RESEARCH ARTICLE

Investigation of Thermal behaviour of Swelling Anti-Fire Composite Materials Identified with RFID Technology

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Passive fire protections are one of the safety systems which are installed commonly in buildings. As every kind of such systems these protections have to controlled according to legal regulations. To facilitate periodic checks RFID technology can be successfully used. In this paper, thermal behaviour of produced swelling materials suitable for passive fire protection was examined and thermal endurance of RFID tags used to identify these protections was analysed as well. The results achieved in this study showed expected thermal behaviour of the swelling materials which fulfilled the whole space of the protections blocking spreading fire and smoke. Further, it was noticed that a gasket sealant and a high-temperature silicone allowed to decrease temperature affecting RFID tags. Paper-face and hard RFID tags withstood the applied thermal exposure and their readability was restored after cooling down the tags to about 120°C. This means that it is likely that these tags can resist small fire incidents on condition that temperature affecting the tags does not exceed a decomposition temperature of materials used for their production.

Introduction

One of the existing methods of keeping people and buildings safe from a negative influence resulting from expanding fire is using passive fire protections. According to the research results presented in the report 'High-Rise Building Fires' published by National Fire Protection Association cooking equipment is the most leading cause of fire **[1]**. Similar results were announced in the report 'Large Loss Building Fires' **[2]**. Apart from that smoking materials, electrical lighting, heating equipment and air conditioner can be also treated as potential sources of rising of fire.

In order to prevent from expanding fire in buildings and at the same time from spreading smoke and high temperature, which are also dangerous for people, passive and active protections can be utilized. The first type of products includes: non-flammable building elements not spreading fire under any conditions, fire-resistant building elements retaining their properties (e.g., load-bearing capacity, fire integrity, fire insulation), even in a situation of developing fire for a specified period of time. For example, in buildings for protecting steel structures, fire-resistant intumescent paints, panel claddings and non-reactive spray coatings are used as passive fire protection measures [**3-7**].

The other type of fire protection systems are active elements, such as: heat sensors, smoke sensors, gas sensors, sprinklers, water curtains, fire doors, fire hydrants and fire extinguishers. Effectiveness of using the mentioned means depends also on passive protections. Therefore, it is recommended to utilize in buildings both types of anti-fire measures which can 'cooperate' to reduce spreading fire and smoke (passive anti-fire measures) and to fight fires (active anti-fire systems) [**8-10**].

Despite a type of used fire protection systems it is essential to select proper swelling composite materials to produce components of passive protections measures, such as intumescent pipe wrap, fire rate intumescent coat, intumescent grille and so on. These materials should allow to prevent against fire spreading a certain period of time, e.g., 120 min, depending on a selected fire resistance class.

The second important issue is to verify if proper anti-fire products were installed in buildings. These activities are made by institutions which are responsible for controlling safety of buildings. It is often necessary to destroy or deinstall some parts of walls to check mounted passive fire protections. In order to make easier the mentioned controlling activities it would be recommended to identify wirelessly presence of the protections mounted in controlled buildings.

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One of the methods which can be utilized for identification of the mentioned products is Radio Frequency Identification (RFID). It is one of the most popular identification systems used in many branches of industry and services. It works mostly in HF 13.56 MHz or UHF 860 – 960 MHz frequency ranges offering read distance from a few centimetres in case of HF RFID tags to several meters in case of UHF RFID tags, respectively [**11-15**]. However, the read performance of RFID tags depends on a design of tags and selection of an RFID reader. The drawback of this identification technology is susceptibility to different materials, in particular to metals and liquids. Apart from them concrete has also a negative influence of propagation of electromagnetic waves by causing their attenuation. Therefore, a decrease in read distance or even a lack of communication between tags and reader are observed for RFID tags mounted near the mentioned materials [**16-17**].

Recently, automatic identification of passive fire protection has been widely tested due to implementation of Internet of Things (IoT) technologies in fire prevention system. IoT provides wireless connectivity between every part of such system. Thus, it allows to reduce installation time by avoiding huge building renovations [**18-23**]. Furthermore, using multiple sensors (temperature, gas, flame, motion) in IoT system can provide accurate data on time to detect fire at the early stage [**24-26**].

However, most studies published so far have focused on technical issues of fire prevention systems, e.g., architecture, sensing capabilities, wireless connectivity. There is a small number of research works in which impact of high temperature on durability of tags during fire incidents has been examined. This durability is especially important when applicability of RFID tags or other electronic circuits in passive fire protection is concerned.

