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Integrated Coolant Leakage Monitoring System In The Pipelines For Sustainable Operation Of Light Water Reactors

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Abstract— The leak before break (LBB) concept is well known for safe nuclear power operations. However, the researchers are continuously working to develop a sustainable leakage detection system in the pipeline. Leak detection morphology is also not well settled enough. Hence, this study was focused to design and propose a leak detection and monitoring system for the safe operation of 3rd generation light water reactor based on integrated sensor units. The system monitors real-time conditions of pipeline degradation and service aging so that maintenance or replacement can be performed before the loss of safety function. This is based on the premise that a detectable leak was developed before a catastrophic break occurs. This research is also focused on design for early detection of leakage and if leakage occurs then identify the leakage properties, such as Leakage size, Position, Direction Localization, and loose part monitoring as well based on detailed data analysis from the vibration sensor. Each integrated sensor unit was used to avoid false signals. The system vibration sensor is used to monitor pipeline conditions, identifying cracks and leakage in a pipeline. Integrated humidity and temperature sensors are used to verify the leakage signal from the vibration sensor to avoid false signals. And finally, ultrasonic sensors are used to monitor the banding and displacement of a pipeline due to large leakage of high-pressure fluid through the pipeline. Through these phenomena, this research showed the analytical process involving such sensor integrated system to monitor all characteristics of the pipeline and any abnormal situation from small internal cracks to pipeline breaks.

Index Terms— Coolant, Leakage Detection, Nuclear Safety, Primary Circuit, Acoustic Sensor

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1 INTRODUCTION

In Light water reactors, acoustic noise and vibration seem whilst a high-pressure fluid outflows from the pipeline, and this noise is a source of data approximation for the reality of depressurization of the Primary circuits and secondary circuits as well. Usually, the waves appear on the surface of pipes while the steam-water mixture comes out of the crack. For many reasons, the contact acoustic vibration approach has become full-size in the reactors. They are also necessary for the presentation of information in the control room. Therefore, it is of high importance that the sensors are reliable, accurate, and fulfill the demands on response time [1]. The acoustic vibration approach is especially a type of contact vibration, but the researchers are working to secure its advantages which are (i) to make it fast performing and, (ii) in principle, allowing us to estimate the magnitude and coordinate of the leak in the pipeline. Ideally, pipeline operators and owners of the water company aim to employ simple, robust, and highly accurate methods for detecting and locating leaks in the water pipeline system.

However, the riskiest phenomena arise at some stage in the interaction of equipment with a glide of fluid medium within the resonance fluctuation area of mechanical elements and float, which gives upward thrust to emergencies and thus goes beyond sustainable heat transfer [2,3]. Hence, it is necessary to get an approach to identify the vibration-acoustic traits and the natural vibration frequencies of the pipelines, their elements, and their connections, in addition to the oscillation frequencies of coolant in these systems in unique modes of commercial Reactor operation to overcome the loss-of-coolant accident (LOCA) due to pipeline failure. Furthermore, it is important to make certain discrepancies among the peaks of spectral characteristics of signals from the sensors measuring working medium pressure pulsations and indicators from the sensors measuring vibrations, displacements, and dynamic stresses.

1.1 Leakage Monitoring Systems Overview

The coolant leak detection of the primary circuit system of an NPP is very essential through the Leak Before Break (LBB) concept with the abilities of the different techniques of leak detection, from the factor of view of the applicability. For light water units, the Integrated Leak Detection System (ILDS) was developed with three subsystems [4] namely: LEMOP (Leak Monitoring of Pipelines) based on acoustic emission monitoring, HUMOS (Humidity Monitoring System) based on humidity monitoring, RAMOS (Radiation Monitoring System) based on radiation monitoring and their integration in the ILDS system.

Moreover, acoustic monitoring in nuclear installations covers a collection of methods that measure the emissions and/or reflections of different processes and components. Such a listening rod was used to detect the sound resulting from leaking water and pressurized pipes like the stethoscope. The system was

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further improved in the 1970s, developing noise correlation and calculating a fundamental difference of the noise to analyze the noise. The LBB technique was published by International Electrotechnical Commission, summarized in Table I, and also found recommended by Slavov [5].

Where the utilization of numbers, A- Can generally be applied to meet the requirements, B- May be acceptable, marginal, or unable to meet the requirements, C- Not normally recommended but might be used to monitor specific locations.

