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Combustion Heat Release Estimation by Means of Thermal Imaging

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Infrared thermography has for many years been used as a standard and reliable method for non-destructive testing of various materials. The paper presents additional applications of the method – for monitoring combustion of different materials and tracking undesirable ignition of certain liquids, gases and coals. It also includes a quantitative analysis of flame temperatures during combustion of samples of different materials

Key words: **infrared thermography, thermal image, combustion monitoring.**

Introduction

INFRARED thermography is a suitable contactless method for estimating temperature and recording the temperature distribution on the surface of an object. Depending on the test approach, the method can be either passive (qualitative) or active (quantitative) [1, 2]. In both cases, the result is a thermal image (IR frame).

In the former, passive, case, the temperature of the test object is only compared to the ambient temperature, so the measurement does not affect the heat balance. However, in the latter, active, case there is an external heat source that acts on the surface of the test object, after which temperature is monitored. Apart from there being no contact, IR thermography is non-destructive and can be used for remote and real-time testing [1].

The first devices of this type were designed for military purposes, to improve visibility during nighttime surveillance, as well as in poor daytime visibility conditions due to inclement weather. However, improved modern devices and increasingly affordable prices have extended applicability to all fields of science and industry. In recent years, based on user requirements, more attention has been devoted to portable IR equipment, including thermal imaging cameras. The majority of contemporary thermal cameras include IR detectors in the focal plane array (FPA).

The most frequently encountered sensors in them are based on narrow-band semiconductors that require cooling. The need for cryogenic technology makes these devices more complex and they are consequently costlier. Discussing cooled thermal cameras would be a thankless task.

Moreover, the best models from recognized manufacturers are subject to export restrictions or their use for commercial purposes requires special permits. The development of IR technologies is incredibly rapid, and improvements in IR materials, thermal imaging cameras and IR systems target high resolution and better performance, although this is still hindered by the inability of leading laboratories to cooperate, mostly because of primarily military and security applications.

The appearance of IR detectors that operate at room temperature – so-called "uncooled" thermal cameras – has revolutionized IR thermography. Namely, the latest technologies offer thermal cameras with "uncooled microbolometers", which are less expensive because they do not require cooling (but the resolution of even the best models is 640 × 512 pixels).

The prices of such thermal cameras have been rapidly dropping in recent years, so they are increasingly being used for commercial purposes. The latest research in this area aims to improve detectivity – which opens new application prospects.

Today, the development of IR equipment focuses on lower production costs of bolometric detectors, while at the same time improving detectivity, portability, the use of FPA for better resolution, and the ability to operate at high temperatures. Low-performance microbolometric matrices are becoming more and more popular.

These days the use of IR thermography is truly widespread. In addition to already being a standard method for testing and assessing of materials, there is virtually no industry (construction, energy, chemical, transportation, mining) or science (human medicine, veterinary medicine, biology, geology, spectroscopy, investigation of cultural heritage) where it is not represented.

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In the past several years, parallel to standard video surveillance, it has begun to be used for equipment monitoring in various manufacturing processes, mining operations and environmental protection [3-10].

Another application of IR thermography, unreported in available literature as far as the authors are aware, is described in the present paper, namely for monitoring combustion of various fuels, both liquid and solid, to assess their calorific value and also prevent self-ignition.

Types of samples

The samples whose combustion was monitored included both liquid and solid fuels. The flammable liquids were those whose ignition temperature is below 60°C and which need to be handled per applicable legislation. These samples included pure alcohol and a mixture of 50% alcohol and 50% plum brandy. The solid samples were coal, beech wood pellets, and cellulose.

At open-cast mines, where mining operations involve a lot of machinery and manpower, ore extraction monitoring systems, especially in the case of coal due to possible self-ignition in the summer months, increasingly include IR thermography in parallel with video surveillance. Also, the quality of coal is one of the major issues of thermoelectric power plants. Namely, an inadequate calorific value (less than 6 MJ per ton of coal) requires additional fuel oil to improve the calorific value during combustion.

Moreover, low-calorie coals and fuel oil increase harmful gas emissions by thermoelectric power plants, potentially violating stringent European legislation.

Checking of the calorific value of coal requires incineration of coal samples under laboratory conditions, so-called bomb calorimetry, which further complicates coal extraction at open-cast mines where the mining machinery is in service 24/7 and any alternative method for assessing the calorific value of coal is welcome.

One of the solid samples whose combustion was monitored by IR thermography was of “Crown Forest Pellets”.

