

A superior way of temperature monitoring using fibre optics

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Abstract: Temperature measurement using fibre optic techniques is preferred now a days due to its few distinguished features such as it is not sensitive to electric current, electromagnetic radiations such as microwaves and not prone to radio frequency interference (RFI). This technology also caters to multipoint and distributed temperature measurement as can be seen from multi-channel operation. It can be used in the places and conditions where constant on site monitoring by humans is a tedious and dangerous task. Hence it offers a robust and an alternative way to conventional temperature measurement techniques.

Keywords: Temperature measurement, fibre optic techniques, electromagnetic radiations

1. Introduction

In older days, for temperature measurement people use to adopt tools and instruments which were either handheld device like mercury thermometers, IR thermometers. Few like mercury thermometers were more fragile, could cause environmental loss on spilling. Real time data transfer was not possible in many cases. Few industrial applications using RTD (Resistance temperature detectors) were plagued as it provided single point measurements only.

The instruments such as RTD's and thermocouples used to give many errors while performing the temperature measurement due the electromagnetic interference [1] due to the presence of other magnetic instruments, machinery other civil and electrical structures in the vicinity such as electric poles and transformers specially in electrical machines such as internal winding temperature of transformers, switch-gear hotspot monitoring, energy industry, industrial microwave industry and medical industry [1]. So, the need was felt to look out for options which could eliminate or minimize these above listed problems and provided the research gap to many scientists and scholars. Fibre optic temperature measurement research and experimentation provided few answers in this direction.

Objective of this paper is to compare the few fibre optic temperature measurement techniques with the traditional methods [2] and establish the superiority of fibre optic temperature measurement in few parameters by experimentation. By experimentation it can be proved that on one-way RTD was measuring temperature at one point only and by using fibre optic temperature measurement, several results can be obtained from multi channels with slight variations as discussed later in this study.

2. Working

To see how these fibre optic temperature measurement instruments work, this study is narrowed down on the following techniques in fibre optic temperature measurement:

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- Fluorescence based
- Fiber Bragg grating
- Raman distributed thermometry

Fluorescence is the ability of certain chemicals to give off visible light after absorbing radiation which is not normally visible, such as ultraviolet light. This property has led to a variety of uses. It is due to the fact that electrons absorb energy and reach to higher energy states and release energy in the form of light and heat to again reach to the stable state. This type of technology use sensor tip contact to the target whose temperature is to be measured; although it is calibrated and converted using different physics principle to finally measure and display the reading. Multiple channels can be used for temperature measurement at different points.

In Fiber grating technique; a microscopic grating pattern is observed in the core of an optical fibre on the application of high intensity light. Optical fibre is connected to hot body whose temperature is to be measured. This portion reflects only the specific wavelength of light (which is known as Bragg's wavelength) but passes other wavelength light through it; hence acting as an optical filter [3].

The relationship between the temperature change ΔT and the shift in the Bragg wavelength [3] $\Delta\lambda_B$ is expressed as:

$$\Delta\lambda_B = \lambda_B (\alpha_\Lambda + \xi) \Delta T \quad (1)$$

where, λ_B is the initial Bragg wavelength, α_Λ is the thermal expansion coefficient of the fibre material, and ξ is the thermo-optic coefficient of the fibre. Here, a single fibre can have multiple sensing points (say up to 20) and the system consists of multiple fibres. Here, as well multiple channels are used.

In case of Raman distributed thermometry technology, whole cable acts as a sensor. Cable can be laid for several kilometres [4]. The fundamental equation governing the temperature measurement using Raman Distribution thermometry technique is based on the Boltzmann distribution. Its temperature sensing is related to the ratio of anti-Stokes to Stokes backscattered light intensities [5-7]. It is stated as Raman spectroscopy intensity ratio equation [8, 9]:

$$R(T) = \frac{I_{as}}{I_s} = \left[\frac{\nu_{as}}{\nu_s}\right]^4 \exp\left[-\frac{h\Delta\nu}{KT}\right] \quad (2)$$

Where, $R(T)$ = The intensity ratio of the anti-stokes to stoke signals. I_{as} and I_s are the measured intensities (or powers) of anti-stokes and stokes bands respectively. ν_{as} and ν_s are the optical frequencies of anti-stokes and stokes scattered light respectively. h is Plank's constant (6.626×10^{-34} Js), $\Delta\nu$ is the Raman frequency shift of the molecular vibrations in the optical fibre, K is Boltzmann's constant (1.38×10^{-23} J/K), and T is the absolute temperature in Kelvin (K). By rearranging the equation, temperature (T) can be determined at any given point along the optical fibre using [10]:

$$T = \frac{h\Delta\nu}{k[\ln\left(\frac{I_s}{I_{as}}\right) + 4\ln\left(\frac{\nu_{as}}{\nu_s}\right)]} \quad (3)$$

Using Raman OTDR (Raman Optical Time Domain Reflectometry) technology testing and Distributed Temperature Sensing (DTS) can be done for optical fibres [7, 8, 11].

