http://dx.doi.org/10.21611/qirt.2004.096

A new experimental techniques for inspection of operating furnaces by use of IR radiometers

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Abstract

The main special feature of elaborated techniques is the dynamic IR thermography, which bases on forming single images which consist of pixels of chosen statistical value, minimum and maximum, noted during adequately long sequence of thermograms with total independence to the moment of its capture. Arrays of these data can be used directly, or as inputs to other artificial images. This paper presents elements of the measuring set which consists from contact and non-contact devices and specialised software. Due to this method, the final “artificial thermogram” offers quality impossible to achieve with a classic “one shot” or “mean thermogram” methods. Many other applications could take advantage of presented idea, algorithm and tools.

1. Introduction

The temperature measurements in operating furnaces are very important tasks world-wide, for many economical and safety reasons. Although IR thermography in petrochemical factory in Plock has been in service almost day by day since early 70's. the measurement of processes heaters and furnaces tubes belong to the more challenging applications. This paper presents chosen results of nine months-long project which concentrated on the modernising of IR thermographic methodology with the main goal to decrease level of furnace tubes temperature measurement errors, as well as on, not presented here, application of thermal transient processes to determine anomalies inside these tubes. Literature survey showed that similar aims of studies and analyses have been executed since late 70s and lately very penetratingly by a few teams of researchers and experienced thermographers[1,2,3] Unfortunately, we stated the lack of enough experimental techniques or analytical methods of “thermographer-friendly” features, convenient for us. Similar conclusion resulted from studies of discussions between IR thermographers conducted in various internet' message boards.

The main reason of mentioned difficulties is that the heating medium in fired furnaces usually cannot be treated as spectrally and radiometrically stationary and homogeneous in the space. Additional difficulties issue from the furnace geometry, structure and high differences of both radiant features of the tested targets and reflected environment. Since fuel burning in process furnaces is an extreme chemical reaction which gives out energy, through convection and radiation, by ever changing mixture of gases and solid particles, it seems to be truly rare to find any

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ideal, unchanged, spectral wavelength or "the ideal filter", as some IR cameras producers advertise... The same factors cause fundamental limitations for applying any simple multispectral or multicolor thermography[4].

Measuring boiler tube temperatures is specific application where the reflected apparent temperature (equivalent energy of radiation, rather) is higher than the target and where the lower transmission through the heating medium, visible and invisible flames, result in increasing of amplitude of detected signals Thus, both these fundamental factors of thermogram correction, are of additive type. Although up today various procedures have been elaborated in order to estimate their values[5,6], "IR temperatures" often demonstrate high discrepancy to the tubeskin temperatures recorded by the plant systems as well as accidental thermal patterns on surfaces of the tested tubes. These effects limit both range and reliability of IR measurements executed using both pyrometers and cameras. Our practice showed that the partial reason of these limitations and inconveniences are fluctuations of the hot particles and gases from the heating medium. Difficulty in thermograms correction lies in the fact that such influences are usually heterogeneous in the image plane and often have to be taken into consideration both in "atmospheric" and "reflected" parts of the radiometric equation[7]

Presented below, the new experimental technique based on studying the dynamic of thermal images of fixed geometry "camera to tested target", capturing long enough sequences of thermograms for processing using innovative algorithm[8]. Although this method, patented by us, was matched to petrochemical furnaces with the aim to minimize fluctuating components in detected signals or to see trough flames, similar method can be applied to minimize fluctuating factors which decrease amplitude of detected signals, e.g. some effects from atmosphere...

2. Basic concepts and instrumentation

Radiometric model for a process furnace, designed to study conditions of the IR thermal surveys have to consist of spectrally and space dependent components expressing radiosity of the tested surface (self-emission and reflections), influence of the optical path (attenuation, scattering and emission) and influence of the measuring system (spectral response and emission of protective window, lenses, filters, their housings and array of IR detectors). As many of these elements cannot be found in any literature and strongly depend on local conditions of measurements, reference thermocouple and especial techniques of measurements have to be applied. These standard procedures often let down if main two conditions of the proper procedure are not fulfilled

- measurements through a "clean flame" (almost 100% transmission for applied a narrow bandpass filter, e.g. 3.9 μm);
- "the background" temperature and directional emissivity of the target can be estimated accurately enough.

Unfortunately :

- flame combustion byproducts contain mixture of gases (mainly water vapor, CO2, CH4, NO2, N2O) and aerosols.
- often occurs influence of combustion particles or other gases , thus optical canal inside the furnace attenuates, scatters and emits energy (in the manner totally different comparing to conditions applied in camera' build-in software);

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- within the heating medium, inside the furnace, undergoes continuous change in composition, mass, shape, size, number and pressure of particles as well as medium's radiant properties,
- the greater length of the sight between camera and target, the greater radiation interference, and hence higher temperature reading
- tested surfaces reflect energy originating in very hot flames (both visible and invisible).