TABLE 1
METHODS OF LEAK DETECTION

Method	**Leakage detection sensitivity**	**Leakage measurement accuracy**	**Leak location**
Sump monitoring	A	A	C
Condensate flow monitors	A	B	C
Radio-gas activity monitor	A	B	B
Radio-particulate activity monitor	B	B	B
Reactor coolant inventory	B	B	C
Humidity	A	C	B
Acoustic monitor	A	B	A
Temperature	A	C	B
Pressure	B	C	C
Tape moisture sensors	B	C	B
Liquid radiation monitor	A	B	B
Steam line radiation monitor (PWR)	A	C	A
Visual	B	C	B

Since 2010, transient analysis methods have also been used to analyze the water pipeline conditions from internal sensors to detect flow rate, pressure, and temperature [6]. But Covas and Ramos [7] showed a wave difference method known as a District Meter Area (DMA) and covered 1500 to 3000 connections. On the other side, an air-coupled V-type ultrasonic leak detection system was proposed by Chamran and S. Shafie [8] for a non-contact method of PVC pipe leak detection monitoring of the ultrasonic transducers (UTs) out of the pipeline with a specific distance and adjusting the sensor head direction. However, this method was also unsuitable for measuring vibration signals from underground pipeline systems, and it only analyzed the vibration data from a single axis.

Therefore, sensor-integrated x, y, and z-axis data collection methods could be a solution to identify the optimum leakage detection system. In addition to these three groups of transient-based analysis methods, many leak detection techniques are available. However, none of these techniques are completely successful or reliable in all leak detection cases because they can be imprecise, time-consuming, or suitable only for limited pipeline segments [9,10].

2 MATERIAL AND METHODS

Initially, a prototype was developed based on the Charman and Covas methodology and with several modifications, a new leakage detection system with greater efficiency was developed to monitor and analyze the leakage condition of the pipeline and valves. In this system, three types of sensors are installed on each sensor unit.

TABLE 2
. SAMPLE & EXPERIMENTAL PARAMETERS

Parameter	**Properties**
Type of Pipe	Stainless steel
Pipe length	2.5 meters
Coolant	Water
Pressure	1-3 Bar
Vibration Sensor Model	ADXL335
Humidity Sensor Model	DHT11
Time sampling(ms)	10
Pipe leaking end distance	1.5 meter
Pipe Diameter	16.8 mm
Pipe wall thickness	1.8 mm
Microcontroller	Arduino UNO (ATmega328p)

A Triaxial sensor (ADXL335) Piezoelectric and Humidity sensor were placed inside the thermal insulator layer with a High-temperature microphone. On the other hand, an Ultrasonic displacement sensor was placed outside of the sensor unit. The ADXL335 sensor uses the first-in-first-out (FIFO) technique to transfer data from the sensor to the processor. Here processor was used with a two-wire interface based on an integrated circuit (IC) connection: serial data (SDA) and serial clock (SCL). Figure 3 shows the placement of the ADXL335 vibration sensor on the water pipe system where the x-axis of the sensor is directly parallel to the water flow of the pipe. The distance between the preset leakage area and the sensor was set at 0.5m for both prototypes. However, pipe leakage pressure varies from 1 bar to 3 bar. Additionally, the EVAL-ADXL335Z, a simple breakout board was integrated that allows quick evaluation of the performance of the ADXL335 accelerometer. The ADXL335 is a 3-axis analog-output accelerometer using the 3.3V pin of Arduino Uno and the sensitivity of the sensor was 330mV/g.

The vibration data are collected from three different axes: x, y, and z axis at intervals of 10 milliseconds. Moreover, all three

TABLE 3
LEAK CASE CONDITIONS

Analyzed leak Case Type	Denotation
No Leak(steady)	P
Normal Operating Condition (NOC)	Q
Leak pressure 1bar	R
Leak pressure 2bar	S
Leak pressure 3bar	T

types of sensors are used to avoid false signals. For the better representation, the analyses of leak cases are denotations are mentioned in Table 3.

