



## VALIDATION OF THE H. HOTTEL- R.J. TUCKER METHOD FOR THE ESTIMATION OF THE PERFORMANCE OF A FURNACE IN A THREE-BED REGENERATIVE OXIDIZER THAT NEUTRALIZES GASEOUS POLLUTANTS

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### Abstract:

*This paper investigates the validity of the method of zones proposed by H. Hottel and R. J. Tucker for enclosures with surfaces exposed to significant thermal radiation. The analysis is focused on a specific combustion chamber in a three-bed regenerative oxidizer and calculates the temperatures and the corresponding thermal flux exchanges among the hot wall surfaces of the chamber. The temperature distribution and the initial composition of the gaseous mixture at the inlet plane were assumed known.*

**Keywords:** Gas Mixture Emissivity; Radiation; Combustion Chamber; Thermal Three Bed Oxidizer; Coefficient Absorption.

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### 1. Introduction

This paper studies the effect of the thermal radiation on the percentage composition of the waste gas outcoming out of the combustion chamber of a three-stage regenerative oxidizer. This thermal oxidizer was employed for the neutralization of the gaseous pollutants in an industrial plant, to be described below, as defined by EPA (Pollution engineering 1996) [1].

The above method was employed for the evaluation of the oxidizer efficiency during the neutralization process of the malodorous organic polluting substances generated during the productive industrial processes of the above plant and was based upon a patent acquired by one of the authors for general application in polluting industrial plants. (European Patent Application. EPO 1409924 **Patent N. Pittas** [2]). The proposed approach attempts to address the emission problems appearing in the waste treatment of industrial plants after a period of only 2-3 months of operation when nearly all relevant plants tend to release malodorous and pollutant gases above and beyond the initial design standards upon which the plant was designed and erected.

There are various techniques such as scrubber chemicals or biological bed techniques employing active carbon or a combination of the above in order to reduce the intensive smell problem created by the malodorous gas emissions within manageable levels. In practice, however, current solutions provide a rather limited reduction on the concentrations of the emitted pollutants of the order of only 8-12%. This neutralization level is insufficient given the rather intensive inconvenience they create to the surrounding communities. This inconvenience involves either health problems or property devaluation or both. So far, the operation of several such modified plants of various capacities, installed by us in local (Greek) industries and addressing the problems associated with malodorous pollutant emissions had excellent results. The present study reports on the optimization of the operation of such plants with minimum atmospheric pollutant emissions.

As it is common knowledge, plants emitting waste gas pollutants are obliged to conform with some very strict governmental regulations and install a monitoring process on a Global scale. In the plant under consideration in the present study the following concentrations were recorded in the waste gas exhaust (chimney). The concentrations were measured after the installation of the concept proposed by our patent and involved (i) Total Organic Carbon (COT), (ii) Nitrogen oxides (NO<sub>x</sub>) and (iii) Carbon Monoxide (CO) and were found to be of the following order:

Concentration COT in chimney  $\leq 20 \text{ mg/Nm}^3$

« NO<sub>x</sub> « «  $\leq 50 \text{ mg/Nm}^3$

« CO « «  $\leq 100 \text{ mg/Nm}^3$

The existing European legislation sets a higher limit for the magnitudes of all these gaseous concentrations.

The deactivation of the malodorous gaseous pollutants is affected by the thermal radiation within the reactor chamber (actually a combustion chamber) that accelerates the oxidation process of the organic pollutants, resulting into the formation of carbon dioxide (CO<sub>2</sub>) and water steam. These reactions are accelerated due to the higher temperature instituted by the chamber wall emissions of thermal radiation. The average temperature level within this chamber was of the order of 750 °C, and the evaluation of the magnitude of the heat exchanged between these walls was evaluated by the method first proposed by H. Hottel [3], known as the “thermal zones” method.

The implementation of the above method, under the assumption that the waste gas temperature being equal to the above level (750 °C), validated the assumption that the chamber wall temperatures could be maintained to within acceptable levels when the radiation energy exchanged by these walls through the intervening gaseous mixture was conserved. This way the operation of the plant is predicted theoretically. This prediction defined clearly the details that had to be taken into consideration (mainly the wall temperature measurements) for an optimum running of the plant.

By comparing the online measurements of the chamber wall temperatures in the specific plant under consideration, the method proposed by Professor H. Hottel [3] was validated for chamber sizes comparable to the one employed in this plant.