Wood pellets are a modern (high-calorie, biodegradable) heating fuel, whose use for heating of homes has become widespread. They are made by pressing lumber industry wastes (bark and sawdust), at high temperatures and pressures, with no binders, chemicals or additives. The sample was cylindrical, diameter 6 mm and 35 mm long. The length varies, generally from several millimeters to several centimeters, but the 35 mm length was used in the experiment for practical reasons – to attach one end and monitor combustion of the other.

Experimental equipment

The well-known manufacturer *FLIR Systems* was among the first to launch the *Lepton* 2.0 thermal camera core in Android [11]. The core is based on an FPA uncooled microbolometer, 80 x 60 pixels, for a long-wavelength infrared (LWIR) range from 8 µm to 14 µm. The pixel size is 12 µm and the temperature sensitivity less than 50 mK.

It can be used to locate warm or cool air losses from homes, heat losses through windows or insulation, and moisture sources in buildings, as well as to detect overloaded power lines, pipes behind walls or under floors, check the radiation energy of floor heating, and for many other applications driven by users’ imagination [11].

One such thermal camera, coupled with a CAT S60 mobile phone, was used in this experiment. The results are thermal images in flir_T10221. jpg format.

The distance of each sample from the thermal camera was always the same in the experiment - 1 m. The room temperature in the laboratory was 20°C and the humidity 45%.

Results and discussion

The combustion of different liquids in two identical cups was captured. The first cup contained a mixture of 50% alcohol and 50% plum brandy, and the second 100% plum brandy.

Fig.1 shows one of the frames captured in flir_20180422T112333.jpg format. The parameters of the recording sequence were: emissivity 0.9; distance of the camera lens from the test object (cup with burning liquid) 1 m; room temperature measured by thermometer 20ºC; and ambient temperature estimated by camera 25ºC. Each IR image was accompanied by a temperature scale whose range was approximately 19ºC to 150ºC.

The thermal images showed, as expected, that flame intensity changed as a function of height.

Fig.2 shows two curves. The red curve is the temperature profile along marker line LI02, identified on the thermal image in Fig.1 (mixture of alcohol and plum brandy). The maximum temperature on the marker line was 119.4ºC. The black curve is the temperature variation along marker line LI01, which was much closer to the plane of the cup holding 100% plum brandy. The maximum temperature on this marker line was 119.7ºC.

Table 1 shows maximum and average temperatures on the marker lines. The marker lines were positioned above the samples whose combustion was monitored. The test samples were in either liquid or solid state. H is the distance from the marker line to the surface of the sample (expressed as the number of pixels).

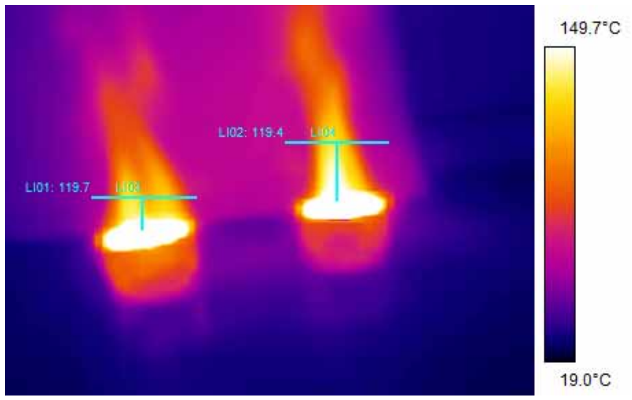

Figure 1. Thermal image of two burning liquids captured by FLIR CAT S60 camera: Left – pure plum brandy; right – mixture of plum brandy and alcohol

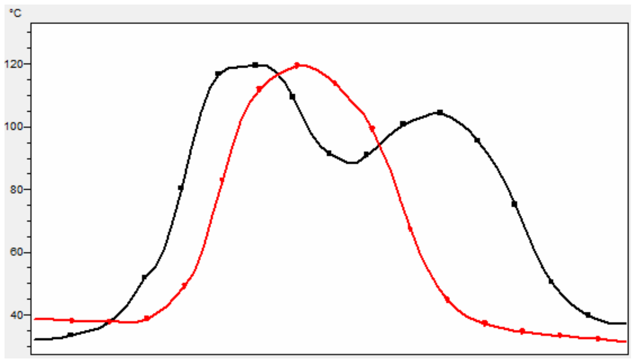

Figure 2. Temperature profiles of marker lines during combustion: Red – mixture of plum brandy and alcohol; black – plum brandy

The heights of the flames (distance from the cup plane to marker lines LI01 and LI02) differed.

