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EXPERIMENTAL AND NUMERICAL EVALUATION OF A NEAR INFRARED FIRE DETECTOR

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Abstract: Near infrared fire detectors work on the principle of detecting fires based on a statistical analysis of the apparent source temperatures of fires. The apparent source temperatures are estimated from the radiation intensity incident on the fire detector at two near infrared wavelengths. However in some instances, the fires are not in the direct view of the detector, and most of the radiation which are incident on the detector reaches it after multiple reflections from the walls of the building. An experimental and numerical study of the effects of these reflections on the temperatures inferred by a near infrared fire detector are presented. The experimental evaluation was conducted using three open and two smoldering fires. The results shows that the near infrared fire detector is capable of discriminating open fires from reflected radiation. However, for smoldering fires, the intensities obtained from reflected radiation are too low to be successfully discriminated from background noise. Numerical evaluation of the performance of the near infrared fire detector in cylindrical and rectangular enclosures were conducted utilizing a photon tracing algorithm in conjunction with the discrete probability function method. The numerical evaluation confirms that the detector can successfully detect fires from reflected radiation if its sensitivity is sufficiently high.

INTRODUCTION

New fire detection concepts and algorithms are justified only if they improve upon existing ones with lower false alarm rates and greater sensitivity to starting fires. In addition, the detectors and signal processing instruments should be easy to operate and maintain, have high flexibility and be relatively inexpensive.[1] Currently residential fire detectors include optical smoke sensors, ionization smoke sensors and temperature sensors.[2]

Conventional smoke sensors utilize light scattering or smoke ionization measurements to detect a fire, while temperature sensors utilize thermocouple measurements. The are three disadvantages with conventional single sensor detectors: (1) there is a significant time delay between the start of the fire and the transport of the combustion products to the location where the detector is mounted; (2) in instances when there are impermeable barriers (such as smoldering inside walls), the fire is not easily detected even in advanced stages, and; (3) single sensor detectors involve a high rate of false alarms due to changes in the operating environment. Combinations of smoke sensors and odor sensors which involve multiple fire signatures are less prone to false alarms.[3] However, multiple sensors involve greater construction cost and increased complexity of signal processing hardware and software.

More recently, there has been increased interest in the use of radiation emission sensors (flame detectors) as an alternative to smoke and heat sensors.[4] The three major advantages of emission sensors are: (1) their ability to survey the entire room for fire initiation, (2) their fast response time, and (3) false signals can be readily distinguished since most fires are unsteady with an unique frequency content, leading to unambiguous discrimination based on the power spectral density of the measured intensities.[2]

Single channel flame detectors operate either in the ultraviolet (where solar radiation is totally absorbed by the earth's atmosphere) or in the infrared (where flame emission is primarily from hot CO_2) parts of the spectrum. Ultraviolet signals from flames are normally very low leading to false alarms from indoor radiation sources such as incandescent lights, arc welding processes, etc. Therefore, ultraviolet sensors are limited to outdoor usage where interfering solar radiation is absorbed by the earth's atmosphere. Another disadvantage of ultraviolet flame detectors is that any contamination of the optical windows causes a significant loss in the sensitivity of these detectors.

Infrared flame detectors are used for large indoor areas such as aircraft hangars and warehouses where direct solar radiation is minimal. Single channel infrared detectors look for radiation emitted from hot CO_2 gases present in most flames at wavelengths around 2.7 μm or 4.4 μm. These single channel detectors have precision band-pass optical filters in front of them to detect fires while successfully rejecting solar radiation. The major problem with single channel detection is that since only one channel of information is present, the chances of false alarms are relatively high.[3,4]

The false alarm problems present with single channel detection can be partially alleviated by using two channels of information. Typically two-channel flame detectors use one channel in the infra-red (typically at 4.4 μm) to detect hot combustion products. The second channel is chosen above or below the 4.4 μm band where there is a high level of solar radiation coupled with low levels of flame radiation. The addition of the second channel is purely for the prevention of false alarms by rejecting interference (such as direct solar radiation) from a continuum source that does not have the ubiquitous 4.4 μm CO_2 band. Fire is still detected using the 4.4 μm infrared channel, and in cases where fire is present along with the interfering source, it might be difficult to resolve the signal unambiguously.[4] Further, highly luminous fires may go undetected if the detector is tuned to non-luminous fires. Commercial production of single channel infrared flame sensors which are insensitive to solar radiation, or a combination ultra-violet/infrared and even two-channel infrared flame sensors has been initiated for use in industrial applications.[4]