3. Methodology

Fig. 1 shows how the fluorescence based optical fibre-based instrument works experimentally to measure the temperature. It is based on single point contact principle in which the probe

containing the optical fibre; and at the end or tip is fluorescent material (acting as a sensor) which is in contact with the body or hot spot whose temperature is to be measured.

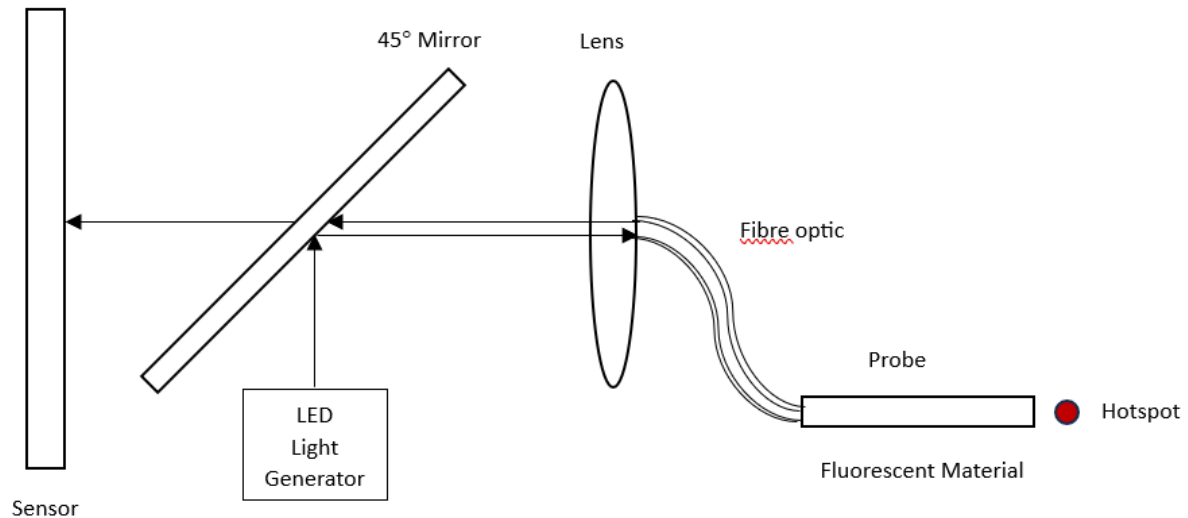


Fig. 1: Connection diagram of hotspot temperature measurement

At the time of temperature measurement, a LED light is generated at a particular intensity, which is deflected and passed through a beam splitter at a particular angle so that it is received by the fluorescent sensor through the optical fibre. With the contact of hot spot, fluorescent molecule is promoted to higher energy state and follows the reverse path losing the fraction of its gained energy. Light now is received by an electronic signal processing unit with decreasing intensity. Detail connection diagram (Figs. 2 and 3) is drawn below. The large range of probe sizes available which makes them accessible in depth of hotspots to be monitored.