The maximum temperatures measured along the marker lines were roughly equal, about 120ºC.

However, given that the combustion temperatures of the liquids were different, the alcohol and plum brandy mixture burned more intensely than pure brandy (i.e. left cup compared to the right cup).

Table 1. Maximum and average temperatures on the marker lines across the flame

Sequence	$T_{max,L}$ (ºC)	$T_{max,R}$ (ºC)	*H* (*px*)
T112333.jpg	78.3	116.2	38
T112335.jpg	81.4	117.3	38
T112335.jpg	40.7	112.6	51
T112103.jpg	39.8	119.1	83

The thermal image shown in Fig.3 belongs to sequence flir_20180422T112456.jpg and was captured 83 seconds after the flame was extinguished.

This thermal image, too, has marker lines, for which temperature profiles are shown in Fig.4.

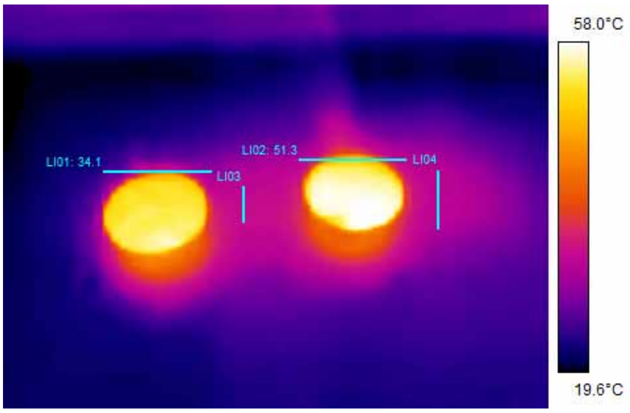

Figure 3. Thermal image captured by FLIR CAT S60 camera after combustion: Left – pure plum brandy; right – mixture of plum brandy and alcohol

Fig.4 shows two curves. The red curve is the temperature profile of marker line LI02, identified in Picture 3 (mixture of alcohol and plum brandy). The maximum temperature on that marker line was 51.3ºC. The black curve is the temperature variation along marker line LI01, positioned closer to the cup plane (like marker line LI02), which contained 100% plum brandy. The maximum temperature on this marker line was 34.1ºC.

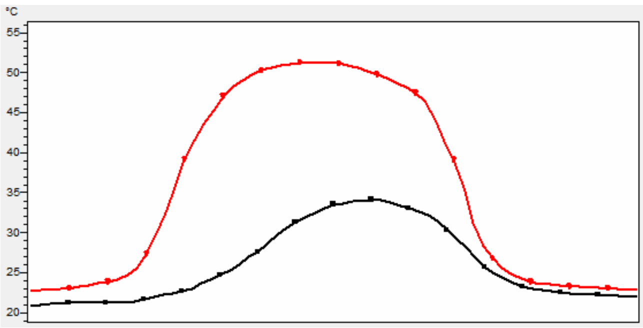

Figure 4. Temperature profiles of marker lines after combustion: Red – mixture of plum brandy and alcohol; black – plum brandy

Fig.5 shows one of the thermal images of an igniting coal surface (1106th frame of the sequence). Numbers 1 and 2 denote blue and green marker lines along which the temperature profile shown in Fig.6 was assessed. The maximum flame temperature of a commercial lighter used to ignite the coal was monitored along blue marker line 1, and the combustion temperature along green marker line 2. It should be noted that these images were captured by thermal camera FLIR SC7200, which includes a matrix of 320 × 256 InSb-based semiconductor detectors in the FPA. This thermal camera was designed for the first two atmospheric windows, or more precisely the 1.5 – 5.1 µm wave range. It is equipped with standard 50 mm optics and the field of view is 11° × 8.8°. [12]

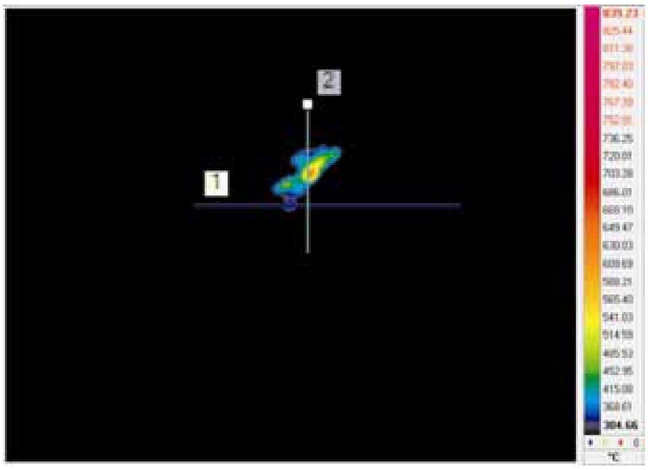

Figure 5. Thermal image of igniting coal captured by FLIR SC7200 camera, sequence *Capture1455*