A fiber optic fire sensor that measures radiation at two wavelength spaced far apart in the visible to 2.0 micron wavelength band has been recently utilized to detect diesel fires.[5] The fiber optic fire sensor utilizes the high degree of correlation between the intensities at the two wavelengths to provide immunity to false alarm sources. However details regarding the hardware of the fiber optic fire sensor or the fire detection algorithm were not reported.

The two most distinguishing features of a natural fire, particularly a luminous one, are its apparent source temperature and the power spectral density of the radiation intensities emitted from it.[6,7] The power spectral density of natural fires show a wide range of frequency present in them. Based on this observation, a two-wavelength near infrared fire detector which utilizes the statistics of apparent source temperatures was evaluated by us previously.[8]

However, in some cases, the radiation emanating from the fires undergoes multiple reflections, from the walls of the enclosure before reaching the fire detector. The effect of these reflections on the estimated temperatures have to be fully understood, before a fire detector based on temperature estimation can be commercialized. Therefore, the objective of the present work was to evaluate the near infrared fire detector utilizing reflected radiation. Experimental evaluation was conducted using five standard test fires specified in the European Committee for Standardization (CEN) guidelines.[9] Numerical evaluation of the effect of reflections on the temperatures inferred by the near infrared fire detector were also undertaken to further support the experimental work.

EXPERIMENTAL EVALUATION

The near-infrared fire detector utilizes the time series of apparent source temperatures, obtained from the measured spectral radiation intensities at 900 and 1000 nm to discriminate fires from background signals.[8] The apparent source temperature, T, is defined as:[8]

$$T = \frac{hc}{k}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) / \ln\left\{\left(\frac{\lambda_2^6}{\lambda_1^6}\right)\left(\frac{I_{\lambda 2}}{I_{\lambda 1}}\right)\right\} \tag{1}$$

where h is the Planck's constant, k is the Boltzmann constant, and c is the speed of light. I_λ is the measured spectral radiation intensity at wavelength λ.

Fire detectors commonly used in residential and commercial buildings are tested using six standard fires specified in the CEN[9] guidelines. A detailed description of the test fires used in our laboratories to evaluate the near infrared fire detector is provided in Ref. 8. Three of the test fires were open luminous fires obtained from the burning of a wooden crib (designated TF1 in the CEN[9] guidelines), an heptane pool (TF5) and polyurethane mats (TF4). Two of the test fires were smoldering combustion from cotton fibers (TF2) and wooden pellets (TF3). The sixth test fire (TF6) was a non-luminous methanol pool fire, which could not be detected by the near infrared detector. The five test fires, TF1 to TF5, were used to evaluate the operation of the near infrared fire detector when only reflected radiation is incident on it.

The test configuration used for the evaluation of the NIR fire detector using reflected radiation is shown in Fig. 1. Direct radiation from the test fires is blocked using screens.

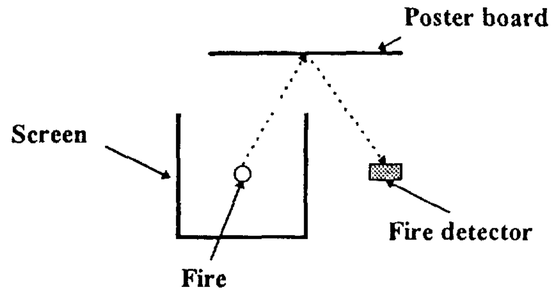

Figure 1. Geometry used to evaluate the NIR fire detector using reflected radiation.

Only that portion of the radiation that is reflected from a poster board is allowed to impinge on the detector. The reflectivity of the white poster board at 900 and 1000 nm is very low. Therefore, the spectral radiation intensities incident on the NIR fire detector from the reflected radiation were an order of magnitude lower than those incident from direct radiation. In addition, the poster board has different reflectivities at 900 and 1000 nm. Therefore, the ratio of the spectral radiation intensities at 900 and 1000 nm incident on the near infrared fire detector changes. This causes either an increase or decrease in the apparent source temperatures calculated using Eq. 1.

