A fibre optic sensor for the detection of hydrocarbon fuel spills

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Abstract

We present a fibre-optic sensor for the detection and location of hydrocarbon fuel spills to a precision of ± 2 m over a total length that may realistically extend to 10 km. The sensor is non-electrical, requires only a low-power laser source and is therefore intrinsically safe. It has been designed such that liquid-swellable polymers transduce their swelling into a force on an optical fibre when activated. Interrogation of the sensor using standard Optical Time Domain Reflectometry (OTDR) techniques provides the possibility of detecting and locating target hydrocarbon fuels and chemicals at multiple positions along the sensor length. Sensor response time after exposure to the hydrocarbon fuel is typically 30 seconds. A detailed explanation of the operational characteristics of the sensor and the underlying technology utilised in its operation is given. The swelling characteristics of the polymer material in a range of hydrocarbon fuels and experimental test results using prototype sensors to detect 50 centimetre-long events at two separate locations are presented. The ability to replace the polymer with materials sensitive to other liquids provides the possibility of sensing many other parameters using the same generic design. Some of the safety advantages in using the sensor and its practical implementation in continuous monitoring of pipelines or fuel containment vessels are discussed.

1 Introduction

Growing public concern over the environmental damage of oil spills or other hazardous liquids has resulted in increasing government regulation in many countries worldwide. Legislation has been drawn up to enhance safety and
environmental protection in sensitive areas where hydrocarbon leakage due to pipeline or containment failure could have serious consequences for both the public and the environment. A simple sensing system capable of rapidly detecting spills would greatly reduce the risk and the damage caused by such events. Fibre optic sensors designed for these applications have recently been manufactured. The sensors are passive and do not require an electrical supply at the sensing location. These features offer advantages over electrical solutions to remote monitoring where there is a risk of explosion. Replacement of the fuel-sensitive polymer with alternative materials offers the possibility of measuring other parameters such as water, pH or ionic concentration.

2 Sensor operational characteristics

The hydrocarbon sensor consists of a 0.9 mm diameter Glass Reinforced Plastic (GRP) strength member that has a 100 μm thick coating of hydrocarbon sensitive polymer. A 62.5/125 graded index multimode optical fibre with an outer diameter of 250 μm is held against the GRP core by applying a helical Kevlar wrap along the entire sensor length as displayed in Figure 1. The polymer coating used in the sensor will swell when exposed to a range of hydrocarbon fuels and solvents, the extent being dependent on the activating fuel and the design of the polymer used. Swelling of the polymer causes the fibre to be squeezed against the Kevlar thread, thus inducing a periodic lateral deformation in the fibre at the exposed location.

Light passing through the optical fibre at the activated location will suffer what is known as microbend loss caused by light being coupled out of the fibre. The period of the deformation has a critical effect on the degree of attenuation that occurs. It was found by Fields \(^1\) that maximum loss will occur in a parabolic index multimode fibre for the specific periodic spacing \(\Lambda\), given by Equation 1,

\[
\Lambda = \frac{2\pi a}{\sqrt{2}\Delta}
\]

where \(a\) is the core radius and \(\Delta\) is the maximum relative difference between the refractive indices of the core and the cladding of the optical fibre. Both Fields \(^1\)

![Figure 1: Section of hydrocarbon sensor.](image-url)
and Deimeer determined that a multiple of the fundamental spacing could also be used to induce high loss. For the multimode fibre used in this particular sensor, the period $\Lambda$ is equivalent to a value of $\sim 1$ mm. The Kevlar wrap may also therefore be applied at $\sim 2$ mm, thus reducing the sensitivity of the sensor to small variations in the pitch that occur in the manufacturing process.

The operating principle of the OTDR instrument that is used to interrogate the sensor is now well understood. It is one of the most commonly used analysis instruments in the telecommunications industry. An OTDR sends very short pulses of light into the optical fibre and monitors the small amount of Rayleigh back-scattered light that is returned as a function of distance. When a section of the fibre experiences bending, the increase in local attenuation causes a reduction in intensity of the back-scattered light for that particular location. The reduction in intensity is displayed on the OTDR trace as a drop in the level of signal received and an increase in the gradient of the trace. Conventional signal processing techniques can then be used to locate many separate events using a pre-recorded unaffected trace as a reference. A schematic layout of the components in an OTDR detection instrument is shown in Figure 2.

Using OTDR techniques, the exact location of microbend events caused by exposure to hydrocarbon fuels as described above can be determined at any position. The sensor can therefore be termed as being fully distributed. A diagram of the expected OTDR trace of a sensor activated at two locations is shown in Figure 3. When the polymer dries out, the force experienced by the fibre returns to its original value and the trace returns to its dry state. Measurements can therefore be taken over several wetting and drying cycles.

