mgr inż. Jacek Antos
Szkoła Główna Służby Pożarniczej
ul. Słowackiego 52/54
01-629 Warszawa
email address: antosj@wp.pl

PhD thesis

„Influence of chosen environmental parameters on automatic fire detection"
under the academic supervision of
university professor dr hab. Marek Konecki and dr inż. Przemysław Kubica

ABSTRACT

1. Dissertation rationale

Fire alarm systems (FAS), i.e. devices to detect fires automatically, are crucial elements of a fire safety concept in buildings where there are installed. Such systems are designed to early detect fires and warn about them in order to take proper actions that include evacuating people and property items from a building, calling fire brigades through alarm transmission systems, as well as activating firefighting equipment, which can significantly reduce the property damage. A significant problem related to the performance of FAS is the internal environment of a building, because it contributes to more or less frequent cases of false alarm activation. Not only do false alarms negatively affect further reactions of building users and individuals maintaining fire alarm systems, but also cause business disruptions. Moreover, such situations generate additional costs related to unnecessary calling for fire brigades in the case of buildings monitored by National Fire Service.

Proper functioning of a fire alarm system is determined not only by its features, but also by the performance of fire detectors that are influenced by various environmental factors, including those not directly connected with a fire, i.e. dust, aerosols, steam, among many others. A fire detector is a device that should sense and react to phenomena that indicate a fire such as smoke, a temperature rise, electromagnetic radiation given off by the flame and fire gases, but at the same time ignore false phenomena. A vital aspect for a fire detector is to have a decision-making system that is able to classify the particular phenomenon as a fire indicator or a false alarm.

According to statistics provided by National Fire Service Headquarters, the number of false fire alarms in Poland in 2019 was 5,1% higher in comparison to the previous year. In 2019, 153 500 fire incidents took place in Poland, and 17 500 of them were classified as false alarms raised by fire monitoring systems, representing 11,4% of all interventions. False alarms related to fire alarm systems performance represented 40,92% of all false alarms.

The problem of false fire alarms is still present although many solutions aimed at improving the performance of fire detectors have already been implemented. Working on the aforementioned matter in order to reduce the number of false alarms is still ongoing. One direction that is related to seeking new ways to detect fires concerns gas sensor technologies. The most common solution is currently the combination of sensors that measure different parameters of the environment, e.g. the dispersion of radioactive aerosols and the amount of carbon monoxide (CO). However, it should be stressed that gas sensors are characterized by an operational life typically stated between 3 and 5 years and need to be replaced after this period. Thus, considering the economic aspects of their operations, their application is limited to special circumstances.

Due to the fact that the most common type of fire detectors used in buildings is the one operating in the IR or/and UV radiation bands, it is the subject of analysis in the following dissertation. In order to reduce the number of false fire alarms, the influence of environmental factors on the performance of fire detectors has been studied. Applying detectors characterized by the appropriate algorithm differentiating real and false fire phenomena based on received IR and UV signals is the basic concept analyzed in the following thesis.

2. Research problem, postulates, scope and purpose of dissertation

Research problem:

In the internal environment of a building there are factors that can cause false activation of currently applied fire detectors. Raising a fire alarm when there is no real danger constitutes an undesirable phenomenon, affecting negatively fire safety issues. Thus, it seems to be reasonable to search for economically affordable solutions that allows to reduce the number of false alarms raised by smoke detector. The possible mechanism of differentiating real and false alarms is identifying IR and UV signals collected by scattered radiation sensors used in fire detectors. Current standardized methods of studying fire detectors do not differentiate combustion products from other aerosols or liquids. Having taken that into consideration, the research problem of the dissertation was defined as *differentiation of scattering electromagnetic radiation of various wavelengths on particles of chosen liquids and aerosols inside buildings, as well as on particles characteristic for combustion products*.

Postulates:

The following postulates of the dissertation were defined:

1) comparing signals collected by chosen fire detectors increases the effectiveness of differentiating real and false fire phenomena,
2) it is possible to develop standardized testing methods that measure the vulnerability of fire detectors to detect false alarms.