The probability density functions (PDFs) of apparent source temperatures estimated from measurements of direct and reflected spectral radiation intensities are shown in Fig. 2. The PDFs of apparent source temperatures obtained with the three open fires (heptane, foam and wood) in the direct view of the detector are shown in the bottom panel of Fig. 2. The apparent source temperatures for the three open fires range from 1300 to 1800 K.

The PDFs of apparent source temperatures for the three open fires when only reflected radiation is incident on the detector are shown in the bottom panel of Fig. 2. For liquid pool fires, the higher temperatures are usually associated with very low soot volume fractions. Therefore, even at these higher temperatures, the spectral radiation intensities could be lower than those obtained at relatively lower temperatures. In addition, at lowest range of temperatures, the spectral radiation intensities are also very low. Therefore, after one reflection, only the middle range of temperatures (with some spectral biasing) are detected by the infrared fire detector.

For the wooden crib fires, information on the correlation between local intensities and temperatures is not available. Therefore, the changes in the shape of the apparent source temperature PDFs could be due to a combination of factors, including spectral biasing of the reflected intensities, shape of the flame, and correlation between local temperatures and emissivities. In addition, the wood fire is transient in nature, and the temperatures obtained from direct and reflected radiation could be at different stages in the development of the fire.

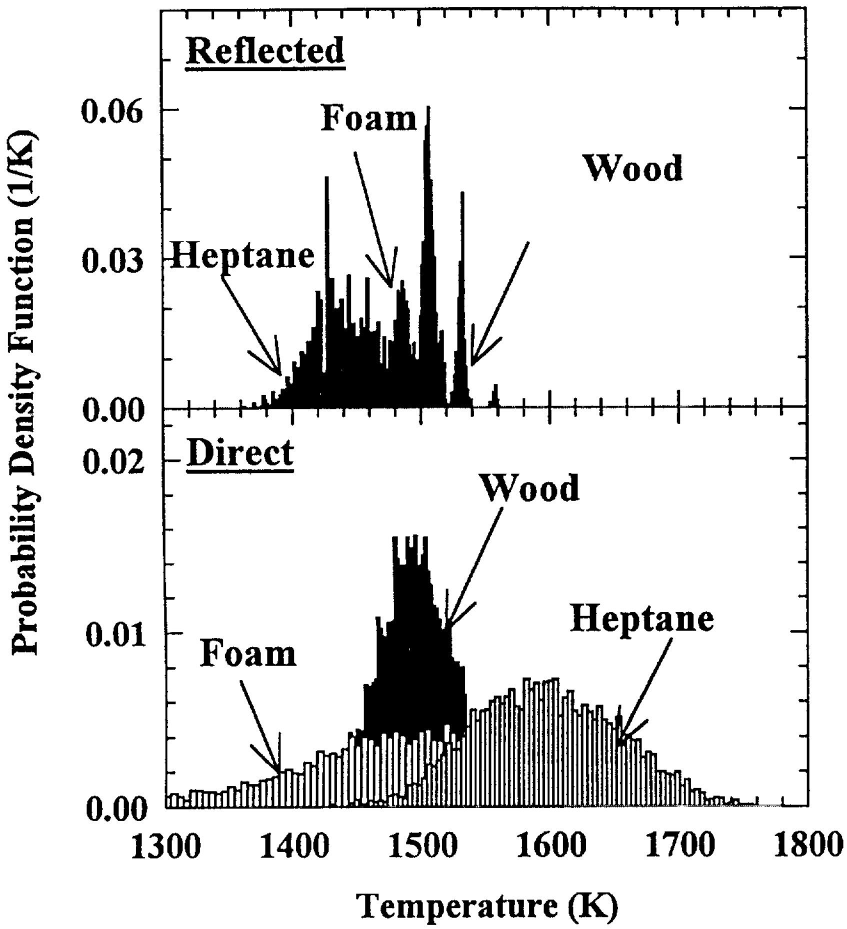

Figure 2. The PDFs of apparent source temperatures for the open fires

For the polyurethane foam fires, only the middle range of temperatures (in comparison with the direct tests) is detected from reflected radiation (similar to the heptane pool fires). Despite the differences in the PDFs obtained from the direct and indirect viewing of the fire, all of the temperatures fall within 1000 to 2000 K. This satisfies the first criteria[8] for the existence of a fire in the vicinity of the detector.