Therefore, the idea of this paper is to investigate thermal behaviour of prepared swelling composite materials which can be used for production passive fire protections and to examine thermal durability of RFID tags which can be utilized in the designed interactive automatic identification system making possible to verify presence of these protections in building.

Experimental

Materials details

Two different swelling composite materials were utilized to prepare passive fire protections used in the study. One of them was a thermoplastic composite, used in an intumescent pipe collar, consisting of a polymer carrier, ethylene-vinyl acetate (EVA) with a concentration of vinyl acetate of 40 %, and a modified graphite with a grain size below 0.1 mm. The ratio of the ingredients was 20 % of EVA and 80 % of graphite. These ingredients were mixed, then processed by extrusion at 80°C and pressing at 50°C. Finally, the composite material enclosed in a metal housing was tested in accordance to the PN-EN 1363-3:2010 standard and received the fire resistance classification of EI120.

The second tested composite material used in an intumescent grille is based on recycled natural fibers. The fillers were graphite (5%), aramid fibers (5%) and basalt fibers (1%) whereas a urea-formaldehyde glue in the amount of 10 % was used as a binder. After a production process the composite material was cut into pieces and then placed in the intumescent grille. Fire resistance of the final product was classified as EI240 according to the requirements of the PN-EN 1364-5:2017 standard.

Characterization and sample fabrication

In the study thermal durability of paper face (ALN-9654 "G", Alien Technology) and high-temperature hard (AXTAG 9020, Axem Technology) RFID tags working in the UHF frequency range were evaluated. In order to enhance thermal properties of the paper face tags a protecting material, such as high-temperature silicone useable up to 285°C or a gasket sealant useable up to 1500°C, was used. The photos of the prepared samples are depicted in **Fig. 1 (a,b,c)**. Another type of RFID tags utilized in the conducted experiments was demonstrated in **Fig. 1(d)**. According to the datasheet [**27**] the second type of RFID tags utilized in the reported investigation is capable to be stored in a temperature range from -40°C to +150°C. This tag is produced from FR4 laminate which exhibits a glass transition temperature at 135°C [**28**] whereas its thermal decomposition temperature is estimated to be at 295°C as it was demonstrated in [**29**].

(a) (b) (c) (d)

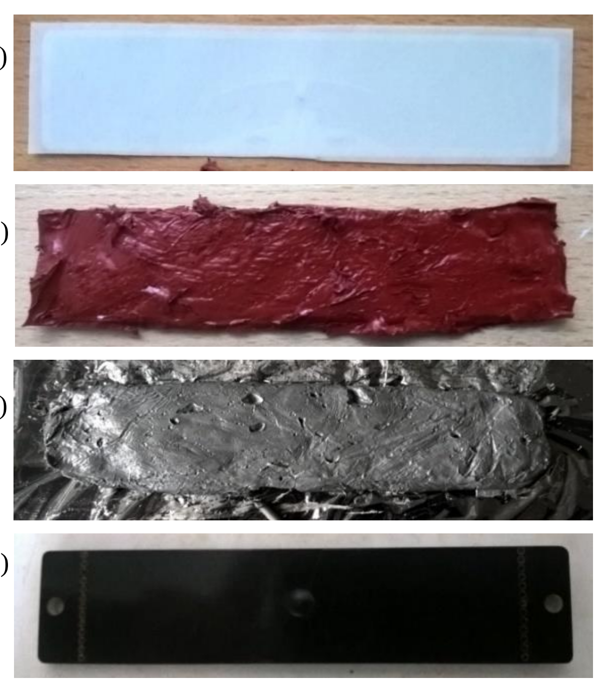


Fig. 1. Samples of paper face and hard RFID tags used in the performed tests; (a) a tag without any protecting material, (b) a paper protected with a high-temperature silicone, (c) a tag protected with a gasket sealant, (d) hard tag, AXTAG 9020, Axem Technology.

Thermal properties of the described above RFID tags were tested in a thermal chamber Venticell which was set to 250°C. Temperature of the samples during the performed investigations was measured with using an electronic temperature recorder APAR. Three thermocouples were connected to the recorder from which two thermocouples were used for measurements of samples' temperature in selected spots and one was utilized for measurements of temperature in the test chamber.

In the last part of the described research, the tested RFID tags was placed in the real passive fire protection in the form of an intumescent pipe collar and an intumescent grille. These products were also subject to influence of high temperature of 250°C with using the same test setup as it was presented above. The exposure time was at least 30 min. ALN-9654 and AXTAG 9020 RFID tags attached to the mentioned products are depicted in **Fig. 2**. The tag, AXTAG 9020, was riveted to the grille in order to avoid its movement during mounting the grille in the test wall made from cellular concrete with using a fireproof sealant compound.

