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ANALYSIS OF HEAT TRANSFER ON THE BASIS OF MULTISPECTRAL IMAGES OF THE ELEMENTS OF CHIMNEYS' STRUCTURE

The article presents an example of the application of non-destructive methods of diagnosing the state of chimneys using thermal imaging equipment and the analysis of the results obtained in such a manner. Thermal imaging studies were conducted on two chimneys of various constructions (brick and steel). The aim of the analysis was to check the exact distribution of the temperature on the surface of the examined objects, assessment of the chimneys' condition and indication of defects in their structure as well as evaluation of their participation in the heat loss of the studied object. The results were the basis for the planning and direction of the repair work of objects and indicated significant usefulness of thermal imaging techniques in the study of objects directly inaccessible.

Key words: heat transfer, multispectral images, infrared camera, visualization methods.

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АНАЛІЗ ТЕПЛОПЕРЕНОСУ НА ОСНОВІ ЗОБРАЖЕННЯ МУЛЬТИСПЕКТРАЛЬНИХ КОМПОНЕНТІВ СТРУКТУРИ ДИМАРІВ

У статті наведено приклад з використання неруйнівних методів діагностики стану димових труб з використанням термічного обладнання візуалізації і аналізу результатів, отриманих таким чином. Тепловізійні дослідження були проведені на двох димових трубах різного будівництва (цегли і сталі). Метою аналізу була перевірка точного розподілу температури на поверхні досліджуваного об'єкта, оцінка стану димоходів, із зазначенням дефектів в структурі і оцінці їхньої участі в тепловтрат об'єкта. Отримані результати послужили основою для планування напрямків ремонтних робіт об'єктів і вказують на корисність тепловізійних методів у вивченні недоступних об'єктів безпосередньо.

Ключові слова: теплопередача, багатоспектральні зображення, інфрачервона камера, методи візуалізації.

Introduction

Multispectral imaging is a technique in which for each pixel of the image, the unique spectral signatures of the observed surface are measured, showing the relations between the coefficient of reflectance and the wavelength [1]. Multispectral image comprises a plurality of channels which are a generalization of the channels of primary colours: R (red), G (green) and B (blue) for any spectral ranges. The data obtained from the scan is described by spatial coordinates (x, y) and the wavelength (λ). This type of imaging in English is called Full Spectral Imaging (FSI).

One of the problems standing in the way of practical implementation of FSI is the speed of image registration in several separate channels associated with bands of wavelengths. To register a multi-channel image in a short time (similar for example to the shutter speed of the camera) a matrix system of sensors (e.g. CCD) is required, with a very high sensitivity and speed of operation and the ability to work in a wide spectral range. Depending on the number of channels under consideration, one may distinguish multispectral (several channels, for example, SPOT satellite - 3 channels) and hyperspectral imaging (several dozen or more channels).

The quality of the imaging device depends not only on the number of spectral channels but also on the spatial resolution and its speed. If only high spectral resolution matters and the measurement is intended to refer to the whole light beam reaching the apparatus (without spatial resolution), the use of a multi-channel spectrometer is the most favourable. In contrast, when the data collection may be performed in arbitrarily long time, both sufficient and the most accurate way is to use a classic spectrometer or a monochromator connected to the broadband photometer [6].

Applications of multispectral imaging are very wide and with the progressive development of technology and the availability of thermal imaging cameras - constantly progressing. Thermography in the initial phase was applied mainly by the army, but very quickly it found application in industry, construction, medicine and other fields of science. In the field of geography, it is used to collect geographic information, in particular in the Land Information Systems. Multispectral data enable getting much more complete information about the area than regular satellite photographs based on the examination of the light reflected by different parts of the area, it is possible to draw conclusions on the nature of rocks and the composition and moisture of soil [2].

In the field of meteorology multispectral images enable testing the distribution of water vapour concentration and the temperature distribution of land, water and air masses. With multi-spectral imaging it is possible to identify objects partially hidden, that are not visible in the images of the traditional colour cameras or through direct observation. Additionally, multispectral photographs of forensic evidence or crime scenes allow quick detection of the micro traces of searched organic substances or chemicals.

Material and methods

The study with thermal imaging camera was conducted on two different chimneys (brick and steel) located on the historic building – the house of the Congregation of the Ursuline Sisters in Lublin, in Narutowicza 10. During taking the measurements, air temperature was approximately 1 ° C and partial variable cloudiness occurred.

Before the relevant measurements were carried out, some preparatory work and initial measurements were conducted. The aim of this work was to determine the proper conditions to perform correct measurements taking into account the position of the investigated objects. Preparatory work before the study consisted of a local vision through which it was possible to determine the location of measuring stations, distribution of measuring stations, performance of test measurements, elaboration of test measurements and adjustments of the measuring stations and measurement conditions. Upon completion of the external inspection of the building and its surroundings and the analysis of the results of preliminary measurements, 5 measurement stations were set. With the infrared camera six different types of images can be generated: multispectral, thermal, thermal fusion, heat penetration, simple digital photograph, picture in picture.