Mentioned limitations occur particularly strongly for coal or oil fired furnaces. The visible flames can be of different shape and height, from various burners, sometimes even of a few meters long...

If temperature measurements are required for assessing catalyst and reformer process performance or evaluation of the state of the tubes, then a more rigorous approach is required. Typical problem is how to find and to convert apparent temperature measurements to those which are representative of actual targets... As mentioned earlier, the base of our method is minimization of parasitic effects caused by flames or conversely: testing energetic features of the heating medium. Technically, both tasks can be executed with almost the same measuring system but with different interference filters.

2.1. Measuring set-up

With the aim to fulfill the basic metrological conditions for accurate measurements in various places inside the furnace, we were forced to elaborate especial thermocouple-probe for reference measurements (Fig.1).

As we did not meet proper model for furnace atmosphere's spectral features calculations, to determine requirements for interference filters MODTRAN (MODerate resolution TRANsmission) an atmospheric model, the direct successor of the LOWTRAN family of codes was applied. Further, basing on camera's spectral response measured by us, we simulated influence of various interference filters. Additionally to standard “3.9 flame filter” we decided to order interference filters of the bandwidth about 80nm with centers matched to CH4, NO2 and in vicinity of 3.7μm assumed as better “flame filter”.

For the purpose of experimental verification of our assumptions, camera ThermaCAM SC1000 has been applied. The basic necessity was supplementation of this camera for the following elements (Fig. 2):

- camera-laptop digital interface to capture long sequences of IR images with 50Hz frequency,
- the filter holder assembly for fast changes of internal optical filters,
- the shielded attachment to the lens for mounting of external optical filters,
- the heat shield for whole camera with a large, highly transparent window attached with the aim to protect both optical elements and the camera body.

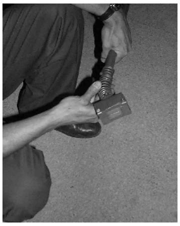


Fig.1 Reference temperature sensor

Figure 2 IR camera with accessories

2.2. Processing of images

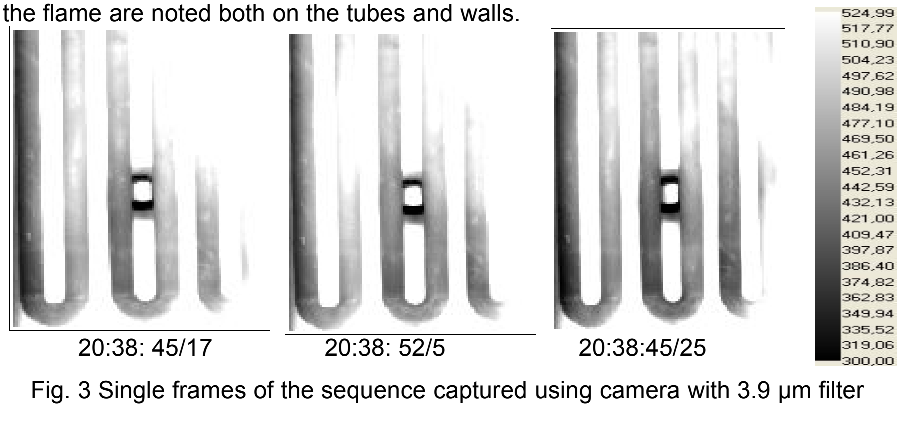
The ThermalAnalyst software was redeveloped after few years of experience in multi-topic research work. Among new algorithms, there were in particular[10] : a) Cropping or area selections – choosing the region of interest for automatic analyze. b) Visualizing and exporting calibration curve after including additional correction and calculation. c) Exporting any data and result in a graphical or text form by the clipboard. d) Importing external data from the clipboard as 2D array of text values to create image (with floating point pixels) for better visualization with palettes and spanning. These very unique features made it possible, for example, to execute any mathematical operation on “the thermogram” or on the chosen part of such thermogram and to observe results with the same geometry and colors as in the preprocessed images. When we applied very narrowband filters of different transmittance, an arduous process of recalibration was obvious for every combination. With the aim to match calibration procedures with various kind of reference data (tables, functions, etc.), a few optional equations were elaborated and implemented.