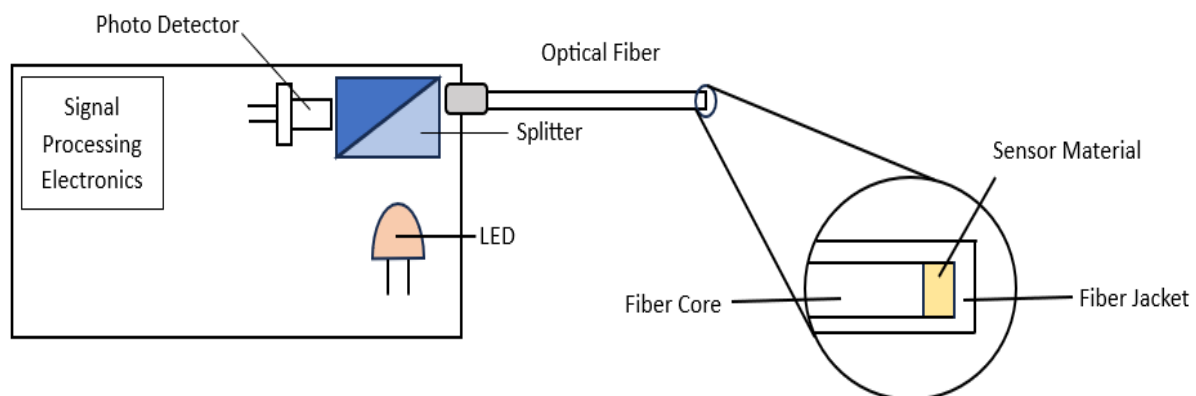


Fig. 2: Block diagram of signal processing unit parts and its role

This decrease in intensity of the light and the time taken to receive back is responsible to determine the temperature of the hotspot. Every fluorescent material follows a particular behaviour which can be understood from its intensity (amplitude in volts) versus time taken (in milliseconds) graph. It is observed that as the temperature to be measured is more; the decay rate will be faster (Fig. 4). Decrease in intensity is due to the fact that the electrons of fluorescent material return to the ground or stable state by emitting the light. In between the optical fibre and sensor an optical lens is also fitted.

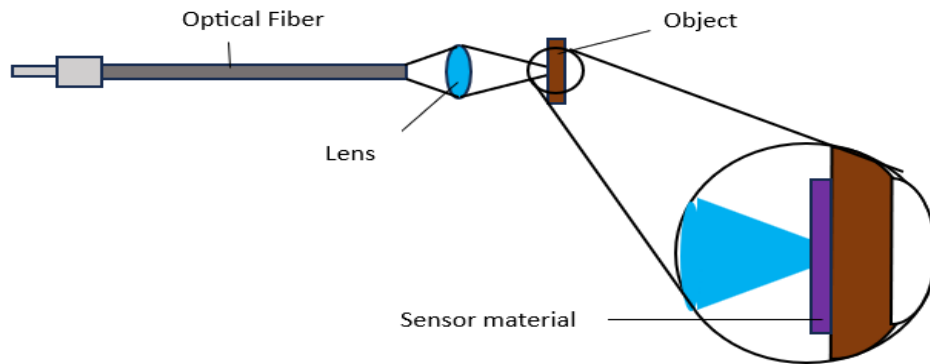


Fig. 3: Diagram describing the flow of optic signals

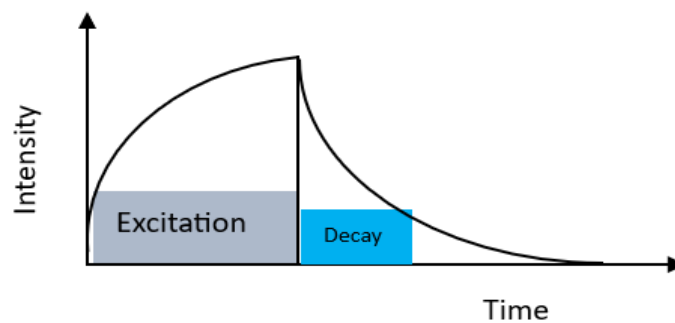


Fig. 4: Waveform depicting intensity Vs time of single light source

Comparison of many light sources (with different time-periods) in intensity Vs time graph (Fig. 5) is shown below. This graph shows the capability of different light sources to measure a large range of temperatures.