Purpose:

The thesis is aimed at verifying postulates mentioned above through performing tests on the influence of chosen environmental parameters (dusts, aerosol, steam) on the automatic detection of fires. The concept of solving the research problem is based on testing a point smoke detector with a dual-sensor system that operates in the range of scattered IR and UV radiation. Performed analyses were based on measuring sensor signals both during test fires, as well as during false fire phenomena. Having obtained the results, the algorithm of differentiating real and false fire phenomena was developed. The most common factors that can result in false fire alarms, i.e. dusts, glycol and glycerin aerosol and steam, were used to reflect false fire environment.

Scope:

The scope of the dissertation is based on literature and experimental research.

The first chapter includes the thesis rationale, statistical data related to the number of fire incidents and false alarms in recent years, a definition of the research problem, postulates and scope of the dissertation, as well as the description of the concept proposed to solve the research problem.

The second part concerns the development of a fire in its initial phase, as well as changes of environmental parameters prior to the fire development. The analysis of parameters of internal environment where fire detectors are placed is also included in this chapter. In the last section the test fires applied while testing fire detectors are discussed.

The third chapter presents information about the concept of detecting fires by fire detectors. It describes aspects such as Rayleigh scattering, Mie scattering and the Tyndall effect. Optical characteristics of smoke and the size distribution are described depending on a combustion type.

The fourth part describes the current state of knowledge about automatic fire detection. The construction and operating principles of chosen fire detectors, as well as directions of their development are studied in this section. It also concerns the purpose of experimental tests of fire detectors in order to develop the appropriate algorithm of differentiating real and false fire phenomena, which can result in reducing the number of false alarms that currently constitute frequent and undesirable phenomena.

The fifth and sixth chapters describe experimental tests conducted on fire detectors. The first of aforementioned dissertation parts concerns testing the performance of fire detectors depending on changes of the internal environment during the initial phase of fire development. The main purpose of such tests was to analyze signals generated by sensors within fire detectors during test fires TF1 ÷ TF5 and TF8, i.e. TF1 – flame combustion of cellulose (wood); FT2 – fast flameless combustion of cellulose (wood); TF3 – flameless combustion of cotton; TF4 – flame combustion of a polymer (polyurethane); TF5 – combustion of a liquid emitting smoke (n-heptane); TF8 – combustion of a liquid emitting smoke with a small amount of heat (decahydronaftalene). The latter chapter describes tests of sensors in a false fire environment conducted at the prototype test stand. Their purpose was to analyze signals generated by sensors within fire detectors reflecting changes of the internal environment due to the application of fire-like factors (dust, aerosol, steam). The result of tests described in chapters 5 and 6 was the equation (presented in the form of a graph) describing SNR (signal-to-noise ratio) values recorded by sensors and *m* parameter.

The seventh part of the dissertation concerns development of the algorithm differentiating values of environmental parameters prior to the fire development and values recorded when false fire factors are present in normal conditions. Based on the equation of IR/UV signal values recorded by sensors and *m* parameter, another comparative criterion to differentiate real and false fire phenomena was applied, i.e. UV/IR ratio ≥ 1,25 and UV/IR ratio ≥ 1,5.

The eight chapter compares detection times and values of IR and UV signals, as well as UV/IR ratio of a standard detector (signals from sensors analyzed independently) and prototype detectors for tests conducted with the presence of dust, aerosols and steam. Next, in order to verify the performance of new detectors, this section describes real-time tests on sensors with a new algorithm for test fires 1-5 and two additional test fires replacing TF8, i.e. flame combustion of a polymer (polypropylene granulate) and flameless combustion of a polymer (polyurethane) that also emitted white and dark smoke. In order to test fire detectors in a greater range of analyzed parameters, another fire-like factor (glycol and glycerin aerosol) was applied. All results of conducted tests are presented in the graph as average response times (fire detection times) for particular detectors.

The ninth part of the dissertation presents the analysis of uncertainties of optical density measurement using densitometer, as well as measurements of intensity of IR and UV radiation recorded by sensors of optical smoke detector.

The last, tenth chapter presents the concept of a test stand to assess the vulnerability of sensors to being falsely activated based on detector experimental research with the application of oak wood dust with 63 ÷ 71 μm particle diameter as a fire-like factor.

The dissertation summary discusses aforementioned postulates and presents conclusions of an educational and practical values resulted from conducted tests.