2.1 Software and Sensors Interference

The methodology and data acceleration process from ADXL335 is shown in the flow chart in fig. 1. Here, the vibration information was read by the ADXL335 sensor, and the data was sent by serial to the data collection and processing system. Initially, the Arduino UNO sets the I^{2}C function to read data from the sensors using the FIFO process. Arduino requests data from the sensor, and the sensor responds. Then the accelerometer degradation of the accelerometer by the three axes of the ADXL335 sensors, which are the x-, y-, and z-axis was measured. However, the accelerometer sensor also starts using I^{2}C to test the communication between the Arduino UNO board and the ADXL335.

Detailed work representations are shown in fig. 2. Where L is the total distance between two sensors and X is the location of the leakage from the nearest sensor. So, the distance between two sensors becomes, $(LA)/(A+B)$; where A and B are the collected sensor data between two sensors.

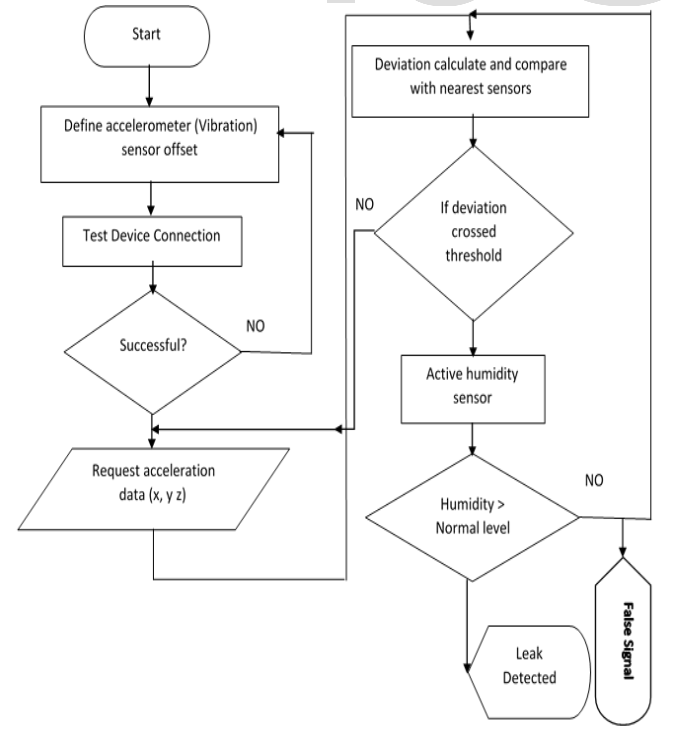


Fig. 1. Experimental Approach

2.2 System Design and Setup

The pipeline experiment sample was designed using a stainless-steel pipe. The test pipeline was connected to a pump to provide flow and pressure in the pipeline and the ball valve was connected to control the pressure and flow rate.

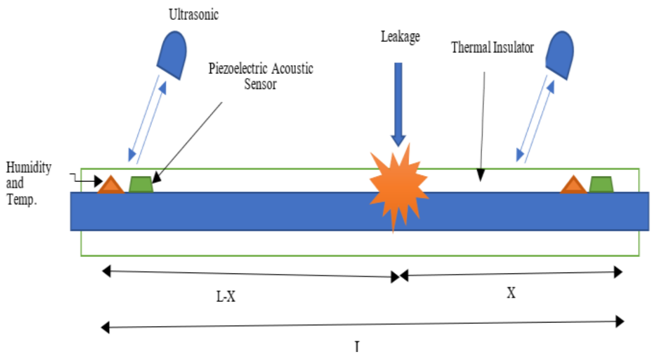


Fig. 2. Proposed leak detection system

The Arduino board via the control board read data from the sensors and collected vibration data at different x, y- and -z-axes. Vibration data is analyzed using the signal analysis method to detect leaks and determine the sizes of leaks. The test was carried out by three different artificial pipeline setups: a stainless-steel pipeline, a pipeline with a crack, and a pipeline with leakage. The test setup integrates the vibration signal from the pipeline system under three different conditions, that is, P, Q, R, S, and T. The inertial state is a signal produced by the pump and outlet valves. The normal and abnormal conditions are that there are no leakage and leakage events, respectively.

Fig. 3 illustrates the system architecture of the pipeline monitoring system used in this work. Moreover, such a leak detection application captures changes in the surface temperature of the pipeline in 1-meter units at least every 10 seconds.