Multispectral images were taken using FLIR infrared camera7440bx with lens FOL 18 mm and resolution of infrared detector 320x240 while the image processing was carried out in Flitr programme. The subjects of the analysis in terms of heat flow were two industrial chimneys made with different techniques. Infrared images were taken in winter at the outside temperature of 1 ° C. An important factor taken into account during the test was the material from which the objects were made. This is a condition necessary to determine the emissivity of the material. The level of emission is within the range from 0.1 to 0.95 (i.e. for a brick chimney it is approximately 0.94). Transmission of radiation also depends on the distance between the camera and the analysed object, which in this study was 5m. The relative air humidity was determined at the level of 50% [5]. For proper display of the objects, a large number of thermal images were made, and arranged in a way that ensures correct readings.

Presentation of the case

Figure 1 shows a thermal image of a infrared camera generated with a report, which is obtained after the test. The image was taken on February 4, 2015 at 10:59. The photo shows stainless steel chimney with a part of the facade. The surfaces have an emissivity of 0.95, which guarantees credibility of the presented temperature distribution on the chimney and on the facade. The pictures were taken from a distance of 5 m. Reflected temperature is 20 ° and it is convergent with the temperature of the external optical system. The air temperature in turn is 0°C and the external transmission of the optical system 1 ° C. The temperature range registered by the camera is in the range of -3 ° C at the coldest spot to 22.1 ° C in the warmest. With the camera used to the tests, the temperature can be measured at any point. In Fig. 1 this point was designated as "Sp1", the temperature in the indicated point is 5.8 ° C.

