293 ± 4	DPSENS-A

*The measurement ranges of DPSENS-A and DPSENS-B are 0 to 25 mbars and 0 to 60 mbars, respectively. All measurement campaigns were completed within ~90 days. The time interval between two consecutive campaigns was ~30 days.

TABLE III

Long-Term Performance Study Using a Prototype DP Sensor*

	Frequency (Hz)	Temperature During Measurement (°C)
Measurement in first week	32525 ± 18 ($n = 10$)	29.5
Measurement in second week	32531 ± 15 ($n = 7$)	31.0
Measurement in third week	32518 ± 22 ($n = 10$)	30.5
Measurement in fourth week	32511 ± 18 ($n = 7$)	28.8
Measurement in fifth week	32531 ± 16 ($n = 9$)	29.0
Measurement in sixth week	32530 ± 12 ($n = 5$)	29.5
Measurement in seventh week	32515 ± 21 ($n = 7$)	30.2
Measurement in eighth week	32519 ± 15 ($n = 7$)	29.4

*In each measurement campaign about five to ten independent measurements were taken at every half-hour interval. The term n refers to the number of independent measurements.

application in PFBR. We have successfully demonstrated control action within a ±1-mbar level in a prototype DP sensor using an in-house–built ON/OFF control unit assembled with solid-state relay (230 V, 10 A) capable of operating a solenoid valve. The DP sensor was pressurized to a fixed upper threshold value (21 mbars). Immediately after obtaining a stable reading, an artificial leak path was created so that the DP gradually decreased from the upper threshold value. When it reached a fixed lower threshold value (20 mbars), the valve opened and permitted the flow of Ar gas from the Ar cylinder into the sensor assembly until the DP reached 21 mbars. Then, the valve closed, and the cycle was continued. Hence, our DP sensing device will also be used as a control pressure switch in PFBR at some specified locations.

In some of the DP sensing instruments that are especially designed to be used in monitoring DP between the MV and the SV and between the SV and the RV during normal operation, appropriate threshold values (setpoints) have been provided. If the DP in the MV and the SV and in the SV and the RV are beyond the threshold values (20 to 25 mbars in the case of the MV and the SV; 25 to 30 mbars in the case of the SV and the RV), an alarm with an LED glow indication will appear on the control panel.

IV.J. Potential Failure Modes

As mentioned in Sec. IV.F (Ref. 22), the sensors have been qualified as Safety Class-II instruments. This new class of pulsating DP sensor is an indigenous development as per the requirements of the PFBR Instrumentation and Control Group. Further, we analyzed some of the potential failure modes, which would provide a guideline to the users for safe handling of this innovative instrument. The pulsating DP sensor fails to work at

TABLE IV

Comparison of Results with Those Obtained from a Commercially Available Instrument Used in Sodium-Handling GB Facility

Number of Measurement Campaign	Differential Pressure Using Present Technique (DPSENS-A) (mbar g)	Differential Pressure Using Photohelic Pressure Gauge[a] (in. WG)
1	2.6	1.1 (2.7)[b]
2	2.7	1.1 (2.7)
3	2.5	1.0 (2.5)
4	2.6	1.1 (2.7)
5	2.9	1.2 (3.0)
6	3.1	1.2 (3.0)
7	3.1	1.2 (3.0)
8	6.2	2.5 (6.2)
9	4.1	1.6 (4.0)
10	4.0	1.6 (4.0)
11	3.8	1.5 (3.7)
12	4.5	1.8 (4.5)
13	4.9	1.9 (4.7)
14	4.5	1.8 (4.5)
15	3.8	1.5 (3.7)

[a]Dwyer, Model A3005.
[b]Numbers in parentheses are the DP in units of mbar g.

temperatures <5°C and >85°C. At such a low temperature, the sensing fluid is observed to be degraded. At elevated temperature (>85°C), the associated electronic components started malfunctioning. The sensor fails to work in the event of accidental overpressurization above 245 kPa with respect to atmospheric pressure. At such a high pressure, the PTFE (polytetra fluoroethylene) components attached to the sensor body come out. But, when the surrounding pressure is 0.75 kPa less than atmospheric pressure, the sensing fluid from the sensor assembly is spilled outside. An absorbed radiation dose >500 Gy affects the sensing fluid. When the current drawn by the circuit is >1 A, the fuse is found to be blown down protecting the electronics circuit. Accidental ingress of a few drops of water particles into the sensor assembly cause the sensor to malfunction since the dielectric permeability of the sensing fluid is totally affected.

V. CONCLUSION

Highly sensitive and reliable DP sensors have been developed in our laboratory. The sensors are of pulsating type and are based on precise level sensing of a suitable nonconducting liquid of low vapor pressure within specially constructed manometer housing of a unique type. The requirement of robust high precision and highly sensitive DP sensors at two different ranges—0 to 25 mbars (0 to 2.5 kPa) and 0 to 60 mbars (0 to 6.0 kPa)—for PFBR inspired us to develop such DP sensing instruments described in this paper. Some of the salient features of this new type of sensor that is suitable for reactor application are highlighted. Stable background frequency in long-term use, high precision in frequency measurement, high sensitivity, high resolution, fast response, direct digital signal from the sensor head, excellent noise immunity, signal transmission over a long distance without any loss, very low-power consumption, insignificant change in the measured parameter at elevated temperature, robust design of DP sensing assembly, suitable calibration utilities for quick multipoint calibration and periodic calibration check, and incorporation of suitable passive features for containment of liquid within the devices in the event of accidental excessive overpressurization or evacuation are some of the key factors behind their high performance. Hence, we are confident that these DP sensing instruments will be most appropriate for use in FBR containments besides the GBs and hot cells used in nuclear facilities.

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