The second criteria[8] that should be satisfied for the existence of a fire in the vicinity of the detector is that the normalized power spectral density (PSD) of spectral radiation intensities at 10 Hz should be 1.5. The normalized PSDs of spectral radiation intensity at 1000 nm for the three open fires are shown in Fig. 3. The normalized PSDs obtained from reflected and direct

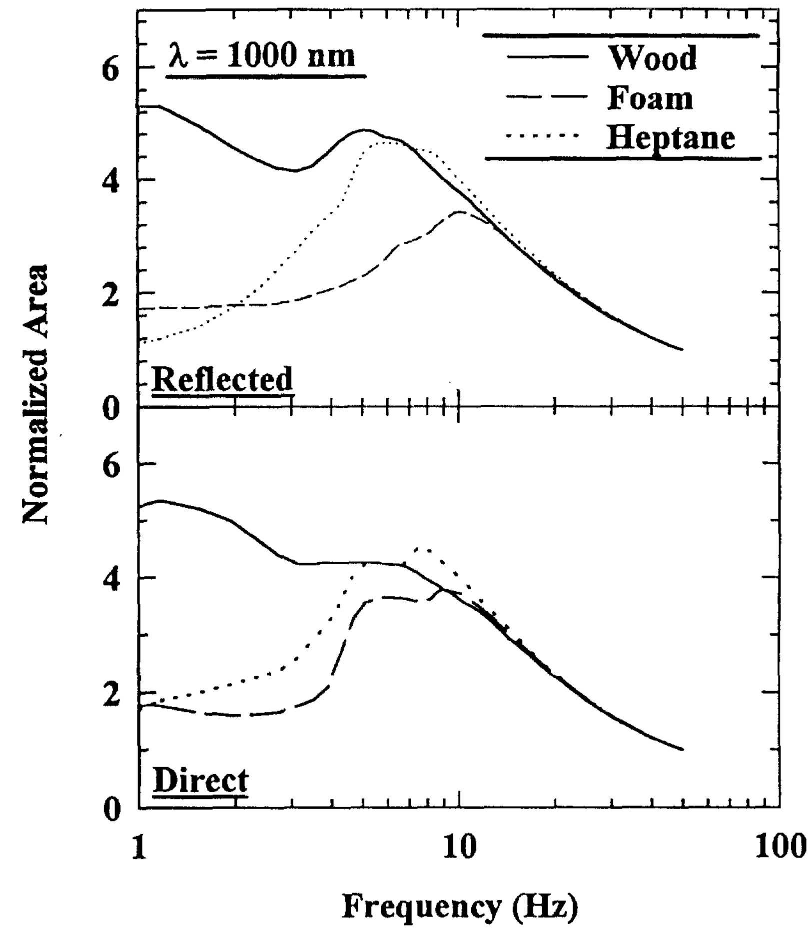

Figure 3. The normalized PSDs of spectral radiation intensities for the open fires.

radiation are shown in the top and bottom panels of Fig. 3. In both cases, the total energy of the fluctuations below 10 Hz are 1.5 times greater than that from white noise, satisfying the second criteria for the presence of a fire in the vicinity of the detector. The PDFs of apparent source temperatures for the smoldering fires (cotton fiber and wooden pellets) are shown in Fig. 4. Smoldering fires have much lower temperatures than open fires.