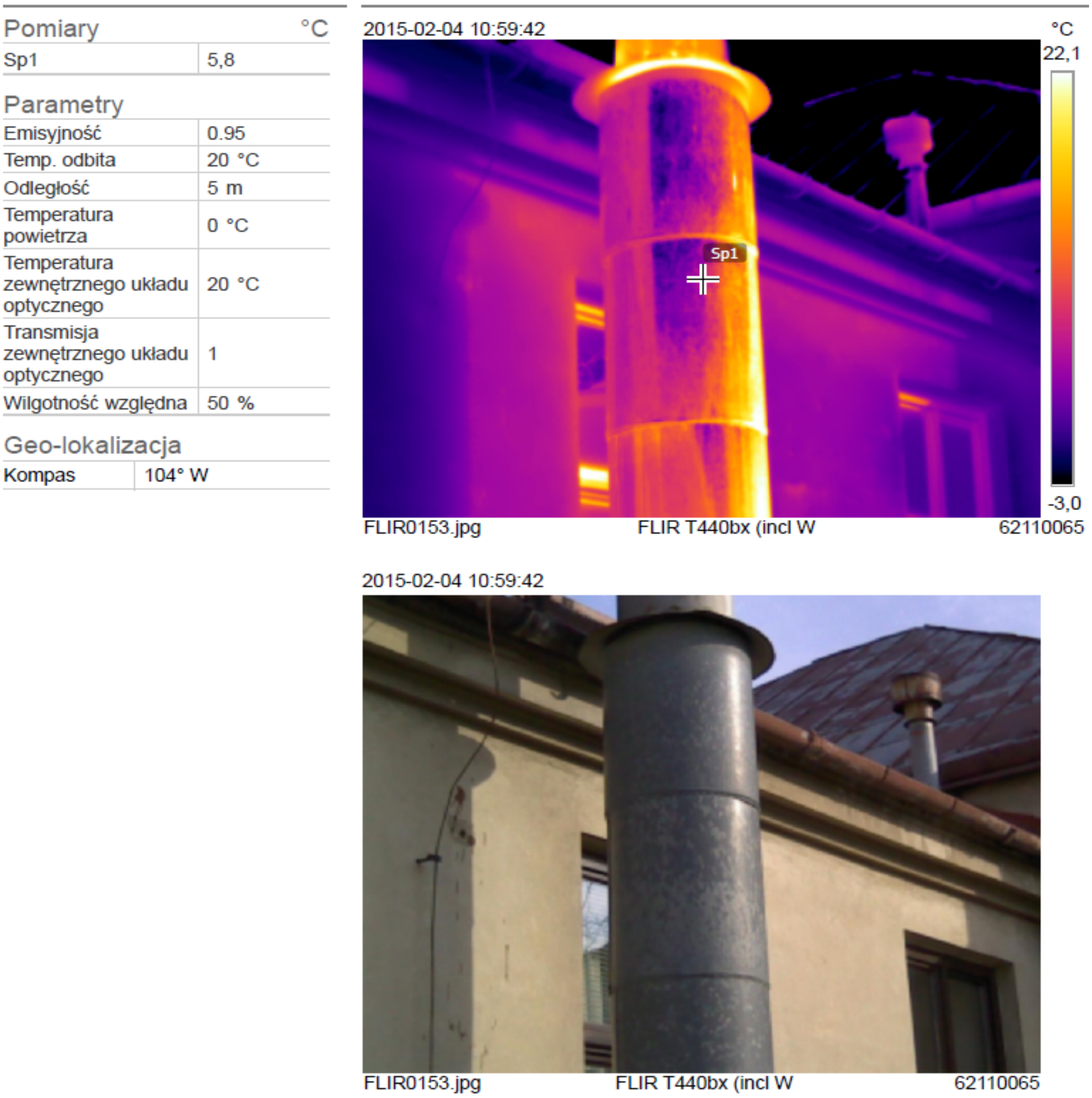

Fig. 1. Report

A place where the temperature is the lowest in Fig.2 is located on the roof on the right side of the image. This is the place where the temperature is -3,3 ° C, and beneath the spout in the chimney which is a place reached by a small amount of the sun's rays. The places marked with ovals are the ones in which measurement errors could possibly occur. Window frames made of plastic, have a higher reflectivity than the surrounding elements, which means that a high value of temperature which was recorded in these areas is the result of reflection of sunlight. It can be inferred from the fact that the right part of the window is still in the shadow of a building and in this place high temperature was not recorded [3].

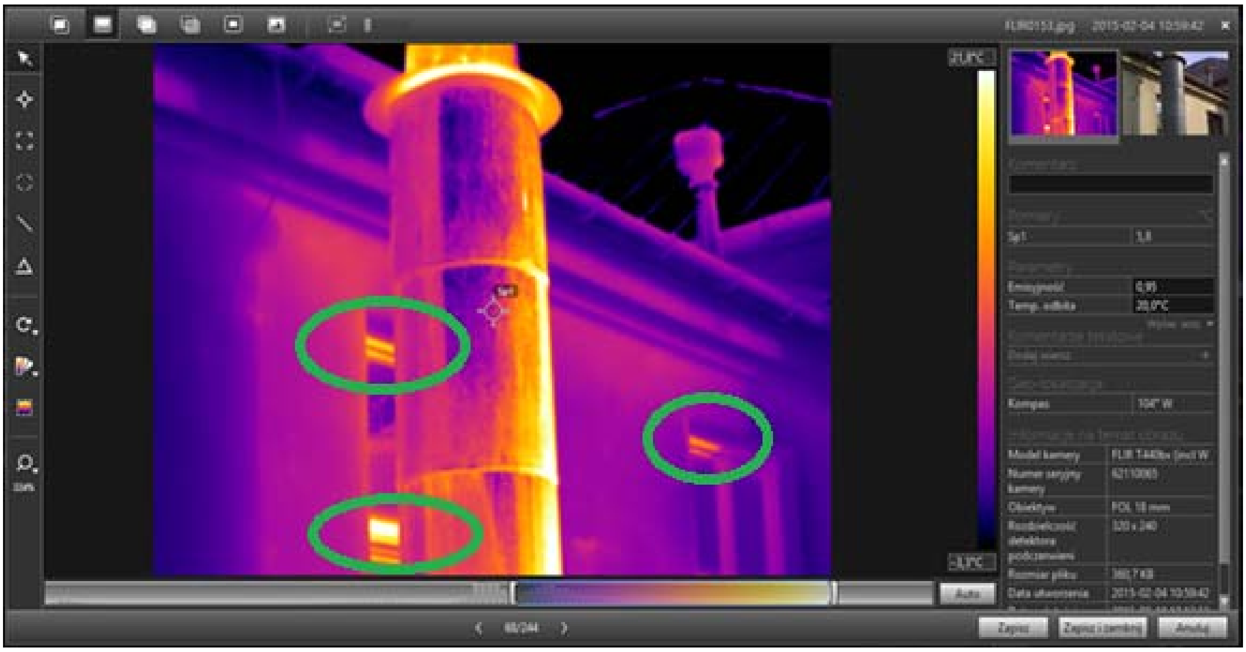

Fig. 2. Multispectral image

Fig. 3 presents thermal fusion which is a combination of digital and thermal image in the desired range of temperatures. These places are marked in green. The emissivity of the picture is the same as in the case of other images and equals 0.95. Reference range of temperature is also similar, ie. from -3.3 ° C to 22.8 ° C. The temperature at the point "Sp1" is 5.8 ° C. The temperature distribution visible on the surface of the chimney is caused by the uneven insulating coating, as well as the diversity of surface reflectivity. In some areas the insulation layer covering the stainless steel chimney is thinner and hence resulting in higher values of the temperature. In addition, these sites have a small heat capacity and heat up in shorter time than properly insulated elements.

