DETERMINATION METHODS OF EMISSIVITIES FOR GAS OR OIL FUEL FLAME AND FURNACE INNER WALL SURFACE (PART 2)

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The validity of the proposed method for total emission determination $\varepsilon$ of furnace inner wall surface behind the flame is verified by experiments. Using the emissions established for an infrared camera (IRC) operating in a relative small infrared wavelength interval, and founded on the infrared thermograms (IRT) processing, two methods for combustion research are conceived: gas oil droplet flame testing and gas fuel testing. Developing thermographic results of the first method, the second method, for industrial gas fuels experiments, can use a small tubular furnace with the necessary measure apparatus. There are established the essential theoretic fundamentals with a scientific justification and new specific notions (for characterization or synthetic comparison of combustion operation regimes at different gas fuels), referring to the stable combustion inner tubular furnace.

5. EXPERIMENTAL RESULTS CONCERNING $\varepsilon$ DETERMINATION METHOD

Experiments have been carried out years ago on the experimental furnaces at the SEGFT and IERAB in order to underline how the present method can be put into practice. The main used experimental furnace at SEGFT having the interior approximate dimensions: $7 \, \text{m} \times 1.5 \, \text{m} \times 1.5 \, \text{m}$ [2], presented an important decrease of inner wall temperature, towards the furnace exit for combustion gases. The furnace inner wall, was made of silimanit refractory bricks with a great content of alumina. The cooled tube as a screen 3 m long, had the outer diameter of 70 mm and inner diameter of 50 mm. This tube (having the symmetry axe perpendicular on flame symmetry axe) was introduced into the furnace in a high temperature zone, at approximate 1800 mm distance from the furnace burner extremity. The thermal flux $\Phi_{bd}$ was measured with a total radiation pyrometer type IFRF; with recording apparatus. Also the recorder has the thermocouple Pt. – Pt.Rh. used to measure the temperature $T_w$. The total radiation pyrometer was calibrated with and without cooled tube. Experimental researches were carried out in the following conditions: with the cooled tube introduced into the furnace volume at different
distances \( z \) (Fig. 2), corresponding to different values of angular factor \( f_j^1 \); without the cooled tube introduction, to determine the apparent emissions \( \varepsilon_a \); experiments without and with burner operation. In a rectangular system of coordinate axes one can represent the variations of \( T_w \) in ordinate, function of the time \( \tau \) in abscissa, for an experiment cycle giving the curve \( T_w = \zeta(\tau) \). For a hot furnace, but without the natural gas burner operation, in a point \( p_1 \) for \( \tau = 0 \) inner furnace the cooled tube is introduced at a \( z \) distance corresponding to \( f_j^1 \), with a small wall cooling, and thus the decreased curve \( p_1 - p_2 \) is obtained. In point \( p_2 \), the gas burner is started and so one obtains an increase of temperature \( T_w \) till the point \( p_3 \). On the \( p_3 - p_4 \) curve portion, having a constant operation regime, the temperature \( T_w \) practically doesn’t vary. When \( z_1 \) decreases till \( z_2 \), the angular factor \( f_j^1 \) increases. On the \( p_3' - p_4 \) portion of curve, \( T_w \) is decreased and on the portion \( p_4 - p_5 \) a stabilization of temperature \( T_w \) (without a sensible variation) is obtained. In point \( p_4 \), the cooled tube is taken out from furnace working volume, to allow the increase of \( T_w \). Again the cooled tube is introduced into the furnace volume at the same distance \( z_2 \), with burner operation stopped, so that on \( p_5 - p_6 \) portion, the temperature \( T_w \) decreases. According to these operation procedures, it can be practically obtained the same \( T_w \) and \( f_j^1 \), together with the apparent emissivity \( \varepsilon_{\text{ad}} \) for the two main cycles. These cycles are the furnace operation without and with gas burner in operation thus resulting also the influence of the combustion gases.

For example from Fig. 4, according the first cycle characteristic without flame, it results that for \( T_w \) varying between 1224 K and 1318 K, the variation of \( \varepsilon_a \) practically is insensible. This result is according to the above presented theoretical
fundaments. Also, the apparent emissivity $\varepsilon_a$ is smaller than one, but close to this value, because the area $A_1$ of $S_1$ does no receive thermal energy from a great part of the experimental furnace bottom which is cooled and also from different slits placed in the furnace lateral wall.