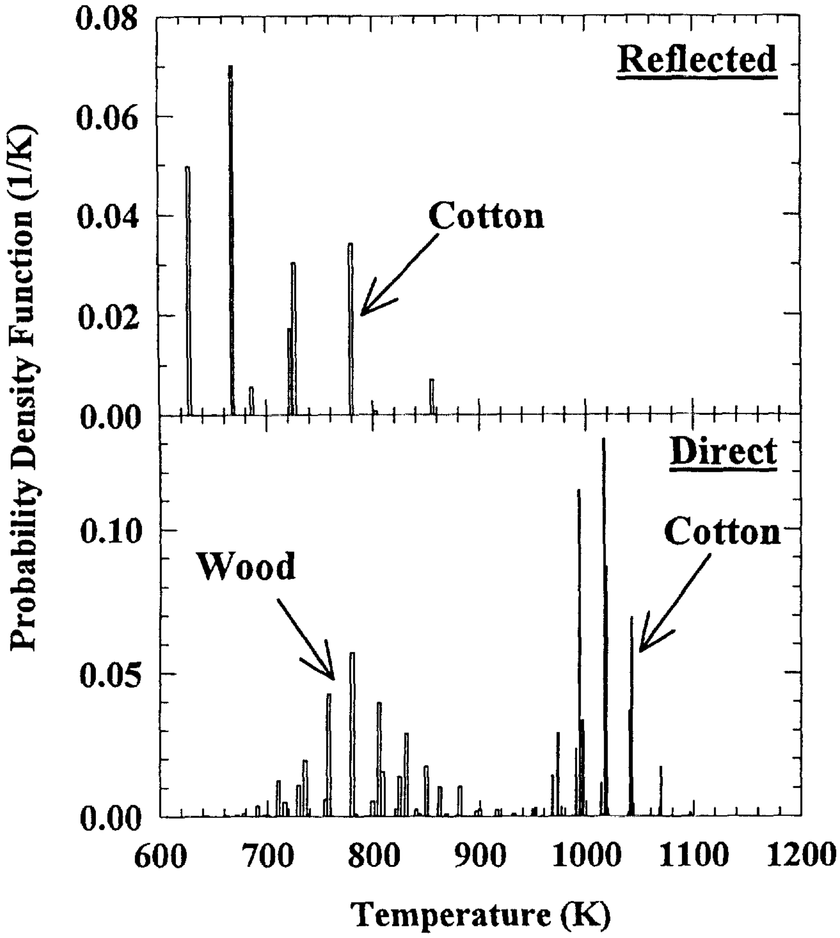

Figure 4. PDFs of apparent source temperatures for smoldering fires.

The PDFs of apparent source temperatures obtained from direct radiation for the smoldering cotton fire varies from 900 to 1100 K, and that for the smoldering wood fire varies from 700 to900 K, as shown in the bottom panel of Fig. 4. The PDF of apparent source temperatures obtained using reflected radiation from the smoldering cotton fire is approximately 200 K lower. In addition, the PDF is not continuous. This is because the reflected intensities incident on the NIR fire detector from the smoldering cotton fire are very low. Therefore, the discretization error of the A/D converter becomes a significant factor. For the smoldering wood fire, the reflected intensities were below the detection threshold of the NIR fire detector.

The normalized PSDs of spectral radiation intensities at 1000 nm for the two smoldering fires are shown in Fig. 5. The intensities obtained from the direct view of the smoldering wood fire

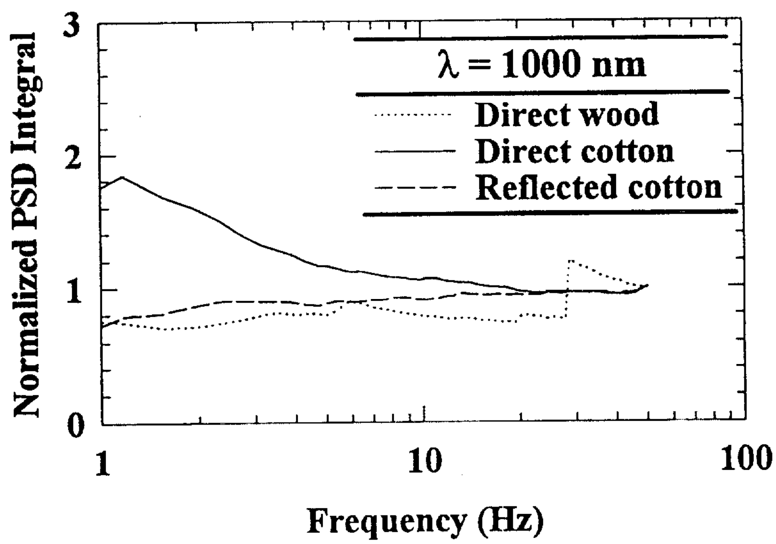

Figure 5. Normalized PSDs of spectral radiation intensity at 1000 nm for smoldering fires.

and from the reflected view of the cotton fire are barely above the noise level, and therefore could not be identified by the near infrared fire detector as valid fire signals.