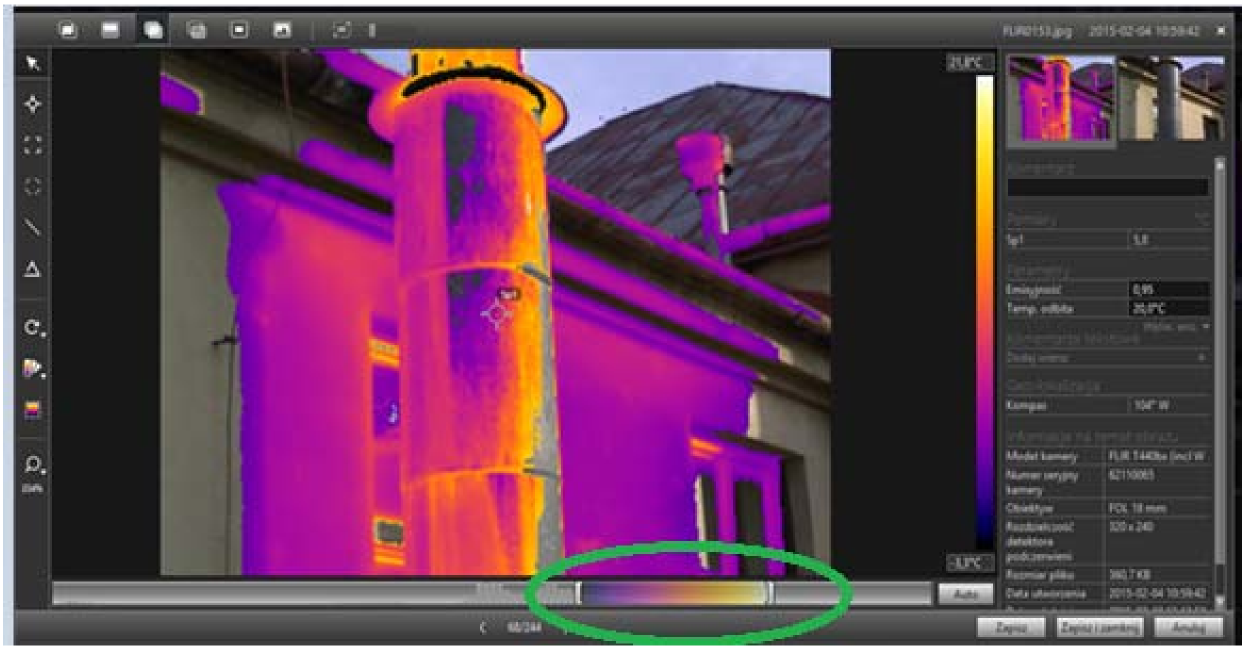

Fig. 3. Thermal fusion of the steel chimney

Fig. 4 shows heat transfer. This means that the thermal image presented on the digital image is generated in a temperature range shown on the horizontal scale. The range of variables of temperature and other parameters do not change. The execution of such a photo only shows positive values in the image, there are no marked places where the temperature is below zero as the selected range of the scale was limited to the values from about 5 to 15 ° C. The function of thermal transmittance allows seeing better the outline of the building of the chimney and its individual elements. The colour was founded to allow presentation of the background of a digital image.