3. Experimental research

The experiment was mainly based on testing sensors that are components of fire detectors. In order to obtain reliable results, hundreds of test fires and tests with the presence of fire-like factors were conducted. The first stage involved performing so-called test fires, i.e. TF1 – TF5 and TF8 with standard detectors including independent sensors and was based on recording the ratio between the intensity of UV and IR radiation scattering. Sensors of the particular intensity values (receiver-transmitter circuits), were elements of a fire detection unit. In order to obtain a representative sample, tests were performed using 8 fire detectors simultaneously. Results were recorded with the frequency of one second. Considering the fact that the fire growth rate is various in real conditions, the time criterion was rejected and the optical density of the environment, described as an *extinction modulus* – *m* (*m* parameter) was considered instead. Having done that, the series of several thousand data of *m – UV/IR ratio* was collected.

The second stage was based on the analysis of the ratio between the intensity of UV and IR radiation scattering in the presence of a fire-like factor, i.e. a sample of chosen liquids, glycol and glycerin aerosol and steam. Test results were presented, as the results concerning test fires, in the form of tag values of the ratio of UV/IR radiation signals collected from sensors of fire detectors, depending on the environment optical density, expressed as an *extinction modulus* – *m*. All results of measurements are brought together in the figure 1.

Based on the average value (UV/IR_{avg}) from all sample tests (TF1 ÷ TF5 i TF8) that was 2,54, it can be concluded that in the case of flaming fires (TF1, TF4, TF 5 and TF8), the UV/IR ratio was of significantly higher values than the average value, and in the case of flameless fires (T2, T4) it was lower than the average value.

To confirm hypotheses, it can be assumed that in conditions reflecting the initial fire stage, in all tests there were cases when the ratio of UV/IR radiation signals was higher than 1,5. Thus, it can be concluded that values higher than this one increase the probability the particular situation is an initial stage of a fire.