The major reason for the very poor performance with the smoldering wood fire is that the smolder surface is face down on the burner and therefore very little of the smoldering surface is visible. The standard test fire (TF3) is specifically designed to test smoke detectors[9] and not flame detectors. For flame detection, an alternative standard test for smoldering wood would be more appropriate. The smoldering cotton fire can be discriminated utilizing a A/D converter with a higher (16 bit) dynamic range.

NUMERICAL EVALUATION

Numerical evaluation of the near infrared fire detector was conducted using a photon tracing algorithm in conjunction with the discrete probability function (DPF) method[10]. The simulations were performed for axisymmetric and rectangular enclosures. The axisymmetric simulations[10] were carried out for a cylindrical enclosure with aspect (length to radius) ratio of 3. The geometry used for the three dimensional simulations is described below. A three dimensional rectangular enclosure of length L, width and height a, has an heptane pool fire at one end. The angular distribution of spectral radiation intensities emanating from a standard heptane pool fire was measured and used as a radiation source for the simulations.

A detector is placed at the other end as shown in Fig. 6. Part of the radiation emitted by the blackbody is absorbed by the walls of the enclosure, and the remainder reflected. The

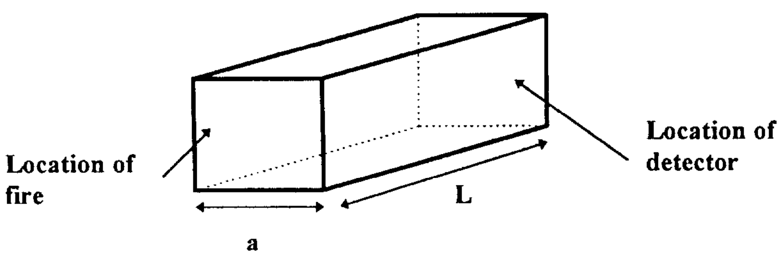

Figure 6. Geometry used for evaluation of the fire detector.

absorptivity of the walls also changes with wavelength. The reflectivity of the walls of the enclosure has both a specular and a diffuse component. The effect of the interaction of the photons with the walls of the enclosure on the temperatures estimated by the NIR fire detector are calculated using a photon tracing algorithm in conjunction with the DPF method.

The accuracy of the calculations were confirmed by comparison with analytical results that are available for limiting cases[10]. For example, when the reflectivity is set to zero, the fraction of photons that reach the detector is just the view factor, and the estimated temperature obtained for a 1500 K blackbody source remains unchanged. In addition, when the reflectivity and the specularity were set to one, all the photons reach the detector with no spectral biasing, and the estimated temperature is again 1500 K.

The PDFs of apparent source temperatures for an axisymmetric enclosure with and without considering reflections from the walls of the enclosure are shown in Fig.7. The aspect (length to radius) ratio of the enclosure was 3. The walls of the enclosure were assumed to have reflectivities of 0.8 and 0.88 for the 1000 nm and 900 nm radiation respectively. The specularity of the reflection was assumed to be 0.4.

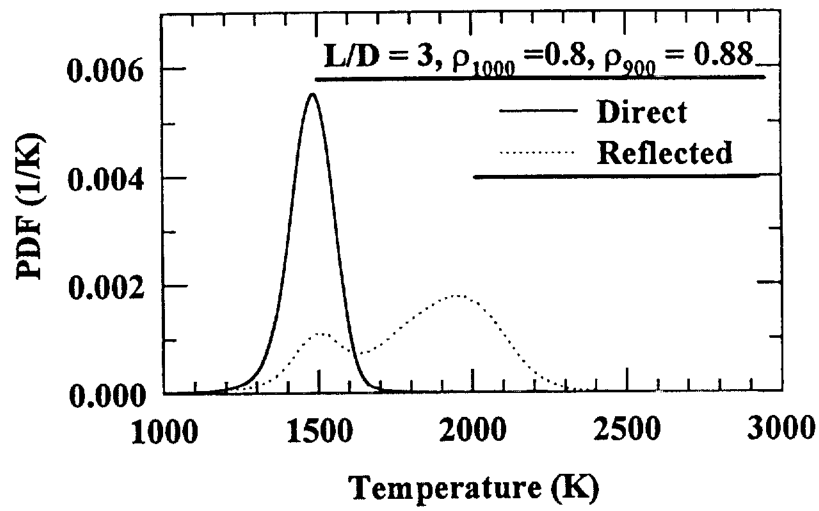

Figure 7. The effect of reflections on the apparent temperatures estimated by the detector.