(a)

(b)

Fig. 2. Test setup with the intumescent pipe collar (a) and grille (b).

Apart from controlling temperature of the tested samples during the performed tests read capability of the tags was monitored with a handheld RFID reader every a few minutes which was equipped with a module to determine Received Signal Strength Indicator (RSSI). RSSI was used in this study to examine influence of high temperature on readability of different RFID tags during long-term thermal exposure. It was done in order to simulate environmental conditions existing during a small fire incident which allows to determine possibility of enduring short-term fires by RFID tags.

Results and discussion

In the first stage of the research concerning thermal durability of RFID tags the paper-face samples were considered. It was noticed damage of the paper parts of the tested RFID tags and deformation of the whole tags after 30 min at 250°C.

The measured temperature distribution for the ALN-9654 tags without and with outer protection materials are depicted in **Fig. 3(a)**. It was revealed that using the gasket sealant or the high temperature silicone caused a decrease in the measured temperature of the tested RFID tags. This decline in temperature was observed particularly at the beginning of the tests in the test chamber, especially for the sample protected with the high-temperature silicone. When the tags were exposed to approx. 20 min a difference in temperature was becoming very small because the samples were heated up equally in the whole volume.

In order to evaluate efficiency of the tested protection materials a temperature difference between the protected samples and the non-protected paper-face tag against thermal exposure time was figured out (**Fig. 3(b)**). It was stated that in the first stage of thermal exposure the high-temperature silicone allowed to decrease the measured temperature of the paper-face tag. After 30 min this difference decreased to 1.8°C whereas its value was the highest (56.3°C) after a few seconds of the applied thermal exposure.

From the practical point of view the essential advantage of the high-temperature silicone over the gasket sealant is flexibility what makes possible to place the tags even on curvilinear surfaces. In turn, the gasket sealant is brittle after thermal exposure and it can be mechanically damaged. Therefore, this sealant should be used only in the application fields where RFID tags are applied on flat surfaces and exposed to really high temperatures.

(a)

(b)

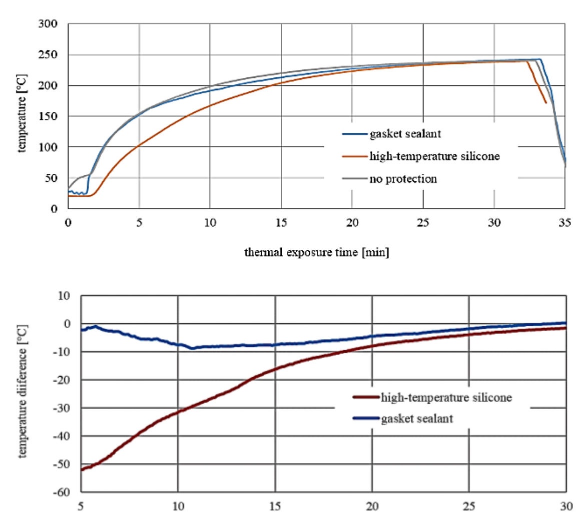


Fig. 3. Measurement results of temperature of the paper-face RFID tags without and with outer protecting materials, exposed to 250°C.

Irrespective of the utilized protection material the performed investigations showed that all the tested samples remained readable after cooling them to about 120°C. This temperature level can be identified as the limit temperature for which it is still possible to establish communication between RFID reader and tags. This conclusion is consistent with the data presented in [**30,31**] where it was said that the upper temperature limit of using conventional electronics components is +125°C. However, the maximum storage temperature of RFID tags can be increased even to 600°C with the maximum exposure time up to 2 hours [**32**]. Other studies [**33,34**] showed that it is possible to produce chipless RFID tags which can operate in an ultra-high temperature range (500°C), but such RFID tags do not have any silicon chip. Therefore, data storage capability of this type of RFID tags is limited, e.g., to 80 bit as it was reported in [**35**], so much lower than in the case of RFID chips equipped with chips (data storage capability is in the range of at least a few kilobytes [**35**]).

The mentioned capability of the RFID tags to establish communication with an RFID reader was monitored during the conducted experiments by RSSI measurements. The achieved results are summarized in **Table 1**. As it was demonstrated application of the tested protecting materials let to extend a period of time in which the tested samples were readable. The samples protected with the high-temperature silicone were readable for the longer period of time what is consistent with the results of temperature measurements (see **Fig. 3**).