The maximum length that can be effectively detected is limited by the dry loss value of the sensor and the dynamic range (related to the total available pulse power) of the OTDR instrumentation. Using the current design parameters, multiple events on sensors with lengths up to 2 km can be easily
interrogated. Altering several parameters in the current sensor design may theoretically extend this range to 10 km.

![OTDR display](image)

**Figure 3: OTDR detection method showing sensor trace**

### 3 Material evaluation

An estimate of the swelling experienced by 200 μm thick polymer film samples for a range of hydrocarbon fuels was conducted by placing them directly into the fuels and weighing them at regular intervals over a one hour period. The highly volatile fluids such as condensate and petrol caused a rapid increase in the volume of the polymer as shown in Figure 4. A 200% increase in the weight of the samples occurred within the first minutes of wetting for the volatile fuels. The less volatile liquids such as diesel, gas oil and dodecylbenzene cause swelling to a lesser degree and the polymer takes slightly longer to reach maximum swell. Time taken to maximum swelling is proportional to the square of the thickness of the material. In the current sensor, with coatings 100 μm thick, typical reaction time is 30 seconds.

To estimate the response of the polymer coating on the GRP rod; a section of the central GRP rod was removed from the sensor and placed into a Laser Micrometer. The diameter of the coated rod was then observed after it was exposed to a range of hydrocarbon fuels. These results demonstrate the rapid swelling that occurs, where maximum swelling is typically achieved within 100 seconds of exposure to the fuel. The more volatile fuels induce the largest increase in the diameter of the core, confirming the observations found for the film samples placed directly into the fuels. Results for these tests are given in Figure 5, displaying the increase in diameter of a 100 micron thick coated rod exposed to a range of hydrocarbon fuels. It is apparent from the results that detection of less volatile fuels would be possible by simply increasing the thickness of the coating. Further evaluation of the materials is being conducted to determine ideal design parameters to sense a particular hydrocarbon fuel.
Figure 4: Swelling response of hydrocarbon sensitive polymer.

Figure 5: Increase in diameter of 100 μm thick coated GRP rod.

4 Prototype sensor evaluation

A series of laboratory tests were conducted to determine the event resolution of two prototype sensors approximately 100 metres long. A Nortech laptop-driven OTDR instrument was used for both of the experiments. Both sensors were spliced onto a 30-metre length of normal optical fibre. Before sensor evaluation commenced, a dry reference trace was taken for comparative purposes. In the
first test, a 1 metre long section located 30 metres along the sensor was exposed to unleaded petrol. After 1 minute of exposure, the dry and wet OTDR traces were compared. The resulting averaged trace shown in Figure 6 clearly indicates an event located at 60 m along the sensor length. The drop in signal measured at this point of the fibre was 0.5 dB, equivalent to a loss of ~500 dB/km. To determine if shorter events could be located, the test was repeated by exposing two 50-centimetre sections of an identical sensor to petrol. The wetted sections located at 53 and 81 metres on the OTDR trace can be clearly seen in Figure 7 and display the sensor ability to make multiple measurements. Both sensors responded visibly on the OTDR trace within 30 seconds and returned to the dry trace reading after the petrol had evaporated.

![Figure 6: Trace showing 1 metre exposed to petrol](image)

![Figure 7: Trace showing two 0.5 metre sections exposed to petrol.](image)
5 Conclusions and discussion

We have demonstrated a distributed microbend sensor that has the potential to monitor hydrocarbons over its entire length. Evaluation of the polymer coating on the sensor indicates that volatile hydrocarbon liquids such as condensate and petrol cause maximum polymer swelling and activate the sensor within 30 seconds. Two separate 0.5m sections of sensor exposed to petrol were detected and located using an off-the-shelf OTDR unit. On evaporation of the petrol, the sensor returned to its unexposed dry condition. Many simultaneous events can be located on a sensor length that currently may extend to 2km. Further development is being conducted to investigate the possibility of increasing the range to 10km.

As stated in the introduction, the hydrocarbon sensitive polymer can readily be replaced with alternative materials that swell due to the presence of or change in other chemical species. The detection of water and changes in pH using materials developed by the Department of Chemistry at Strathclyde University has been previously reported using the same sensor design.

There are many potential applications for a distributed liquid measurement capability, such as early fuel spill detection in refineries and chemical plants. Other potential applications that have been identified include the continuous monitoring of pipelines and detection of leaks of coolant oil in high-voltage power cables. Due to its passive and non-electrical properties, the sensor is particularly suitable for environments where there is a risk of explosion. The distributed nature of the sensor also offers significant cost-effectiveness if extensive plant area requires monitoring. Previously demonstrated water sensors have potential applications in monitoring water spills in sensitive areas or ensuring the early detection of leakage from landfill sites. Fully automated sensors with the ability to detect and locate the presence of specific parameters along the entire length could have many uses in the oil and chemical industries.

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References