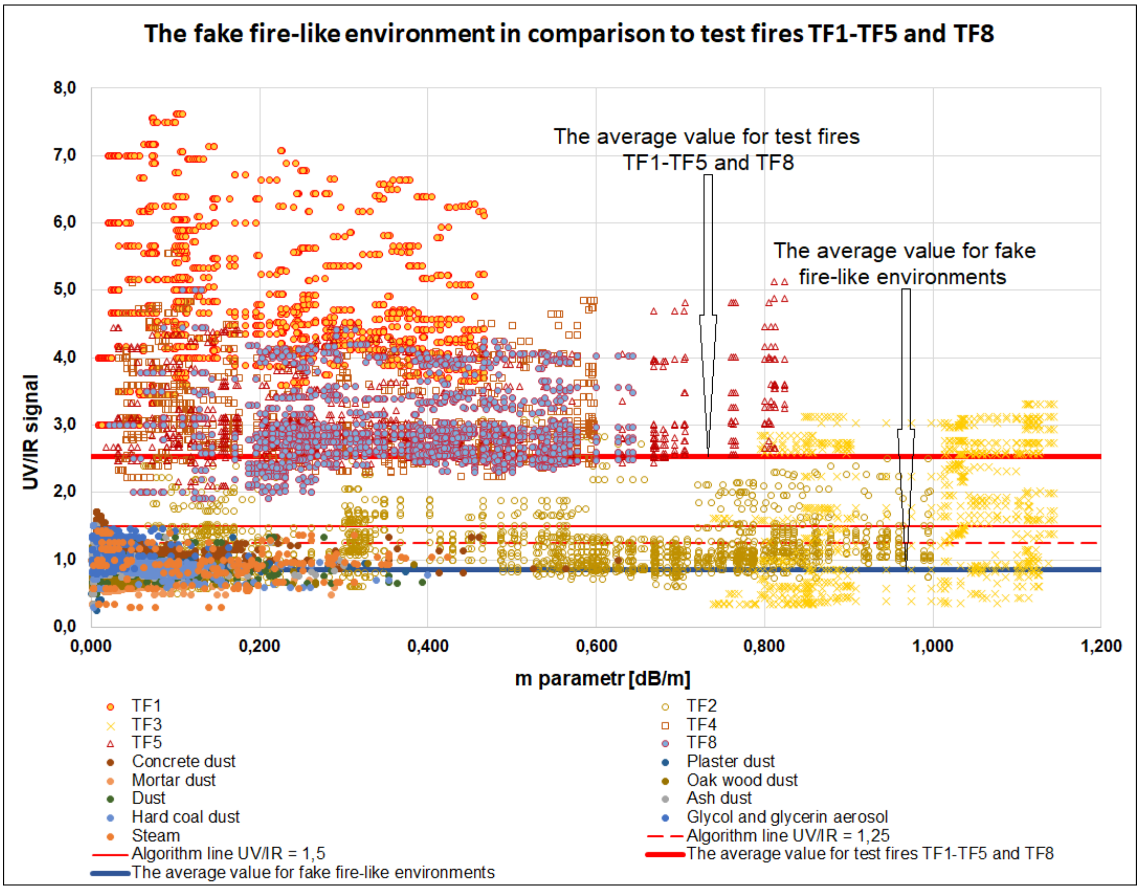

Fig. 1. *The relationship between values of the ratio of UV/IR signals for tested sensors and m parameter for test fires TF1 – TF5 and TF8 in false fire environment.*
Source: own elaboration.

It needs to be emphasized that in the case of a real fire, a flameless phase turns into a flaming phase. Therefore, the certain phenomenon is the presence of particles characteristic for flaming combustion for which, according to performed measurements, the reading of UV sensors was twice as high as the intensity of signals of IR sensors (UV/IR > 2).

Comparing results of tests with the presence of fire-like factors, when the ratio of the intensity of UV radiation scattering and IR scattering was measured as well, it was observed that scattering took place on the particles reflecting fake fire-like environment. Values of the UV/IR signal ratio was between 0,3 ÷ 1,7 (98,9% of results were lower than the adopted UV/IR average value of 1,5, and 92,0% of results were below the adopted UV/IR average value of 1,25). Moreover, values concerning fake fire-like environment were less dispersed than values collected for test fires.

To confirm hypotheses, it can be assumed that in conditions of fake environment, in every test except for the one with concrete dust, the ratio of UV/IR signals was lower than 1,5. In comparison to tests conducted for test fires, values of signals from detectors with IR and UV sensors were changing in a significantly different way, i.e. in most cases, the value corresponding the IR radiation signal was higher than the value of the UV radiation signal. Thus, it can be concluded that when the value of the IR signal from detector sensors monitoring the internal environment is higher than the value of the UV signal, the probability of activating sensors by a fire-like factor is increased.

Based on results obtained during test fires, it has been concluded that in the case of fire conditions that are present in the initial phase of a fire, the value of UV/IR signal ratio is significantly higher than in the case of tests in a fake fire-like environment. For further analyses, the threshold value that reflects the environment condition that can be classified as a fire was defined as UV/IR ≥ 1,25, considered to be a test value, and UV/IR ≥ 1,5 that was the average value of data collected from all test fires reduced by standard deviation. The aforementioned values were used to create a prototype algorithm of fire detector software.

The third stage concerned the comparative analysis comprised of further tests (test fires) for fire sensors working independently and for those with applied values of UV/IR ≥ 1,25 and UV/IR ≥ 1,5. It was found that sensors with a new algorithm that did not raise a fire alarm while being tested in the fake environment reacted properly to fire incidents. Fire detection times were comparable with times measured for sensors that work independently.

In order to confirm the second postulate, a concept of a test stand was developed and verified in practice. The stand was created by the modification of a measuring tunnel used for performing standardized tests of fire detectors. One step of the modernization was installing a liquid atomization system. Such a test stand allowed to reproducibly perform measurements in the fake fire-like environment, created by application of oak wood dust with 63 ÷ 71 μm particle diameter.

4. Conclusions:

Smoke detectors using IR and UV sensors are currently the most common types of fire detectors used in building fire protection. Taking that into consideration, the main objective of the thesis was to use the potential of commonly applied solutions, limited to two sensors using the Tyndall effect, to scatter radiation in the IR and UV frequencies. The tests and analyses conducted for the needs of the thesis allow to draw the following conclusions:

Conclusion 1. It has been confirmed that UV radiation scattering occurs with higher intensity in comparison to IR radiation scattering on the smoke particles created in flaming fires comparing to smoke particles present during flameless fires that, in turn, scatter IR radiation in a stronger way.