Resulting images, after mentioned processing, let visualize various unique distributions, as for example:

- „the image of minima” (IMIN) - composing from pixels of minimum values noted down during the sequence - thus for example thermogram with eliminated influence of additive disturbances and consequently more reliable,
- “the image of maxims” (IMAX) - composing from pixels of maximum values noted down during the sequence - e.g. for the heating medium' visualization, as well as for the minimizing of influence of parasitic fluctuating factors representing attenuation by medium colder then measured surface - typical for many other applications…
- group of images presenting special, artificial distributions as e.g. “the image of mean value” (IMEAN), “the image of standard deviation” (ISTDV), 2D distributions of absolute or relative temperature errors etc.

3. Results

For comparison of potential errors of hitherto applied “one shot” and modernized methods figure 3 shows single thermograms from the sequence of the furnace tubes measured by ThermaCAM 1000SC equipped with standard 3.9 μm flame suppression filter. Presented perturbations showed to be both very fast and of significant amplitude, even tens of degrees. Significant and diverse reflections from the flame are noted both on the tubes and walls.



20:38: 45/17 20:38: 52/5 20:38:45/25

Fig. 3 Single frames of the sequence captured using camera with 3.9 μm filter

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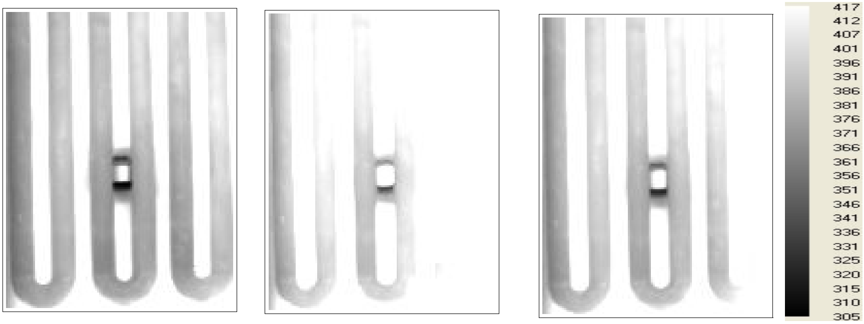
Figure 4 and figure 5 concern the same measuring conditions as above but presents artificial images obtained using the new experimental technique.



I MIN I MAX I MEAN

Fig.4 Numerical thermograms after statistical processing of the 227 frames

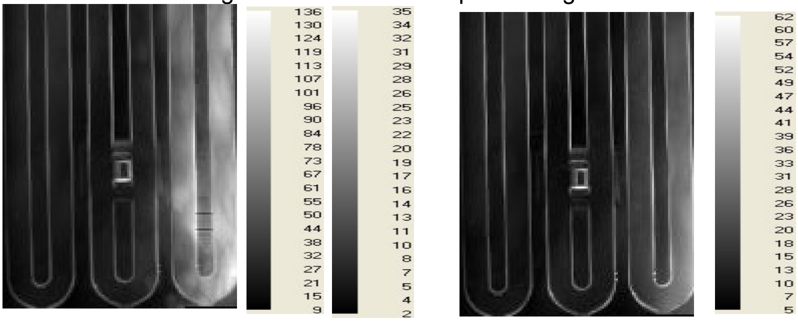


Fig.5 I MAX – I MIN [C] [%] I MEAN – I MIN [C]

Figure 5 presents 2D distribution of absolute errors i.e. (IMAX–IMIN), in C deg. and shown on the left side scale) and relative errors 100%(IMAX-IMIN)/IMIN in [%] It stands to reason that possibilities to transfer thermograms or images to txt files and back, widen range of analyses and applications.

Fig.6 I MEAN [sig] I STD. DEV. [sig]

Fig. 6 Numerical thermograms for sequence captured with CH4 filter.

Figure 6 presents example of application our method for visualisation of the heating medium features. Potentially, this method posses a great potential for testing of medium’ heating energy. The 12s long sequence thermograms was captured by the IR camera equipped with CH4 filter. Unfortunately, as the main spectral band of methane absorption was partly blocked by the short-wave part of camera' spectral

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response, at the moment it is hard to decide what kind of sources from heating medium we captured. In this case both images of Mean and Standard Deviation distributions are of greater interest than representation of Maximal values of pixels.

4. Conclusion

Although preliminary, the results obtained clearly show the great potential of newly elaborated experimental techniques to test operating furnaces. These findings showed to be significantly more reliable in comparison to “one shot” measurements. In the case of tubes temperature measurements we noted errors lower even of tens of Kelvins or signal percent's. Idea of this proved method seems to be attractive for many other applications if only fluctuations of additive or amplitude reduction types of disturbances dominates

ACKNOWLEDGEMENTS

The authors would like to recognize help provided by J.Firak, M.Kwasny, J.Terpilowski, Z.Zawadzki from Military University of Technology, Warsaw

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