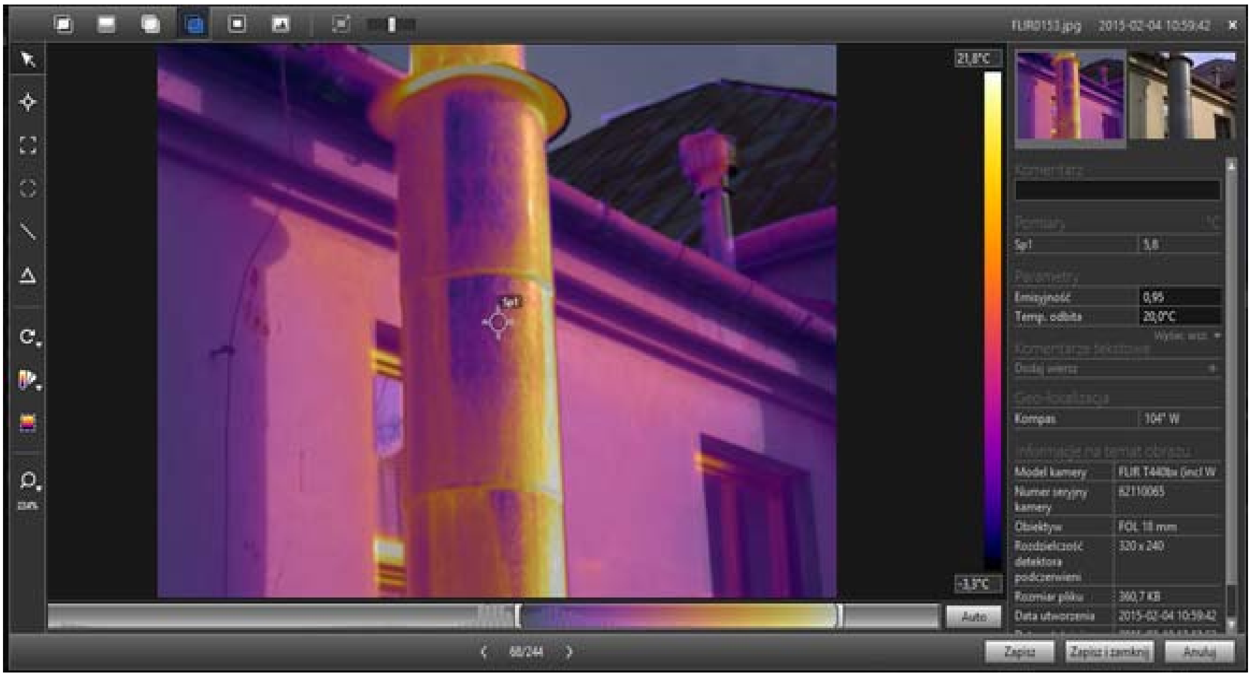

Fig. 4. Heat transfer on the example of steel chimney

Discussion of the results

The next figures show the measurement results in the form of images from the infrared camera of the upper part of the chimney. Fig. 5 presents a view of the finished report generated in the Flir program. These photos were taken on the same day as the previous ones. The picture was taken at 11:03. It was found that the emissivity of the surface is maintained at the standard level of 0.95 so the image accurately reflects the temperature distribution on the surface of the chimney. The distance is 5 m, the angle of the camera, however, changes, resulting in decreased accuracy of the temperature measurement in the selected area. The transmission of the external optical system and the air temperature are not variable. The temperature range changes from -4.3 ° C for the coldest spot to the maximum of 24 ° C. At the test point marked as "Sp1", the temperature is 7.4 ° C. The program prepares a report with two photographs: the first image is a multi-spectral picture; the second one is a simple digital image. The image was taken with the digital zoom. In Fig. 5 there are highly visible changes in the temperature distribution in the spots of the loss of the coating protecting the chimney against rust. The highest temperature occurs in the areas where the coating is missing or is very thin. Metal ladder leading to the top of the chimney located in the shadow of the north side is cooled and has temperature lower than the air temperature measured from the south side. It can be expected that the measurement conducted on the north side would lead to the receipt of different images of temperature distribution [4]. However, due to the location of the chimney, there was no such possibility. It was considered that the differences are predictable and therefore less important.

The thermal fusion in Fig. 6 does not represent the most extreme values. It is a combination of the thermal image with the digital one in the range shown on the horizontal scale, i.e. from approx. 5 to 15 ° C. Reflected temperature is 20 ° C. Like in the case of the other pictures, the lens and the resolution of the infrared detector were not changed. The use of digital zoom in the camera may slightly interfere with the reading of the temperature distribution. In the picture it is not possible to locate the area where the temperature reaches the maximum value of 30.7 ° C - the reason for this may be too long distance from the surface of the image covered by the measurement.

Another image shows the distribution of temperatures on the steel chimney itself, but without the zoom. In the image presented in Fig. 7, the temperature distribution is in the range from -3 to 30.7 ° C. In the selected point "Sp1" the temperature is 8.6 ° C. As in the other cases, on the chimney there are considerable differences in temperature. The colour scale assigned to the temperature values is consistent with the scale of the electromagnetic wavelength of the spectrum deployed. It corresponds also to greyscale in non-colour images. The regions of the lowest temperature in the tested range were those of the maximum density.

Pomiary	°C
Sp1	7,4

Parametry	
Emisyjność	0.95
Temp. odbita	20 °C
Odległość	5 m
Temperatura powietrza	0 °C
Temperatura zewnętrznego układu optycznego	20 °C
Transmisja zewnętrznego układu optycznego	1
Wilgotność względna	50 %