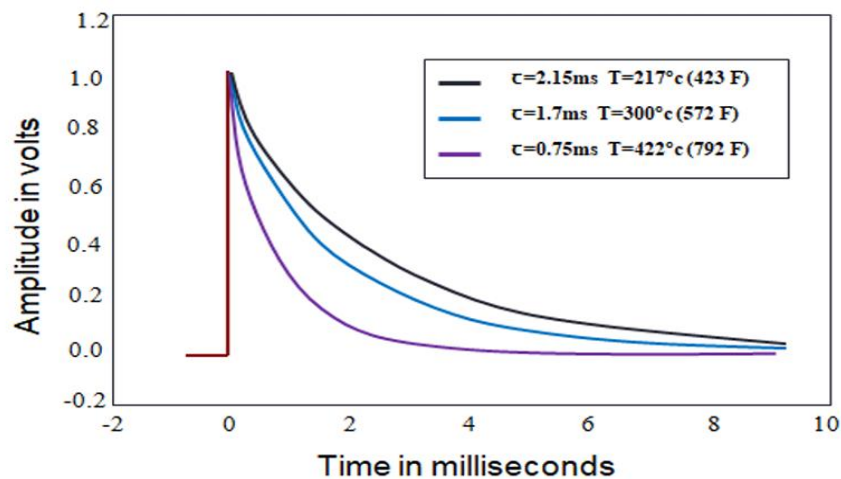


Fig. 5: Comparison of many light sources in intensity Vs time graph

Now, finally this receiving light intensity signal from the known fluorescent material is calibrated from Analog to Digital converter and the reading are observed in the form of LCD or seven segment displays on the top of the instrument. Instrument may contain many channels whose reading may differ slightly from one other. In actual applications, such as to measure the internal winding temperature of the transformer; the set-up is pre-fitted on the transformer tank. As and when the measurement is required; the light is triggered and the measurement can be read.

Fluorescence lifetime sensing measures the specific time a molecule spends in an excited state before returning to its ground state. Because this decay rate depends on the local environment rather than probe concentration, it enables highly precise, quantitative sensing of oxygen, pH, ions, and temperature [12].

Since the fluorescence decay-based temperature measurement (where especially ruby or rare-earth doped crystals are used) is dependent entirely on temperature, this method is considered as highly accurate. Its decay equation [13] can be defined as:

$$I(t) = I_0 \exp\left(-\frac{t}{\tau}\right) \quad (4)$$

Where, $I(t)$ is fluorescence intensity at time t , I_0 is fluorescence intensity at time $t = 0$ (just after excitation), and τ is fluorescence lifetime (or decay time). In multi-component systems where, different physical transitions exist simultaneously; the decay follows a multi-exponential format [14]:

$$I(t) = \sum_{i=1}^n A_i \exp\left(-\frac{t}{\tau_i}\right) \quad (5)$$

The Fluorescence Intensity Ratio (FIR) technique measures the relative intensities of two distinct fluorescence emission peaks. By taking the ratio of these emissions, researchers can quantify parameters like temperature, pH, or analyte concentration independently of machine variations or dye degradation [15, 16].

3.1 Industrial measurement system

Temperature measurement using fluorescence optical fibre instruments can be performed using two different approaches. In the first approach, a fluorescence optical fibre probe is inserted directly into or placed in contact with the hot or cold object whose temperature is to be measured. In the second approach, a permanent sensing system is installed in close proximity to the object, such as for continuous monitoring of the internal winding temperature of a power transformer. In both cases, the other end of the optical fibre probe is connected to a signal processing unit. This unit analyses the fluorescence signal received from the sensor and converts it into an accurate and easily readable temperature value for display and monitoring.

3.2 Calibration procedure

These instruments are calibrated once in the factory and do not require periodic recalibration [17]. Experiment was performed on the instrument from the company “TEMPSENS” and the instrument name was “FluoroSenz”. During calibration temperature is fixed in a master setup system and (8 channel or 12 channel) multi-channel temperature readings is recorded to see how the instruments is working. If the instruments channels are displaying the results within the permissible range, it is considered good and ready to use. One such set of readings are given in Table 1.

Table 1: Readings measured from Industry for 8-channel instrument based on Fluorescence optical fibre

Set Temp (°C)	CH-1	CH-2	CH-3	CH-4	CH-5	CH-6	CH-7	CH-8
90	90.5	90.5	90.8	90.3	90.5	90.4	90.2	90.4

4. Results and Discussion

Results of temperature measurements showed that it was unaffected by the presence of magnetic bodies present in the vicinity and also not affected by radio or electromagnetic waves.

The multi-channel response of the Fluorescence based optical fibre instrument is listed above which showed the excellent results, which was very close to set temperature. It also reflected the accurate results obtained from the experimentation. Few of the readings were also repeated, as listed in the Table 1.

Table 2: Comparison of Fluorescence based optical fibre temperature measurement over traditional ones [18, 19].