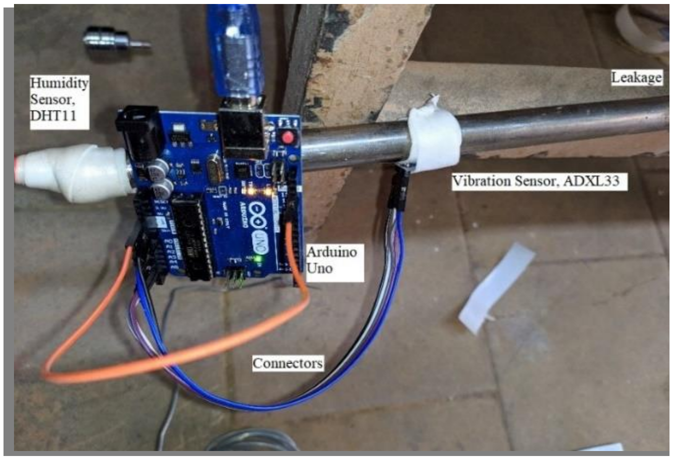
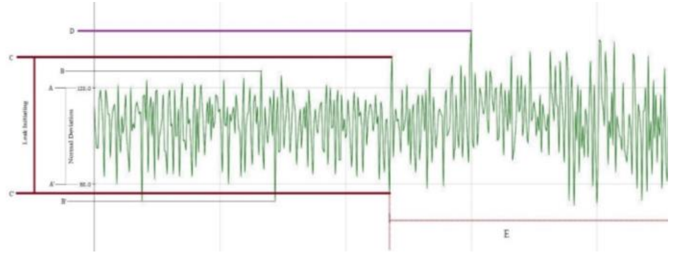


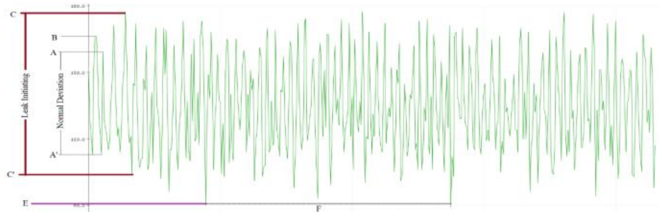
Fig. 3. Demonstration of the system architecture

3 RESULT AND DISCUSSION

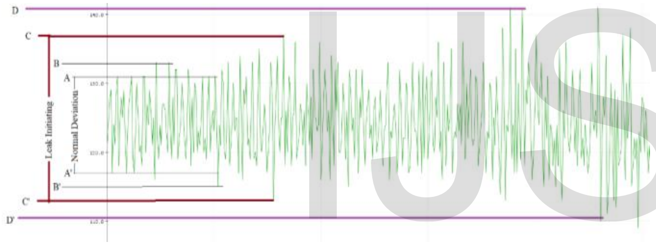
The ADXL335 sensor generates 3 types of signals from three axes. Those signals describe the condition of the pipeline and the properties of leakage. Figure 4 represents a 10-bit resolution signal merged about the x, y, and z-axis in normal operation.



(a) X-axis leakage Signal



(b) Y-axis leakage signal



(c) Z-axis leakage signal

Fig. 4. Acoustics signal for leakage about X, Y, and Z axis

Each axis provides maximum and minimum amplitude of that signal, and those maximum and minimum data presented the deviation of the amplitude in a different state, which is represented in Table 4.

Analyzing the normal deviation, the leakage of a pipeline was observed properly. The sample output signals in the abnormal condition in the x-, y-, and z-axis are shown in fig. 4. The signal from the sensor shows normal deviation amplitude varying between 80° to 120° which is mentioned by A and A′. Moreover, it is possible to observe the vibration amplitude crossing over A and A′ due to losing parts which are mentioned by B and B′. It also represented the strength of the attachment connection between the pipeline and the basement. When leakage has been done a little bit artificially then a peak in amplitude was observed in both positive and negative sides of the x-axis generated signal, which is denoted by C and C′. The time is represented by the initialization state of leakage. So, it showed a high peak in a positive direction and this is the stage where leakage occurred. After leakage occurred the signals from the x-axis showed abnormal deviation which is denoted by E.