Fig.6 shows two curves. The green curve is the temperature profile of marker line 2, identified on the thermal image in Fig.5 (burning coal surface). The maximum temperature on this marker line was 598ºC. The blue curve is the temperature variation along marker line 1, positioned across the lighter flame. The maximum temperature on that marker line was 383ºC.

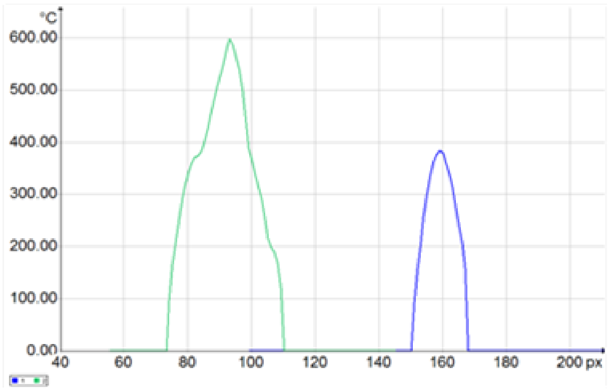

Figure 6. Temperature profiles of the marker lines shown in Picture 5

Fig.7 is one of the thermal images of a burning piece of paper (582nd frame of the captured sequence). Numbers 2 and 3 denote the green and blue markers lines along which the temperature profiles shown in Fig.8 were assessed.

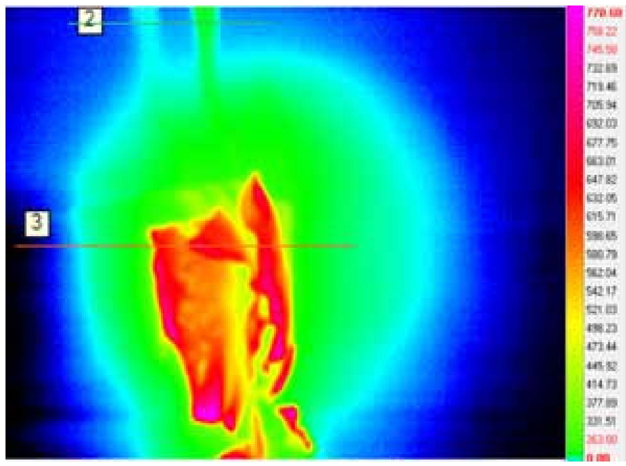

Figure 7. Thermal image of igniting piece of paper captured by FLIR SC7200 camera, sequence *Capture1454*

Fig.8 shows two curves. The green curve is the temperature profile of marker line 2 shown in Fig.7 (flame above burning paper). The maximum temperature on that marker line was 220ºC. The brown curve is the temperature variation along marker line 3, positioned across the burning paper. The maximum temperature on that marker line was 700ºC.

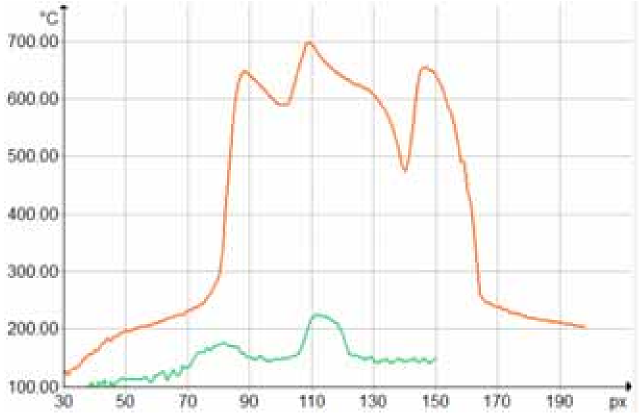

Figure 8. Temperature profiles of the marker lines identified in Picture 7

Fig.9 shows one of the frames captured in flir_20180422T132121.jpg format. The parameters were: emissivity 0.9; distance between lens and object (wood pellet attached on one end and burning on the other) 1 m; room temperature measured by thermometer 25ºC; and ambient temperature estimated by camera 24.4ºC.