S. No.	Feature of comparison	Mercury thermometer	IR thermometer	Fluorescence optical fibre
1	Safety and Ecofriendly	Since it is highly toxic & volatile even at room temperature. Environmental hazards if it spills.	At the end of their life span when disposed; it causes ecological damage due to the presence of batteries, PCB, and plastics	Although it does not carry electricity itself but can be damaged by external sparks or explosions.
2	Fragility	More fragile	Less fragile	Medium fragile
3	Physical handling	Yes	Yes	No
4	Remote sensing	No	Yes, but it requires pairing the device with microcontrollers and transmitters	Yes, real time data can be transferred.
5	Immunity	Yes, immune to EM waves.	Not completely EM wave immune; can be affected by dust, smoke and reflections.	Yes, immune to EM and radio waves.
6	Temperature range and data storage	-39 °C to 350 °C. No record stored.	-50 °C to 2200 °C depending upon the internal sensor used and calibration. Data storage feature generally absent.	-200 °C to 450 °C depending upon the material used. Can store and send data.
7	Extension of temperature range	No	No	Yes
8	Application and range of placement	Limited, can't be place anywhere. Spot measurements only.	Limited, reliable only for spot measurements.	Can be placed into tight, hazardous spaces as well.
9	Accuracy	Shake back error and accuracy can drop to about ± 1.5 °C for temperatures above 100 °C.	Depending upon the surface emissivity of the object, accuracy can lie between ± 1 °C to ± 2 °C.	± 0.5 °C to ± 1 °C.
10	Measurement type	Contact type surface temperature	Non-contact type surface temperature	Contact type internal or surface temperature

Table 3: Comparison of FBG-based optical fibre temperature measuring techniques over traditional ones [20-23].

S. No.	Feature of comparison	Mercury thermometer	IR thermometer	FBG-based optical fibre
1	Safety and Ecofriendly	Since it is highly toxic and volatile even at room temperature. Environmental hazards if it spills.	At the end of their life span when disposed; it causes ecological damage due to the presence of batteries, PCB, and plastics	It's set up is considered ecofriendly as it contains silica, glass and does not contain toxic heavy metals or chemicals which are leaked to the environment.
2	Fragility	More fragile	Less fragile	Medium fragile
3	Response time	Slow	Medium	Fast (approximately 2 to 10 times the IR thermometer)
4	Remote sensing	No	Yes, but it requires pairing the device with microcontrollers and transmitters	Yes, real time data can be transferred.
5	Immunity	Yes, immune to EM waves.	Not completely EM wave immune; can be affected by dust, smoke and reflections.	Yes, immune to EM and radio waves.
6	Temperature range	-39 °C to 350 °C	-50 °C to 2200 °C depending upon the internal sensor used and calibration.	-270 °C to 1100 °C depending upon the material used.
7	Operation ability	Dependent upon the melting point of mercury	Affected by the emissivity of the surface	No such problem and can measure both temperature and strain
8	Application and range of placement	Limited, can't be place anywhere. Spot measurements only.	Limited, reliable only for spot measurements.	Multi-point sensors on single fibre line, more reliable.
9	Accuracy	Shake back error and accuracy can drop to about ± 1.5 °C for temperatures above 100 °C.	Depending upon the surface emissivity of the object, accuracy can lie between ± 1 °C to ± 2 °C.	± 0.1 °C to ± 0.01 °C.
10	Measurement type	Contact type surface temperature	Non-contact type surface temperature	Contact type internal or surface temperature

Table 4: Comparison of Raman Distributed Thermometry based temperature measurement over traditional ones [24-28].

S. No.	Feature of comparison	Mercury thermometer	IR thermometer	Raman Distributed Thermometry
1	Fragility	More fragile	Less fragile	Medium fragile
2	Measurement range	No	Maximum 50 inches	Yes, measurement range can last up to 30km to 70 km for multimode and single mode fibres.
3	Immunity	Yes, immune to EM waves.	Not completely EM wave immune; can be affected by dust, smoke and reflections.	Yes, immune to EM and radio waves.
4	Temperature measuring range	-39 °C to 350 °C	-50 °C to 2200 °C depending upon the internal sensor used and calibration.	-40 °C to 300 °C
5	Measurement point	Applicable for spot measurements only.	Applicable for spot measurements only.	It provides continuous temperature readings along the fibre optic cable and the measuring points can be up to thousands in one metre.
6	Accuracy and range	Shake back error and accuracy can drop to about ± 1.5 °C for temperatures above 100 °C.	Depending upon the surface emissivity of the object, accuracy can lie between ± 1 °C to ± 2 °C.	± 0.1 °C to ± 1 °C. Although accuracy depends upon distance, averaging time and calibration.
7	Applications	Generally limited to homes and labs.	Hazardous zones and clinics.	Tracking leakages in oil pipelines and monitoring fire risks in HV cables.

The comparison of various fibre optic techniques for temperature measurement such as fluorescence based optical fibre (Table 2), FBG-based optical fibre (Table 3) and Raman Distributed Thermometry (Table 4) over traditional ones for different parameters is shown above.