The PDFs of source temperatures with and without considering the reflected photons from the walls of the enclosure are shown by the dotted and solid line in Fig. 7 respectively. A fraction of photons is directly incident on the detector without undergoing any reflections from the wall. Therefore, the apparent source temperatures obtained from these direct photons are not changed. The effect of the reflections is to increase the apparent source temperatures inferred by the NIR fire detector since the longer wavelength photons are preferentially absorbed. Therefore, the PDF of apparent source temperatures obtained taking the reflected photons into account has a bimodal behavior. Despite the higher values for the estimated source temperatures, the NIR fire detector could successfully discriminate the fires from background radiation., since most of the temperatures are still within 800 to 2500 K.

The PSDs of intensities do not vary with reflections in the simulation (as well as in ideal experiments) since the time taken by the photons to undergo multiple reflections with the wall is much lower than the smallest time scales present in the flow.

The effect of the wall reflections on the PDF of apparent source temperatures for the rectangular enclosure is shown in Fig. 8. Similar to the axisymmetric case, the walls of the enclosure were assumed to absorb 20% of the photons at 1000 nm, and 12% of the photons at 900 nm. The specularity of the reflectivity was also set at 0.4. Similar to the results of the

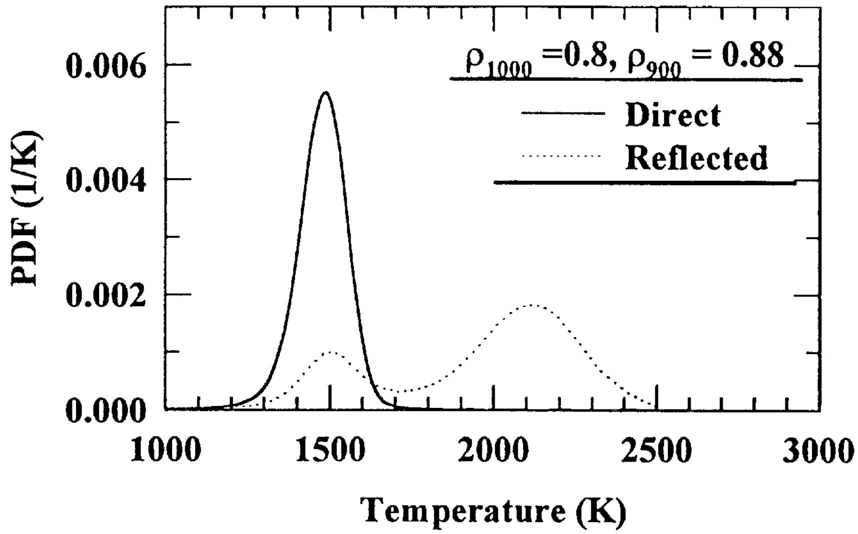

Figure 8. Effect of reflection on the apparent temperatures inferred by the detector.

axisymmetric enclosure, the preferential absorption of the longer wavelengths leads to an increase in the apparent source temperatures (shown by the dotted line in Fig. 8.). In addition, the combination of direct and reflected photons result in a bimodal PDF for the apparent source temperatures. Despite the changes in the PDF caused by the reflections, the range of temperatures still satisfy the criteria[8] for the presence of a fire in the vicinity of the detector.

CONCLUSIONS

The two major conclusions obtained from the experimental evaluation of the NIR fire detector are: (1) open fires can be detected with very low false alarm rates even when the fire is not in the direct view of the detector, and (2) smoldering fires can be detected only when the fire is in the direct view of the detector. The major conclusion obtained from the numerical work is that the performance of the NIR fire detector, even with significant spectral biasing for radiation reflected from building materials, is satisfactory.

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