The IR image was accompanied by a temperature scale whose range was approximately 19.6ºC to 150ºC. As expected, the thermal image showed that flame intensity was lower along marker line Li1, from T_{min} = 24.4ºC at the ends of the flame to T_{max} = 78.4ºC in the middle.

The wood pellet was at room temperature prior to lighting. The pellet temperature at marker point Sp1 shown in Picture 9 (positioned in the middle of marker line Li1) was 75.6ºC, while at Sp2 near the glowing pellet which had not yet ignited it was 119.2ºC.

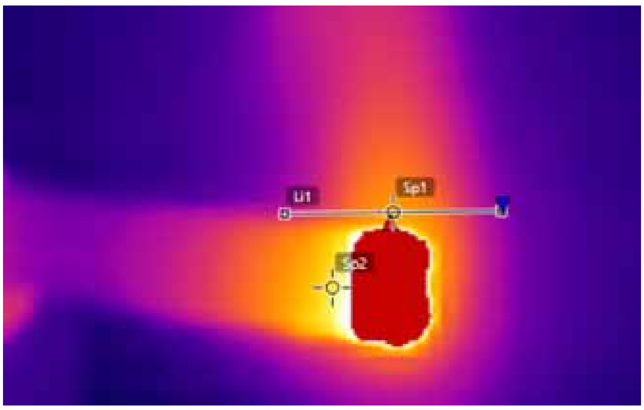

Figure 9. Thermal image of burning solid fuel (wood pellet) captured by FLIR CAT S60 camera

Fig.10 shows two identical cups. Their diameter is 23 mm and they are 30 mm high. Both are half-filled with 25 ml of flammable liquids.

The cup on the left contains 100% plum brandy and the cup on the right a mixture of 50% plum brandy and 50% commercial alcohol.

Marker lines L1 and L2 on the image are positioned at the same distance above the cups, and the two liquids (pure brandy in the left cup and a mixture of 12.5 ml each of plum brandy and commercial alcohol in the right cup) are burning simultaneously.

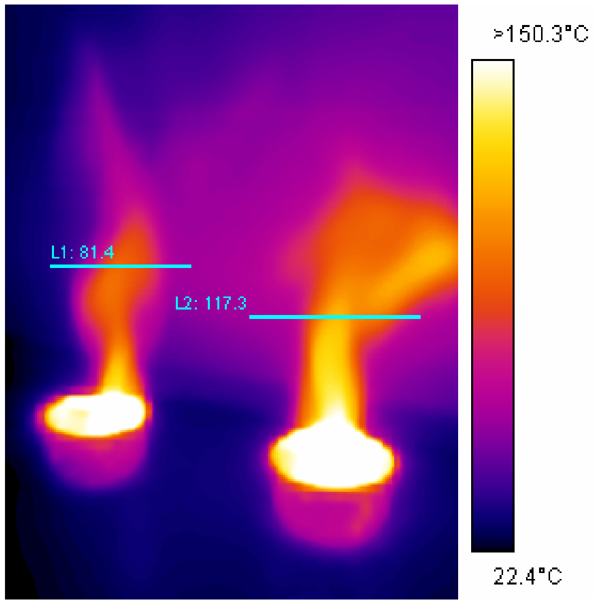

Figure 10. Thermal image captured by FLIR CAT S60 camera after combustion: Left – pure plum brandy; right – mixture of plum brandy and alcohol

Fig.11 shows two curves. The red curve is the temperature profile along marker line L2, identified on the thermal image in Fig.10 (mixture of alcohol and plum brandy).

The maximum temperature on the marker line was 117.3ºC. The black curve is the temperature variation along marker line L1, which was much closer to the plane of the cup holding 100% plum brandy. The maximum temperature on this marker line was 81.4ºC.

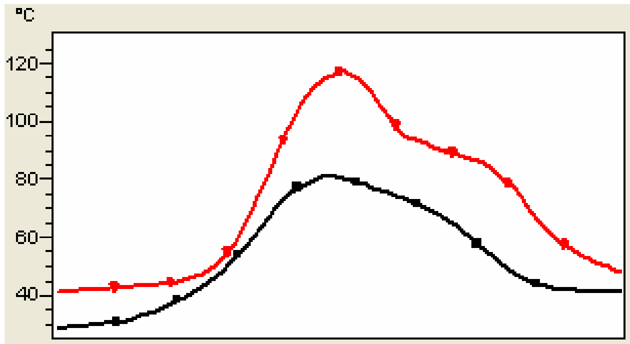

Figure 11. Temperature profiles of marker lines during combustion: Red – mixture of plum brandy and alcohol; black – plum brandy

Table 2 shows maximum temperatures in the flame measurement range, during combustion of the test samples (liquid and solid), measured above the sample, for comparison.