Geo-lokalizacja	
Kompas	95° W

2015-02-04 11:03:34

FLIR0164.jpg FLIR T440bx (incl W 62110065

2015-02-04 11:03:34

FLIR0164.jpg FLIR T440bx (incl W 62110065

Fig. 5. Photo report of the steel chimney

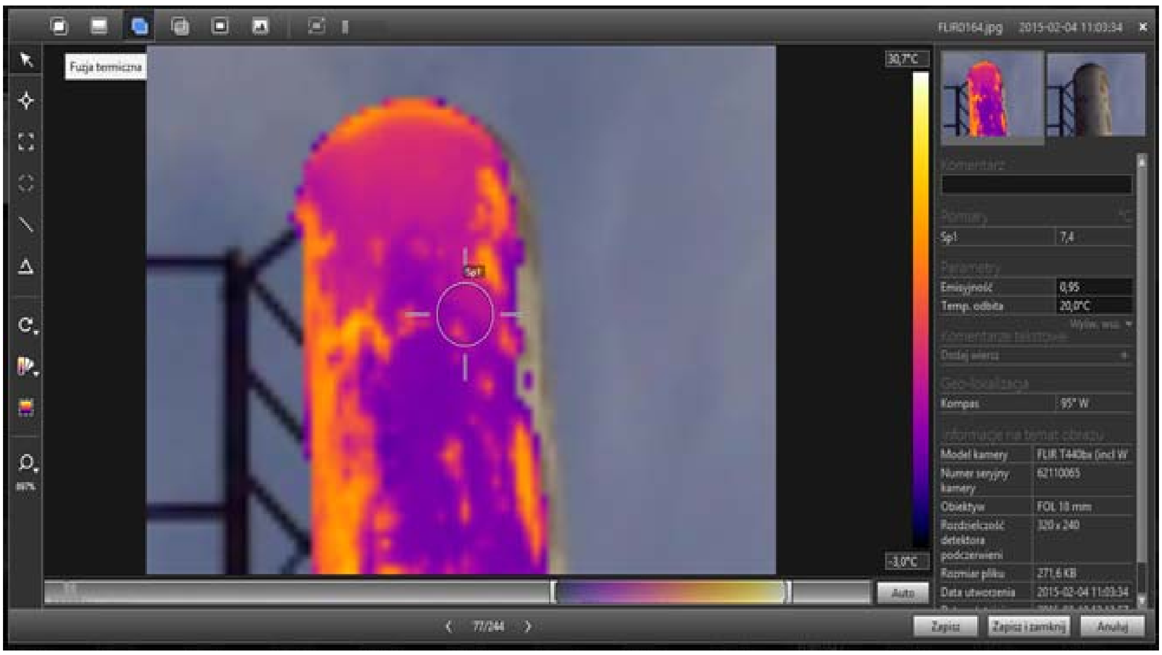

Fig. 6. Thermal fusion of the top of the steel chimney

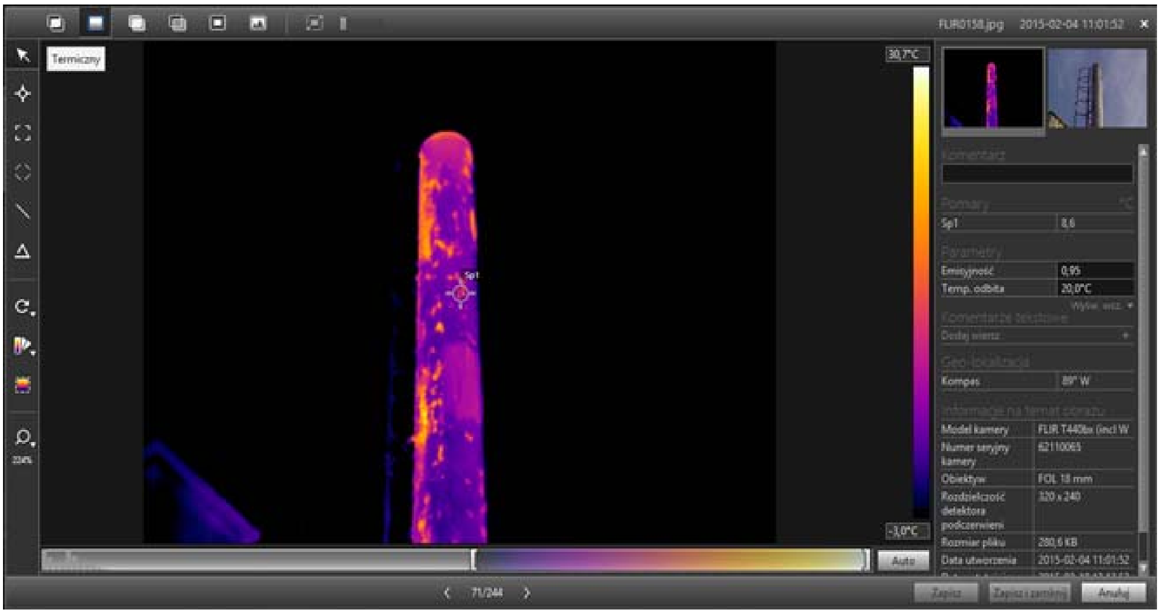

Fig. 7. Thermal image of the steel chimney

Another object of the tests and measurements is a brick chimney located in the same building near the previously described steel chimney. The date of measurements with infrared camera of the brick chimney is February 4, 2015 at 11.08 on the sunny weather. Emissivity, distance, transmission of the external optic system and other parameters remained unchanged. Again, the report of camera test presented in Fig.8 was prepared.