Table 1. Measurement results of RSSI depending on a used protection method of paper-face RFID tags during thermal exposure.

thermal exposure time [min]	non-protected paper-face tag	gasket sealant	high-temperature silicone
0	-38	-27	-52
5	*x*[1]	-26	-41
10	*x*	*x*	-41
15	*x*	*x*	-58
20	*x*	*x*	*x*
25	*x*	*x*	*x*
30	*x*	*x*	*x*

x[1] – RFID tags are not readable by RFID reader.

Similar tests were also done for the high-temperature RFID tags, AXTAG 9020. During the applied thermal exposure thermocouples T1 and T3 were responsible for measurements of temperature for the tag whereas a thermocouple T2 was used as a reference measuring temperature in the tested chamber. The obtained test results are depicted in **Fig. 4** which showed that in the initial period of exposure duration there was the greatest temperature difference between the ambient conditions and the surface of the tested sample. The maximum difference was 71.6°C. The observed difference was becoming smaller and smaller with time of thermal exposure.

For the high temperature tag the reading test was also carried out during the applied thermal exposure. It was noticed the same behaviour like in the case of the paper-face tag. After 10 min AXTAG 9020 wasn't able to establish communication with the reader, but when it was cooled down its readability was restored. In the literature it was reported that during high-temperature cycling tests damage of the tested RFID tags was due to cracks between a pad and an antenna layer [**36**]. In another study [**37**] it was found that improper work of the tested RFID tags was caused by cracks in the antenna layer. Furthermore, changes in a chip to antenna attachment material can be taken place what may cause variation in the impedance matching between chip and antenna. The mentioned issues should be taken into account when behaviour of RFID tags during fire incidents is analysed.

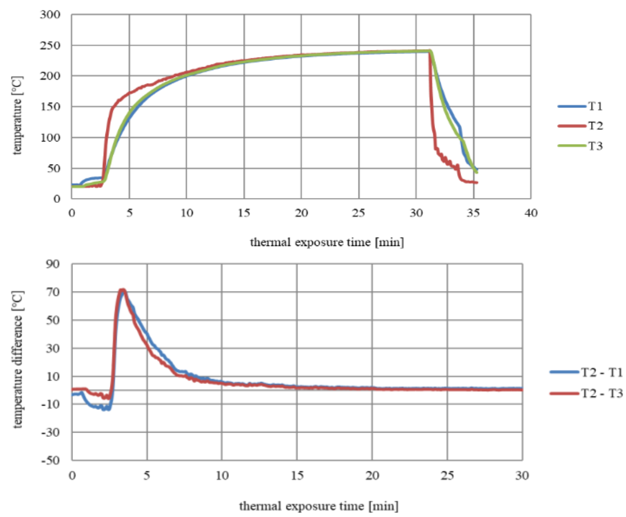


Fig. 4. Measurement results of temperature of the hard RFID tags without any outer protecting materials, exposed to 250°C.

Apart from the described above investigations of thermal endurance of different types of RFID tags experiments with the use of the pipe collar and the intumescent grille were conducted as well. After the performed exposure the composite material in the pipe collar was swelled. The thermocouples measured temperature distribution in the composite material near inner (T1) and outer (T2) parts of the pipe collar. The obtained measurement results (**Fig. 5**) indicated that it is more beneficial to locate RFID tags near the inner part of the pipe collar due to lower thermal exposure of the tags. Furthermore, such placement of the tag is also favourable because a distance between metal parts of the pipe collar and RFID tag is bigger what should facilitate establishing communication between the RFID tag and the reader.

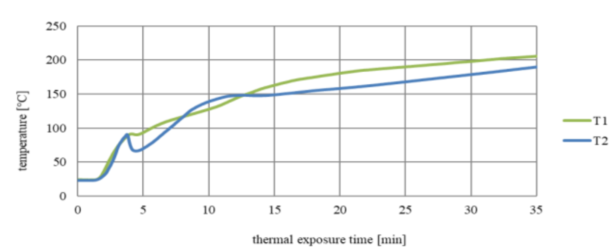
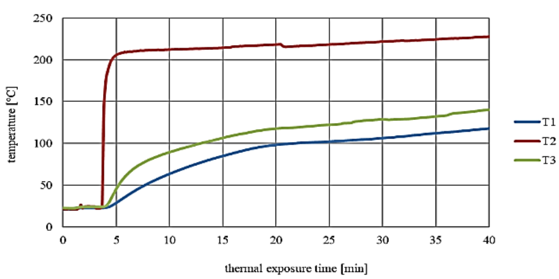


Fig. 5. Temperature distribution in the swelling material of the pipe collar during the applied thermal exposure.