There are other optical fibre temperature measuring instruments as well such as Fabry interferometers which works on the principle of shifting of optical interference patterns (due to change in refractive index) and can measure the temperature up to 1200 °C.

The process defining the temperature measurement using Brillouin scattering [29] involves passing of high intensity light through a medium which can be optical fibre, liquid or gas. This light interacts with the material's inherent acoustic waves. Now, since acoustic velocity is highly dependent upon temperature; resulting in the scattering effect. The frequency shift

changes linearly with temperature (shifting may be around 1 - 1.3 MHz/ °C if carried out on standard optical fibres).

Typically, this technique can help in temperature measurement ranging from -160 °C to 1000 °C.

Temperature measurement using Rayleigh scattering is applicable for fluids specially the gases. The gas molecules constantly move at random fashion due to the energy gained from the heat and changing temperature. Whenever the high intensity light falls on these molecules, thermal motion shifts and broadens the wavelength of the light scattering and affects the overall intensity of the scattered light. There are two methods which uses Rayleigh scattering for temperature measurement (a) Rayleigh thermometry and (b) Doppler broadening [30, 31]. Typically, this technique can help in temperature measurement ranging from -73 °C to 1250 °C.

5. Industrial applications

Different fibre optic sensor-based instruments and techniques have wide range of temperature measurement from cryogenic level to thousands of temperatures. Similarly, the temperature measurement of solid, liquid and gas are possible.

Few of industrial applications for fluorescence-based optical fibre measurement can be mapping localized temperature variations in tiny fluid volumes, measuring sub-cellular thermal fluctuations in living tissues and tracking protein stability through intrinsic or extrinsic dye markers, monitoring the true temperature of polymers and resins in real-time during extrusion, providing safe, accurate readings inside nuclear reactors, HV substations, and industrial microwave system, monitoring hot spots in aircraft combustion chambers, turbines, and high-temperature boilers where extreme temperatures and electromagnetic interference rule out standard sensor [32].

Similarly, FBG-based optical fibre specializes the monitoring power transformer windings, HV substations, and cable temperatures. They are used in wind turbine blades and solar panels for thermal management, as well as in cryogenic environments for superconducting magnets. It is helpful in deploying distributed temperature sensors (DTS) along pipelines, in geothermal wells, and in storage tanks. Because optical fibres carry no electrical current, they provide intrinsically safe, explosion-proof monitoring. Other aerospace and defence applications, nuclear and medical applications [32].

Raman Distributed Thermometry monitors HV power cables (underground or subsea) [33], electrical transformers, and reactors to detect overheating or "hot spots" before failures occur, it provides rapid, highly localized early-stage fire detection in subways, transportation tunnels [34], and expansive buildings (like conveyor belts and warehouses) where traditional smoke detectors are ineffective, monitors temperature along pipelines to track fluid flow, identify pipeline leaks, and detect "thermal anomalies" deep underground [32]. Rayleigh scattering is applicable for fluids temperature measurements specially the gases [30, 31].

6. Advantages and Limitations

Although the fibre optic-based techniques have many advantages such as wide range of temperature measurement, immunity to electromagnetic interference, temperature monitoring in dangerous and explosive environments, real time data measurement and transfer, continuous

and long-distance monitoring, no problem of frequent calibration [17] and applications (as listed above), it still suffers from few limitations.

The awareness and range of these instruments as of now is less. It requires pre-installation, display monitoring and data storage device or it has complex system integration. Hence it can't be used in house hold application such as measuring flame temperature. Hence it is getting stiff competition from present devices based on IR technology. Special coatings are required for high temperature measurements.

Also, the instruments using these techniques are not easily available at market or online, because of no bulk production, broadly it is made on demand or customised according to the need. Hence, it is costly as well. Mercury and IR thermometers are hand held devices and does not require any installation whereas installation of fibre optic instruments require special care as it is fragile and minimum bend radius is to be taken care of to prevent any light signal leakage.

7. Conclusion and future work

This fibre optic techniques are used to fulfil the requirement of measuring different physical parameters including temperature, strain, pressure, and vibration, based on the technique being used. Based on experiments and data measurements it can be concluded that these are reliable and accurate instruments which can sense and monitor the temperature in multiple points, as illustrated 8 channel operations of the instrument and over long distances.

Future research can be carried out in the direction to make optical fibre measuring instruments more rugged, so that the effect of signal loss in bending can be minimized. The working range should be increased with research in the direction that coatings can sustain extreme temperatures in both the directions. The product should use such material which makes it economical.

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