Pomiary		°C
Sp1		0,3
Li1	Max	4,5
	Min	0,5
	Average	2,3
Li2	Max	0,8
	Min	-3,4
	Average	-1,1

Parametry	
Emisyjność	0.95
Temp. odbita	20 °C
Odległość	5 m
Temperatura powietrza	0 °C
Temperatura zewnętrznego układu optycznego	20 °C
Transmisja zewnętrznego układu optycznego	1
Wilgotność względna	50 %

Geo-lokalizacja	
Kompas	93° W

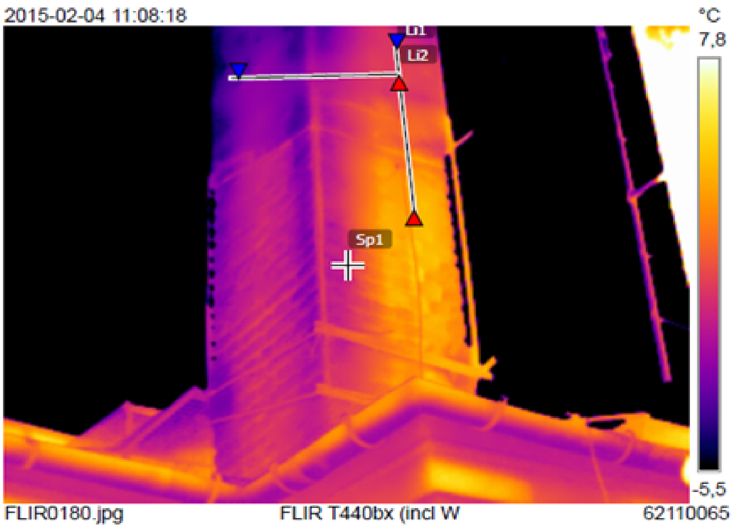

Fig. 8. Report regarding the brick chimney

The report in Fig. 8 shows that the temperature range is from -5.5 to 7.8 ° C. The temperature distribution on the brick chimney is very regular; there are no big differences in temperatures. This can be observed concerning the temperature range in which the amplitude is significantly lower than in the case of the steel chimney. Additionally, the measurement points were marked, in „Sp1" the temperature is 0.3 ° C. Using the camera's capability, linear measurement of the temperature distribution on the surface of the object was made. These lines were successively marked with symbols "Li1" and "Li2." This feature allows for more accurate temperature reading. In the case of "Li1" the temperature was measured at the beginning and at the end of the line, the maximum temperature is 4.5 ° C and the minimum 0.5 ° C while the average temperature in this section is 2.3 ° C. For the "Li2" section, the maximum temperature is 0.8 ° C and minimum -3,4 ° C. The average temperature of this section is -1.1 ° C.

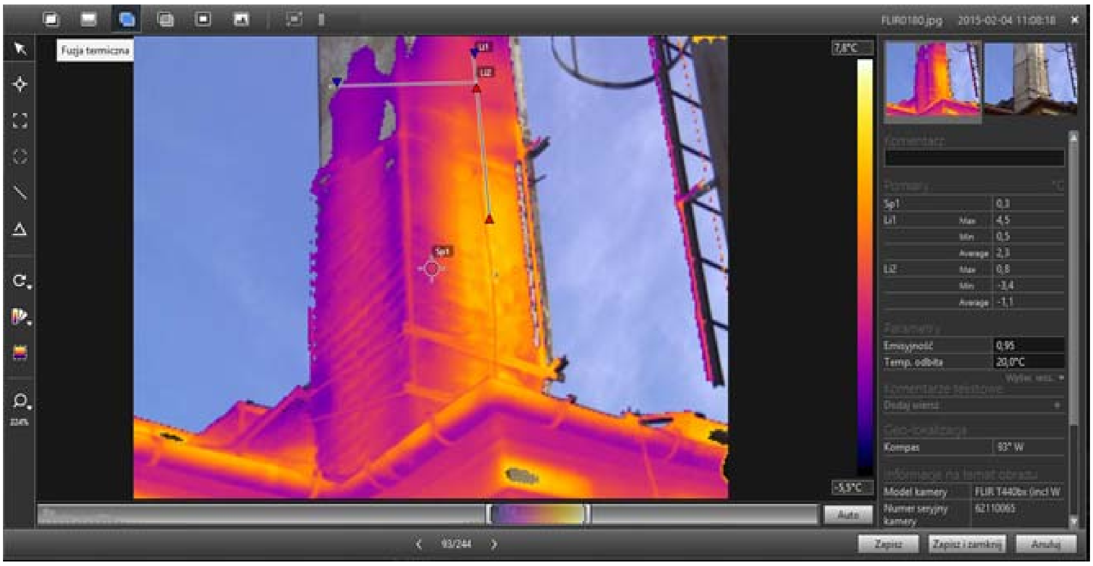

Fig. 9. Thermal fusion of the brick chimney

Figure 9 shows the thermal fusion. In the photo the extremes of temperature are not indicated. It is thus noticeable which areas have the highest and which the lowest temperature. In this photo the highest temperature occurs on the steel chimney that was in that part of the image presented as an ordinary digital image. The lowest temperature is maintained at the left side of the brick chimney. Places marked in yellow are the spots reaches by greater amounts of sunshine.