In Fig. 5 there are graphically presented the functions of calibration $\Phi = \xi (\Delta v)$ where are denoted the radiation flux $\Phi$ in ordinate and tension variation $\Delta v$ in abscissa, for the used total radiation pyrometer, with and without cooled tubular screen. For the precision of the measurement, before the two cycles of experiments, the calibration of the total radiation pyrometers was performed. There will be presented the same characteristic results obtained in the two cycles of experiments, as follows: for $f_j^1 = 0$, $T_w = 1303$ K, $\varepsilon_a = 0.965$; for $f_j^1 = 0.16$, $T_w = 1250$ K, $\varepsilon_{ad} = 0.75 (0.70)$; for $f_j^1 = 0.48$, $T_w = 1173$ K, $\varepsilon_{ad} = 0.72 (0.74)$; for $f_j^1 = 0.8$, $T_w = 1089$ K, $\varepsilon_{ad} = 0.70 (0.71)$. The results written in round brackets are referring to $\varepsilon_{ad}$ when the furnace gas natural burner was in function producing combustion gases with low emissivity. The value for each experimental point represents the practical arithmetic mean for three measurements of $\varepsilon_{ad}$. The combustion gases presence has a sensible influence on $\varepsilon_{ad}$ for small values of $f_j^1$, but for $f_j^1 = f_r^1 \cong 0.8$ when $z_r \cong 2.6$ cm, the influence on $\varepsilon_{ad}$ is smaller as 2% (in addition) referring to $\varepsilon$, because the screening effect of cooled tube is much greater and it acts on walls radiation together with combustion gases radiation. For numerous experimental results for relative large value of $f_j^1$, mark that using new refractory bricks inner furnace, are obtained near values for surface wall emissivity $\varepsilon$, resulted by classic method (using electric heating of wall brick). Indeed in this last case, the silimanit brick radiates only the flux $\alpha \sigma T_w^4$ because $\Phi_w$ doesn’t exist. For example, we will
present two characteristic experimental results obtained in laboratory by electric heating of brick and on furnace with new bricks (written in round brackets), as follows: for $f_{i}^{1} = f_{r}^{1}$, $T_w = 1089 \text{ K}$, $\varepsilon = 0.68 \ (0.70)$; and for $T_w = 1303 \text{ K}$, $\varepsilon = 0.63 \ (0.64)$. Thus in general, the increase of $\varepsilon$ measured on effective furnace operation with natural gas combustion doesn’t overtake 3 % (as a positive systematic error which can be eliminated) from the value obtained in laboratory.