Conclusion 2. The combustion type (flaming or flameless) determines the creation of particles characterized not only by different size, but also different properties. The value of the *m* parameter, that describes macroscopic optical properties of smoke, is growing along with the increase in their optical properties (the refractive index) and the number of smoke particles generated during the combustion process. In contrast, it is decreasing along with the increase in particle size and density.

Conclusion 3. The ratio between the signal value of the UV sensor and the signal value of the IR sensor (UV/IR ratio) has been applied as a criterion of differentiating scattering electromagnetic radiation on smoke particles generated during a fire and particles generated by fake factors (dust, aerosol, steam) during building utilization. The differentiation of sensor reactions is related to the size and properties of particles generated in both types of environment.

Conclusion 4. The UV/IR ratio calculated with the Rayleigh equation (21,37) was higher than the values of the UV/IR ratio measured during conducted tests (7,7). The reason for such a discrepancy is heterogeneity of smoke particles. Due to the fact that sensors within detectors record resultant scattering of radiation resulted from the presence of particles in the measuring space, the measured value was different from the theoretical value.

The number of particles that satisfy the Rayleigh equation was higher in smoke generated during flaming combustion – in this case, the value of the ratio of UV/IR signals significantly exceeded 1. In turn, for the flameless combustion process, which generates particles of both smaller and greater sizes, both cases of $UV/IR > 1$ and $UV/IR < 1$ were recorded. Next, dust aerosols reflecting fake factors are mostly characterized by particles of greater sizes, thus the situation in which in the measuring space there would be mostly particles of smaller sizes, determining $UV/IR >> 1$, was practically not recorded in the course of the experiment.

Conclusion 5. Based on conducted tests, applying differentiating algorithms $UV/IR \geq 1{,}25$ and $UV/IR \geq 1{,}5$, for new fire detectors it was eventually decided to apply the following algorithm that constitutes the criterion differentiating real and false fire phenomena:

$$UV/IR \geq 1{,}5$$

It has been found that the above criterion can be properly used in fire detectors. Performed tests have proved the effective performance of detectors in the fire environment, at the same time reducing the number of activations for fire-like factors.

Conclusion 6. In the group of representative fires there are always cases in which the ratio of UV/IR scattering signals in the sensor exceeds the value of 1,5. Cases resulted from the presence of a fire-like factor represented only 1,1% of all incidents.

Conclusion 7. While testing detectors in the fake fire-like environment, the value of the ratio of UV/IR intensity does not exceed 1,5, except for tests with concrete dust (in this case a slightly higher value of 1,7 was recorded).

Conclusion 8. While testing detectors in the fake fire-like environment, a standard detector (a signal from detectors analyzed independently) raised a fire alarm in all cases. The detector with the applied algorithm of UV/IR ≥ 1,25 did so in 22% cases, and the detector with the algorithm of UV/IR ≥ 1,5 signalized only the prealarm condition due to exceeding intermediate values (i.e. values lower than the alarm threshold) for the internal environment.

Conclusion 9. It has been proved that both standard fire detectors (independent sensors) and newly developed detectors (algorithms UV/IR ≥ 1,25 and UV/IR ≥ 1,5) detect fire incidents and raise a fire alarm in similar amounts of time. It confirms that the detector with the prototype algorithm UV/IR ≥ 1,5 is as sensitive as a standard detector, but it raises false alarms with lower frequency than the latter one.

Conclusion 10. Fire detectors with the algorithm being a differentiating criterion (false or real fire environment) UV/IR ≥ 1,25 are more vulnerable to false activation (they raised the alarm in 10 out of 45 trials), but performing as effectively in terms of detecting representative fires as detectors with the algorithm UV/IR ≥ 1,5.

Conclusion 11. It is proposed to implement an additional test to verify the detector vulnerability to false activation during the process of certification tests. The proposed test is based on checking fire detectors with the presence of a mixture of air and oak wood dust with 63 ÷ 71 μm particle diameter flowing at the speed of 2 m/s. The basic criterion for an effective performance of a detector is no indication of a fire alarm. The aforementioned test is supposed to make producers apply solutions preventing detectors from false activations and, in turn, it is expected to reduce the number of false alarms raised by fire alarm systems.