Table 2. Maximum flame temperatures above liquid and solid samples (CAT 60 camera)

T_{max} (°C)					
100% Alc.	100% Plm	Plm 50% Alc. 50%	Gas	Paper	Wood pellet
25 ml	25 ml	12.5 ml 12.5 ml	Commercial lighter	A4	Crow Forest
112.6	40.7	-	68.8	91.4	78.4
-	78.3	116.2			

Fig.12 shows the thermal images of a burning piece of paper (captured by FLIR CAT S60 camera). The maximum temperature on marker line Li1 was 91.4ºC (minimum and average temperatures were 39.7ºC and 75.0ºC, respectively).

Figure 12. Thermal image captured by FLIR CAT S60 camera after combustion: Left – burning paper (cellulose); right – maximum temperature along flame marker line was determined

Fig.13 shows the previously-stated main parameters of the experiment and the image of a burning piece of paper (photograph of captured sequence frame of burning paper (cellulose)).

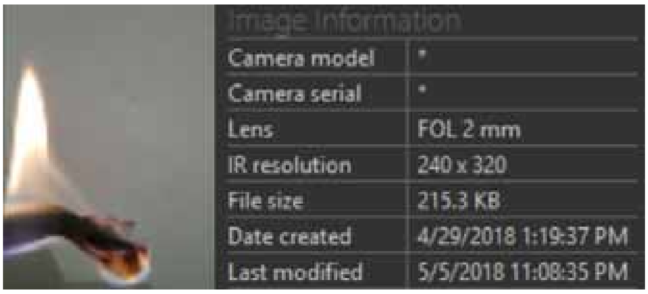

Figure 13. Main experiment parameters during combustion of solid fuel: Left – photograph of burning paper (cellulose); right – parameters of thermal camera FLIR CAT S60

Fig.13 shows burning paper (cellulose) and image information (lens FOL 2 mm, IR resolution, file size and date created).

Conclusion

Infrared thermography strives to achieve the highest possible performance at the lowest cost. New technologies have contributed to enormous advances in infrared devices and have made breakthroughs into new markets, but also new applications – monitoring of automated processes in many industries and ambient control.

The paper presented the first step in the estimation of the calorific value of flammable fluids and solid fuels, based on combustion monitoring by infrared thermography. The equipment used in the experiment is commercially available and affordable.

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Procena količine oslobođene toplote sagorevanja termovizijskom kamerom

Infracrvena termografija se već dugi niz godina koristi kao standardna i pouzdana metoda pri nedestruktivnom testiranju različitih materijala. U radu su navedene još neke mogućnosti primene ove metode - za praćenje procesa sagorevanja različitih materijala i za praćenje procesa neželjenog zapaljenja pojedinih tečnosti, gasova i ugljeva. Izvršena je kvantitativna analiza temperatura plamena pri sagorevanju uzoraka različitih materijala.

Ključne reči: **termografija, IC termografija, termogram, sagorevanje, toplota sagorevanja, plamen, kvantitativna analiza.**

Оценка количества свободной последующей теплоты сгорания термовизионной камеры

Инфракрасная (ИК) термография уже много лет используется в качестве стандартного и надёжного метода неразрушающего контроля различных материалов. Другие возможности применения этого метода приведены в статье - для контроля процесса сгорания различных материалов и для мониторинга процесса нежелательного воспламенения определённых жидкостей, газов и угля. Проведён количественный анализ температуры пламени при сгорании образцов различных материалов.

Ключевые слова: **термография, ИК-термография, термограмма, сгорание, теплота сгорания, пламя, количественный анализ.**

Estimation de la quantité de chaleur libérée de combustion au moyen de la caméra de thermo vision

La thermographie infrarouge est employée depuis des années comme une méthode habituelle et sûre pour les tests non destructifs des matières différentes. Dans ce papier on a cité quelques unes des possibilités de l'utilisation de cette méthode pour le suivi du processus de l'ignition non désirée chez certains liquides, gaz et charbons. On a fait une analyse quantitative de la température de flamme pendant la combustion des échantillons de matériaux variés.

Mots clés: **thermographie, thermographie IR, thermographe, combustion, température de combustion, flamme, analyse quantitative.**