6. APPLICATIONS USING THE COMBUSTION INFRARED THERMOGRAM WITH ESTABLISHED EMISSIVITY

We present two representative examples of the infrared thermography applications in oil droplet [5] and gas fuel combustion, using the established emissivity $\varepsilon_s$ for infrared thermograms (IRT). In consequence, from the first application it results a research-testing method using the emissivity near unity for some characteristics points of a single fuel oil droplet flame resulted by diffusion combustion with a great quantity of soot particles. For experiments it is used a tubular miniaturized furnace (combustion simulator), which permits the combustion at a inner furnace temperature relatively low, near the environmental air temperature $T_{eq}$. An experimental fuel oil droplet had the initial mean diameter $d_0$ with temperature $T_0$. An infrared camera (IRC) has been used operating in the infrared wavelength band $\Delta \lambda = 3.4 – 5 \mu m$, in order to obtain the thermal images in thermograms. In general, IRT gives the fields of apparent temperatures $T_a$ of burning droplet at a real-time $\tau$ of the combustion process development. The values of $T_a$ are functions especially of: diameter $d_0$, time $\tau$ variation and fuel oil properties, but also of the combustion regime. From the IRT initial analysis it resulted that for a given fuel oil the apparent temperatures are greater when $d_0$ is greater and the $\tau$ time is closer to the value corresponding to the droplet flame maximum volume $DFMV$ (which is taken as the reference value). For example, in Fig. 6 there are presented two IRT. Using an appropriate IRC, the mean real temperature $T_r$ corresponding to $T_a$ can significant characterize the fuel oil combustion process development. $T_r$ temperature results when the emissivity $\varepsilon_s$ in normal incidence direction of $xOy$ plane is known, within the $\Delta \lambda$ band of IRC. The point $O$ represents the symmetry centre for liquid of burning droplet. To obtain a small variation of $\varepsilon_s$ (in normal direction at $x'x$ axe in the thermogram plane) for the interval of burning droplet, with a reduced difference between $T_a$ and $T_r$, it is necessary to burn with abundant soot and the environment giving a very low emissivity. The spectral emissivity $\varepsilon(\lambda)$ slowly varies with wavelength $\lambda$, for some droplet flame zones with abundant soot, similar as for solid objects. For example, in the normal direction to $xOy$ plane surface, for the point $O$ where the released soot is larger and in addition, the liquid droplet represents a background screen, the
emissivity $\varepsilon_s$ for an industrial fuel oil diffuse combustion has a great value which can approach to black body emissivity. The influence of emissivity $\varepsilon_s$ is much less significant as temperature $T_a$ variation. For this reason, the analysis and comparison of $T_a$ temperature fields from IRT, according to $\varepsilon_s$ estimation, gives valuable date on diffusion combustion development. Analysing IRT obtained by experiments performed in the same initial combustion conditions of droplets, for a tested and standard fuel oil, there are established objective criteria of the fuel combustion quality determination. In order to characterize and compare, the gas oil combustion quality at $DFMV$, there were defined: $T_{ax}$ – average of flame apparent temperatures in normal direction on the $xx'$ axe contained in $xOy$ plane; $T_{ut}$ – average of total flame apparent temperatures in normal direction on $xOy$ plane, obtained by conversion of total radiation energy in $\Delta \lambda$ band, from the burning droplet; $T_{ao}$ – apparent temperature in normal direction on the $xOy$ plane, for the point $O$. An incorporated computer in IRC allowed fast graphic representation of the above mentioned characteristics. Experimental researches and testing have been carried out using the above presented un-cooled combustion simulator, and different types of gas oils, intermediate and heavy fuel oils, in the same initial conditions, characterized by: temperatures of environmental combustion air $T_{ev}$ and fuel oil $T_0$; natural draft for combustion air feeding; and initial mean diameter of droplet $d_0$ [mm]. During the majority of fuel oil testing, variation of above mentioned criteria, for $\varepsilon_s = 1$ and $d_0 = 2$ mm, was: $T_{ax} = 568 – 630$ K; $T_{ao} = 660 – 720$ K and $T_{ut} = 536 – 566$ K. In the same initial conditions of the numerous experiments carried out, it resulted that by gas oils combustion intensification, the values of criteria $T_{ax}$, $T_{ao}$ and $T_{ut}$ increase. The type of the obtained thermograms of Fig. 6 stimulates in addition to conceive another combustion research-testing method, presented above.

![Fig 6](image_url)

**Fig 6** – a) Infrared thermogram for an intermediate fuel oil ($d_0 = 2$ mm, $T_{ev} = T_0 = 295$ K) at $DFMV$, with representation of curve $T_{ax} = \phi(y)$; b) infrared thermogram for a superior gas oil droplet ($d_0 = 1.7$ mm, $T_{ev} = T_0 = 295$ K) at $DFMV$. 

In general, for energy saving and to obtain the necessary high technologic temperatures, the furnace heat losses in environment have a relative very small value for modern industrial furnaces with a suitable exterior thermal insulation. But using an IRC to obtain the infrared thermogram IRT (similar as above presented) of furnace exterior wall can verify this industrial usual situation. The procedure of infrared thermography, in special operation conditions and with additional measurements together with developed theoretical fundaments, can generate a method for gas fuel combustion research-testing using a small tubular furnace without exterior thermal insulation. This tube as furnace is especially made of refractory steel or rarer of refractory ceramic materials. In this case (Fig. 7a), neglecting the heat transfer of conductivity in rectangular direction of (\(\Delta\)) axe:

\[
\Phi_m = \Phi_{ce} + \Phi_r, \tag{25}
\]

where \(\Phi_{ce}\) – thermal flux yielded, to the ambient air by natural convection of heat transfer due the air flow on hoot exterior tubular surface; \(\Phi_r\) – thermal radiation flux emitted to the ambient medium of the hoot exterior tubular surface. In general, the convection heat transfer \(\Phi_{ce} \ll \Phi_{re}\) because the air flow around the hot exterior tube, is usual in laminar regime.

Taking into account the \(\Phi_{re}\) expression, it results:

\[
\Phi_m = \Phi_{ce} + \varepsilon e \sigma T_e^4, \tag{26}
\]

where, in general, \(T_e < T_w\) is the temperature of exterior tubular surface when the corresponding interior tubular wall surface is \(T_w\) and \(\varepsilon e\) represents the total emissivity of exterior tubular surface. By replacing (26) in (1), one obtains:

\[
\Phi_{ce} + \Phi_w = \varepsilon \sigma T_w^4 + (1 - \varepsilon) \Phi_w + \Phi_{ce} + \varepsilon e \sigma T_e^4. \tag{27}
\]