TABLE 4

MINIMUM & MAXIMUM DEVIATION: GLOBAL AXIS

Condition	X_{Min}	X_{Max}	Y_{Min}	Y_{Max}	Z_{Min}	Z_{Max}	T_{dev}
P	118	126	136	137	102	102	9
Q	111	134	129	167	87	123	97
R	107	133	117	169	74	130	134
S	107	135	110	165	71	132	144
T	106	137	102	179	68	135	175

TABLE 5

LEAKAGE MONITORING PROPERTIES AT THE X, Y, AND Z AXIS

Signals	Loose parts	Leakage	Size	Leakage localization
X-axis	yes	yes	no	no
Y-axis	no	yes	yes	yes
Z-axis	no	yes	yes	yes

3.1 Angular Direction Localization

In this study, the angular direction of a leakage in the cross-section [10] of that pipeline was also identified by analyzing the deviation of x-, y-, and z-axis data.

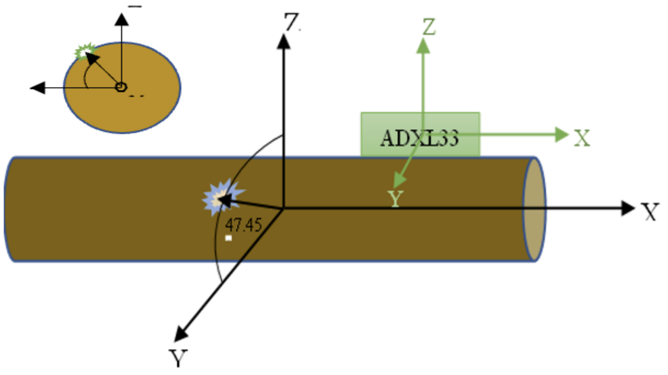


Fig. 5: Leakage angular location identification

Fig. 5 represents the sensor setup location with the three-dimensional position according to the sensor and possible leakage angular direction identification which can be identified by the deviation data analysis. Fig. 6 represented the deviation data

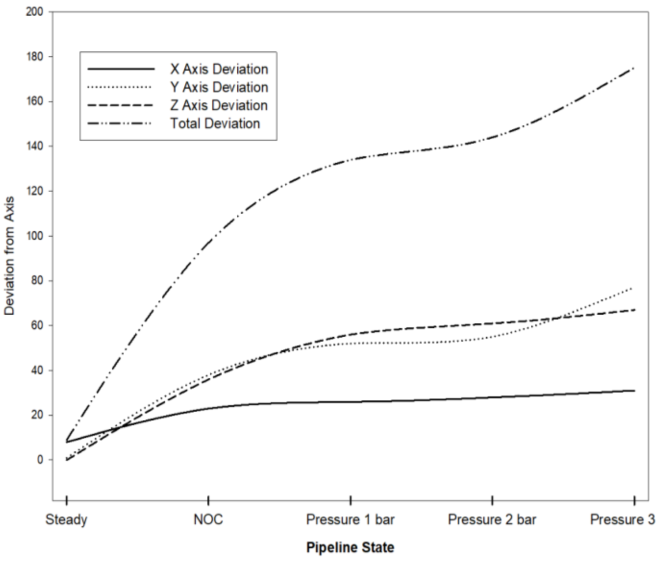


Fig. 6: x-, y-, and z-axis deviation data in a different state.

To measure the leakage angular direction a guideline was also developed to get the analytical data. Each axis sensor data has a maximum and minimum amplitude of vibration data. There has a median value between max and min amplitude vibration data. Hence, it is possible to calculate the positive and negative deviation from that median value then it can identify the strength direction of that vibration data. The purpose of this median value calculation is if leakage occurred on the upper side, then the vibration force of direction will be outward and another opposition will be applied to the back but the sum of the applied force was outward.

Median value = (Steady Max. Value- Steady Min. Value)/2

Negative Deviation = ∣Median Value – Sensor Min. Value∣
Positive Deviation = ∣Median Value – Sensor Max. Value∣
Leakage Sensitivity = ∣∑Negative Deviation - ∑Positive Deviation∣

If leakage occurred on the top of a pipeline the water will go out at the 90-degree angle with force F_1 and another opposition force was applied in the opposite direction F_2 which is lower than F_1. In this way, vibration has occurred due to leakage. And that's why the maximum and minimum value of the vibration amplitude was collected to get the total force F_T

$F_1 = X. F_2$ where, $X<1$

$F_T = F_1 + F_2$

If leakage occurred between the left and right side or somewhere in any direction of a pipeline, then 3-dimensional data need to analyze from the sensor. After analyzing all collected data from the sensor, a detailed deviation calculation was enforced to get the projections on different axes.