The second application experiment concerned thermal durability of the high-temperature RFID tag placed on the grille mounted in the test wall made from cellular concrete. Thermocouples T1 and T3 were used to measure temperature of a tested RFID tag, AXTAG 9020, placed in the fireproof sealant compound and a thermocouple T2 was a reference responsible for indicating temperature in the test chamber. It was noticed (**Fig. 6(a)**) that the measured temperature level was considerably lower than in the case of the tags directly exposed to influence of high temperature. The observed difference in temperature was larger than 130°C after 30 min of the thermal exposure (**Fig. 6(b)**) when temperature distribution shown in **Fig. 4** and **Fig. 6** is compared. It is likely to be caused by thermal capacity of the test wall, the fireproof sealant compound and the intumescent grille. This means that during small fire incidents a probability of destroying RFID tags assembled on intumescent grilles becomes lower because heat coming from fire is absorbed by objects located in the proximity of tags exposed to influence of high temperature. The mentioned probability is decreasing with increase in a fire duration as well as it depends on construction of building and objects in these buildings.

(a)



(b)

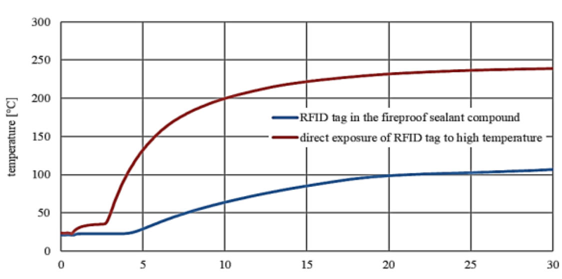


Fig. 6. Temperature distribution in the AXTAG 9020 RFID tag placed in the test wall during the applied thermal exposure.

Similarly, to the previous experiment read capability of the tested RFID tags was monitored. It was revealed that these tags were readable after 30 min of the applied thermal exposure when the samples were cooled down. The same behaviour was also observed for the samples exposed to 250°C for a few hours. This means that during a small fire incident the probability of damage of high-temperature tags is quite low even after long-term thermal exposure. However, this conclusion is only true when temperature during fire is not increasing above the mentioned decomposition temperature of materials used for production of RFID tags.

Conclusion

Thermal behaviour of different types of RFID tags placed in passive fire protection measures were reported in the study. Paper-face tags were enclosed in a gasket sealant or a high-temperature silicone to evaluate impact of these encapsulation materials on temperature distribution inside the samples and their thermal durability. The results achieved showed a decrease in temperature in the first stage of heating at 250°C for the encapsulated paper-face tags compared to the bare one. This indicated that the sealant and silicone can be used as an effective protection against short-term fire incidents. In case of passive protection with curvilinear surfaces it is recommended to use high-temperature silicone due to its flexibility. This silicone allowed to achieve readability of the paper-face tags for a longer period of time compared to the samples protected with the gasket sealant. The same thermal behaviour was observed for the hard RFID tags.

In case of the pipe collar it was revealed that it is recommend to place the paper-face tags near the inner part of the collar due to lower thermal exposure as well as higher distance from the metal housing to facilitate data transmission between the reader and the tags. Furthermore, the hard tag riveted to the intumescent grill turned out to work properly after the conducted thermal exposure. The tests showed that heat was absorbed mostly by the test wall and in effect the tag was exposed to lower thermal stress. It means that short-term fire cases are likely not to destroy totally the hard tags.

When readability of the tested tags is concerned all of them became not readable after excessing the temperature of about 120°C. After their cooling below the mentioned temperature communication with the reader was restored. Such behaviour of the tags was noticed for short- and long-term thermal exposure. It is needed only to bear in mind that restoring of data transmission between the reader and the tags is only possible to be guaranteed when temperature of the tags is not above decomposition temperature of materials used for production of RFID tags. The opportunities to enhance thermal behaviour of RFID tags presented in this study may be applicable in other electronic systems used in various facilities. One of them are IoT systems installed currently in the buildings which make them intelligent. So, it is planned in the future to examine sensor elements utilized in such systems with taking special attention to their resistance to environmental factors.

Acknowledgements

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Conflicts of interest

There are no conflicts to declare

Keywords

Passive fire protection, swelling composites, RFID, pipe collar, intumescent grille.

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Graphical abstract

Scheme of identification process of a pipe collar with swelling anti-fire composite material with the use of RFID technology