Considering \(\Phi_{ce}\) negligible in comparison with \(\Phi_{re}\), and with condition \(\Phi_{ce} = 0\), it results:

\[
\Phi_{re} = \varepsilon e \sigma T_e^4 = (\Phi_w - \sigma T_w^4) \varepsilon + \Phi_{ce}. \tag{28}
\]

As a first approximation, and because there is refractory steel material of furnace tubes for which the total emissivity \(\varepsilon e\) is appreciatively equal to the emissivity value \(\varepsilon_{cw}\) in the wavelength interval of the used IRC, one can admit \(\varepsilon e \cong \varepsilon_{cw}\). Thus it can be determined \(\varepsilon_{cw}\) by applying the presented classical method, like for \(\varepsilon e\) but using a TRP in place of IRC. By measuring \(\Phi_{re}\) and admitting \(\varepsilon_{cw}\) known, from the obtained infrared thermogram it results the temperature \(T_e\) in the picture of field apparent temperatures field. Also we can admit for new furnace tubes, as exiting a very small difference between \(\varepsilon e\) and \(\varepsilon_{ce}\). Applying the Fourier law in direction (\(\Delta\)), it can be obtained the temperature \(T_w\), from relation:

\[
T_{w} = (\delta \Phi_{re} + \lambda T_e)^{\frac{1}{\lambda}}, \tag{29}
\]
where \( \delta \) is the thickness of the furnace tube, and \( \lambda \) represents the thermal conductivity of furnace tube material. Because for the steel tube material, \( \lambda \) has a relative great value and \( \delta \) has a small value, in general it is admissible to consider \( T_w \approx T_e \). But for tubular furnaces made of ceramic refractory material, in general it is an important difference between \( T_w \) and \( T_e \) due to the small value of \( \lambda \) and relatively larger value of \( \delta \). Usually with a thermocouple Pt.Pt.-Rh., we can measure \( T_e \) and by measuring \( \Phi_{re} \), using the first part of the relation (28) according to the above consideration, one can obtain the local value of \( \varepsilon_e \). In general, taking a mean value for the emissivity of furnace exterior tube surface, the apparent temperatures differ even very little of surface real temperatures \( T_r = T_e \). Such as, for example if we admit \( \varepsilon_{e1} = 0.9 \), for which in IRT the temperature \( T_{a2} \) is determined, but in reality \( \varepsilon_{e1} \) decreases with an important value of 0.10 (becoming \( \varepsilon_{e2} = 0.8 \) in the considered point, it results \( T_r = T_{a2} = 1.0298 T_{a1} \), that results a relative small error on \( T_r \) value. IRC can automatically realize the correction of emissivity \( \varepsilon_e \), but for the whole IRT. Thus the influence of emissivity variation is much less important as temperature \( T_a \) variation according to the Stephan Boltzmann’s law, which gives \( T_{a2} = \varepsilon_{e1}^{0.25} \varepsilon_{e2}^{0.25} T_{a1} \). For this reason and according to (28), the analysis and comparison of \( T_a \) temperature fields from IRT for a mean value \( \varepsilon_e \), give valuable data on combustion process (very dependent of \( T_e \) temperature). Indeed, by IRT picture variable in time (due the continuous combustion process), one can obtain a thermal image of combustion process development, especially determined by the thermal fluxes \( \Phi_w \) and \( \Phi_c \), (where for high temperatures furnaces, the following relation can be valid \( \Phi_c \ll \Phi_w \)). These thermal fluxes are dependent of burned gas fuel type, burner thermal power variation, type of combustion regime (stable or instable), combustion excess air, type of gas burner, system of mixing between air and gas fuel. But these, can be variable, slow, quick or very quick according to the type of realized combustion regime. Thus, the thermal images from infrared thermograms can characterize: the stable flame, with combustion pulsation at high frequency; instable flame with pulsation of combustion at low frequency or appearance of suspended flame. The first condition for a correct experiment is that the burner operation to give a stable flame. When in a fist approximation are considered \( T_w = T_e \), \( \Phi_c = 0 \) and \( \varepsilon = \varepsilon_e \), from (28) results the temperature \( T_e \) independent of total emissivities, and the main influence on \( T_e \) value having the thermal flux \( \Phi_w \). The local total emissivities can be determined directly from the experiment. A comparison between burner operation variants, usual is carried ou for the same burner thermal power \( P = BH_l \), where \( B \) is the fuel consumption and \( H_l \) represents the low heating value. The value of burner thermal power must assure a combustion process stability and practical a complete combustion. But in fact, for a scientifically and synthetically analysis especial for
comparison of stable combustion regimes in tubular furnace, it is necessary to define and use the following specific characteristics:

- the elapsed interval of time $\tau_e$ until a stabilized thermal regime for tubular furnace is obtained, with the tube heating dynamic ($THD$) due to the combustion process characterised by $T_e$ change, in time passing $\tau_p < \tau_e$ but $\tau_p > 0$. Thus, $\tau_e$ is the minimum elapsed time, till this curve from Fig. 7b doesn’t practically change in time;

- the maximum temperature of exterior tube $t_{\text{max}}$ obtained from the traced curve $T_e = F(y)$; distance $y_{\text{max}}$ between the burner end and the point with $t_{\text{max}}$, usually measured on the vertical symmetry axe; mean temperature of the tube exterior surface $t_{\text{em}}$, which results $t_{\text{em}} = \int_y^l F(y)dy$. This mean temperature referring to the time $\tau_p$ (with decreased value of mean temperature) can be the main factor for THD calculation. The $T_e = F(y)$ curve can be traced in IRT by the IRC computer (at a mean value of determined emissivity $\varepsilon_e$), which also comfortably determines $t_{\text{em}}, t_{\text{max}}$ and other characteristics. But this curve can be disadvantageous obtained, using mounted numerous thermocouples on the furnace tube vertical generatrix.

![Diagram](image.png)

**Fig. 7** – a) Schematic-conventional representation of a section by a small tubular furnace together with the characteristics $\Phi_{\text{w}}, \Phi_{\text{c}}, \Phi_{\text{re}}, \Phi_{\text{ce}}, T_w, T_e, t_{\text{max}}, y_{\text{max}}, t_{\text{em}}$, and the determination possibilities of emissivities $\varepsilon_e, \varepsilon_{\text{ew}}$ using TPR and IRC; b) Variation of exterior surface temperature $T_e$ for tubular furnace on the vertical tube generatrix, in two characteristic cases: stable combustion when $T_e = F(y)$ and combustion with suspended flame when $T_e = f(y)$. 
At combustion flue gases exit from tubular furnace, so there it must be placed a special small device, for correct drawing analyze probes of CO₂, O₂, CO or other gases resulting from an incomplete combustion, together with eventual noxious products. According to the theory and complementary experiments that has been carried out, one can approximately determine the main factors which influence the variation of the proposed characteristics and conditions for efficient experiments at a stable combustion.

Certain differences can accidentally appear among similar experiments especially when the heating stable operation regime was not still obtained for a certain experiment cycle, together with the change of burner operation regime. In consequence, the main stages for an efficient application, that has to be carried out are the following: the preliminary experiments for obtaining a stable combustion in the conditions presented above, together with the testing of measurement devices; the experiments for optimal emplacement (at distance A, to avoid superheating) and use of IRC; the main experiments according to the established program obtaining the specific combustion infrared thermograms with processed data, together with the analysis of combustion gases composition at tubular furnace exit; the comparative analyses or only characterization of the combustion operation regimes, according to the obtained processed thermal images and interpretation of others experimental results. The data on the field of temperatures can be ample with the elimination of operation variants with incomplete combustion, or with eventual important noxious products. Using IRT, one can research more details with significant pictures, of different important phenomena for efficient gas fuel combustion. The research of combustion in small tubular furnace, can also determine useful simulation for predicting the main industrial combustion effects which can determine a gas fuel consumption reduction with environment pollution decrease. Long ago, at IERAB an important research activity was developed [6] to create the efficient burners with previous mixing between natural gas and combustion air. Using such a system, there have been carried out researches on tubular furnaces (burning as fuel the natural gas, containing especial CH₄ ≅ 98 % ) with inner diameter d = 52 mm and tube length l = 350 mm, together with other larger different lengths. For many combustion operation regimes, we have determined: the heating of furnace tube by temperatures measurement with thermoucuples (because later are conceived IRC) which recommended in addition to use IRT; the stable and instable combustion process development; and the possibilities of burner improvements (referring to the increase of combustion stability field, degree of complete combustion effecting chemical analysis of tube exhaust combustion gases… etc.). It result, for example, that for a variation of the thermal energy release rate per unit of cross-sectional area of furnace tube Iₘ ≅ 52 – 93 W/m², a stable combustion is obtained. Also by increasing Iₘ, it resulted a decrease of the stability range (established by superior and inferior rates between
consumptions of combustion air and natural gas). The temperatures on tube generatrix were varying between 800 K and 1300 K, depending on the combustion regime. It is underlined the advantage of numerous possibilities to obtain a stable and practical complete combustion, with direct applicability.

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