Hence, to calculate leakage force (L_{Fx}) for the positive and negative deviation from the median value the leakage applied was identified for the leakage direction. Table 5 represents the calculation of the leakage applied force. These data deviation, ΔF results about the x, y, and z are based on the basic mean deviation rules. In this case, the Y and Z axis showed the influence of the leakage force and the y- & z-axis both are positive. So, it is to be stated that leakage occurs between the +y & +z axis which means this model extrapolates the leakage position perfectly.

TABLE 6

FORCE DEVIATION IN X, Y, AND Z AXIS-AXIS

	About X-axis (L_{Fx} = -6)		**About Y-axis** (L_{Fx} = +46)		**About Z-axis** (L_{Fx} = +38)	
Conditions	ΔF_x+	ΔF_x-	ΔF_y+	ΔF_y-	ΔF_z+	ΔF_z-
P	4	4	-0.5	+0.5	-0	+0
Q	11	12	-7.5	+30.5	-15	+21
R	15	11	-19.5	+32.5	-28	+28
S	15	13	-26.5	+28.5	-31	+30
T	16	15	-34.5	+42.5	-34	+67
Force	-61	+55	-88.5	+134.5	-108	+146

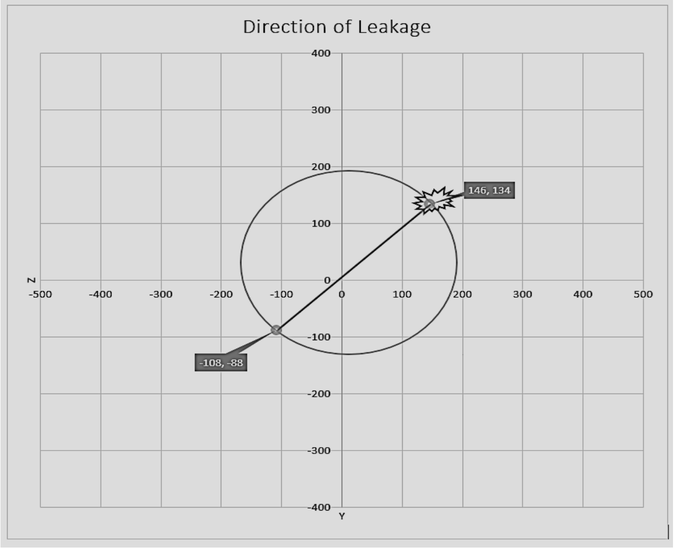


Fig. 7. Direction of Leakage

The least-squares and deviation extrapolated the leakage degree and operation condition. Hence, it defines that the leakage occurs between positive Y & Z axis in cross-section angular direction by 47.45° angle which also matched with the predefined leakage position direction with only 0.027% of error thus confirming the validity of the model.

$$\text{Angular direction, } \theta = \tan^{-1}\left(\frac{\text{Max applied force in Z−axis}}{\text{Max applied force in Y−axis}}\right)$$

$$\theta = \tan^{-1}(146/134) = 47.45^{\circ}$$

Furthermore, the reliability interpretation R-squared values of the considering residuals and the analytical results were found as 0.96, which is recommended as in the excellent range [12]. However, this ADXL335 Piezoelectric system deviation results also showed an average of 1.13% error compared with the predeveloped LBB and ILDS DiagAssist SW [3] systems.

4 CONCLUSION

The experimental analysis showed the possibility to detect different stages of leakage such as cracks inside the material of the pipeline, microleakage to identify leakage, and displacement of the pipeline, etc. This study proposed a cost-effective, precise sensor-integrated software-based approach to measure the zone and angular location of leakage of a pipeline based on the humidity and acoustic method. Considering uncertainties in the hydraulic transient propagation, data noise, and multiple local optima issues in large parameter calibration schemes were also considered to identify detectability in the practical field of NPPs and other powerplants at any loading condition. Moreover, the experiments were run for a single pipeline as well as for a gathering/distribution network. However, the sensor traceability showed errors in pipelines of more than 2.8 meters. Hence, a repetitive sensor attachment needs to be attached to the pipeline every 2.5 meters considering tolerances. The research outcomes also stimulated the researcher to consider all regulatory requirements, inherent systems, etc to use this system as a critical part of emergency response in the primary circuit. However, a complete CFD analysis and risk assessment are necessary before full-scale application.

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