The heat penetration shown in Fig, 10 has the same temperature range as in the case of the other images relating to the brick chimney. The figure shows also the sections determined by the thermal imaging camera. Under "Sp1", the temperature is 0.3 ° C. In the "Li1" section, the highest temperature recorded was 4.5 ° C, and the lowest was 0.5 ° C. The average temperature for this section was 2.3 ° C. For the "Li2" section, the maximum value recorded was 0.8 ° C while the lowest was -3.4 ° C and the average temperature for the "Li2" section is equal -1.1 ° C.

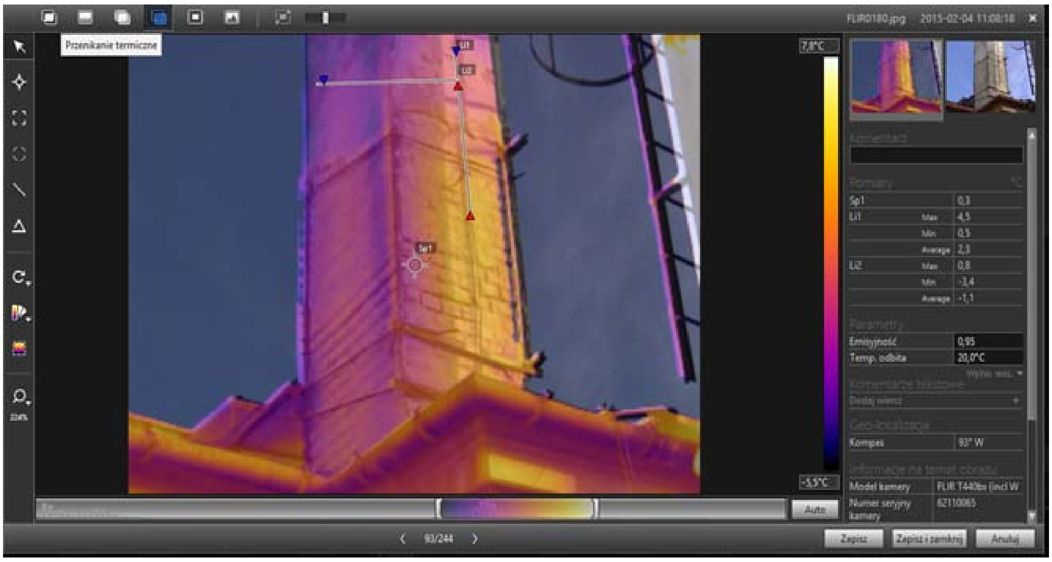

Fig. 10. Heat transfer in the case of the brick chimney

During the performance of the tests 5 measurement stations were used, enabling the correct processing of received measurements. Comparison and analysis of the generated thermal images in terms of temperature distribution, maximum and minimum values made it possible to determine the general condition of the structure of each of the chimneys. They were determined The places where there are defects and irregularities causing a leak of objects' walls were determined [1].

The studies demonstrated that the brick chimney that was subject to analysis was characterised by proper insulation, the temperature distribution on its surface was regular despite visible cavities in the structure. On the basis of the thermal images could also be concluded that the chimney was not used at the time of measurement. On the second of the analysed chimneys, made of steel, there were observed defects in the surface layer designed to protect the facility against corrosion. In areas of chipping paint there were significant differences in values between the isotherms of up to 27 ° C.

Conclusions

The reasons for any errors of thermal imaging measurement methods during these tests may include an error related to incorrect estimation of the object emissivity. The capabilities of the camera should be also taken into account as it is not always possible to accurately and remotely measure the temperature of the object and to eliminate the influence of an incorrect estimation of emissivity on the measurement accuracy. Another issue that should be taken into consideration is the impact of the ambient radiation reflected by the tested object. The importance of this radiation increases the more, the lower the emissivity of the object is. The measurements are the basis for the beginning of the repairment or safety work of the objects under study. The occurring defects such as cracks and damage to the material were determined, which are not visible in direct observation. The obtained values of the measurement results will feed a database used by the authors to verify the simulation analysis of heat transfer in numerous unique elements of construction objects.

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