The analysis of the waste gas composition involved the calculation of the components **partial pressures** through Dalton's law.

It was assumed that the waste gas components (vapor and carbon dioxide) were grey and followed Lambert's law.

The model of this mixture representing the waste gas assumed a composition of vapor, CO<sub>2</sub> and a non-reacting gas.

The energy exchange among two surfaces of the chamber were evaluated with the help of the beam attenuation constants provided by H. Hottel [3], These data were supplied in the form of diagrams as functions of the parameter  $pl$ , where  $p$  represents the partial pressure of either the water vapor or the carbon dioxide, and the gaseous mixture temperature. The length  $l$  represents the mean beam length between the two surfaces under consideration. The correct value of the attenuation parameter was evaluated through a regression analysis from the experimental data provided by these graphs at a temperature 750 °C. The weak influence of the overlapping interaction of the emission wavelengths of water vapor and carbon dioxide were added to the above analysis. A final correction was introduced for the fact that the chamber pressure was sub-atmospheric. These experimental data were next inserted into the conservation equations for the energy exchanged among any two surfaces. These equations were essentially those provided by R.J. Tucker [4]. The details of the theoretical model employed for the energy exchange analysis will be discussed below. Applying the thermal zones model, the thermal zones must be appropriately chosen (surface and gas zone) dividing the chamber in specifically 11 zones, because due to the construction details the wall materials are different and have different absorption-emissivity coefficient for each zone. The aim was to calculate the thermal balance for each zone in order to evaluate the chamber wall temperatures and compare them against the corresponding measurements on the plant under consideration.

## 2. Short Description of the Three Bed Thermal Regenerative Oxidizer Plant

The above facility was installed on a larger plant producing fish feed near the city of Corinth, Greece, operated by Zoonomi SA.. This plant is illustrated in figure 1 below



Figure 1: The three bed thermal regenerative oxidizer plant in Lecheum-Corinth operated by ZOONOMI SA

The operation of the plant generates malodorous gas emissions that have to be treated thermally, before exhausting into the surrounding atmosphere. Untreated they create a very bad smell that disturbs the inhabitants in the neighborhood.

The emissions contained organic material that involved malodorous gases. These materials in order to be neutralized had to be heat treated at a rather high temperature inside the regenerative oxidizer facility. The overall geometry of this facility is illustrated in figure 2.

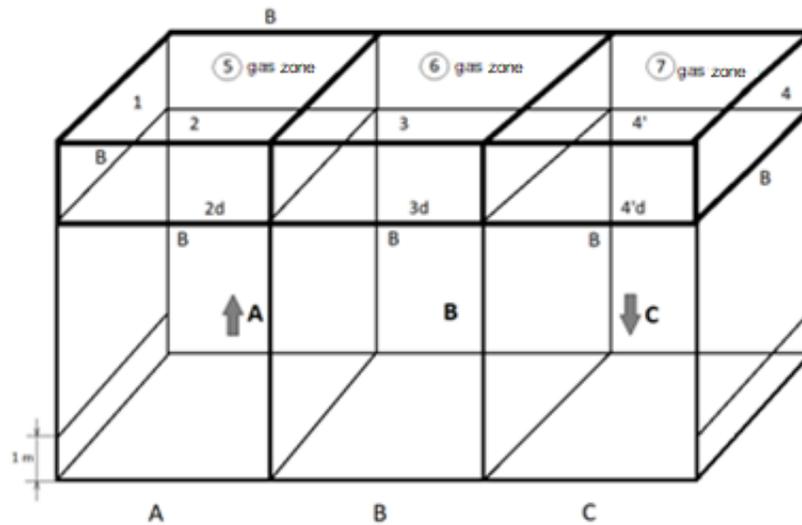


Figure 2: Tree bed thermal regenerative oxidizer

The operation of the facility is periodic. In order to facilitate the description, it is assumed that the gas emissions enter chamber A, as described in Figure 2. The ceramic bed matrix had been heated by the previous cycle of operation (or the consumption of propane at the initial starting of the plant). This reheating operation rises the temperature of the gases and facilitates their oxidation into  $\text{CO}_2$  and water. The hot gases coming out of this process deposit part of their enthalpy into the corresponding ceramic matrix of one of the other two chambers (B and C), as they exit the facility. The chemical reactions for the oxidation take place both inside the ceramic matrix and the spaces available above the matrix. The maximum temperatures on the walls of the facility must appear on the smaller chambers above the matrix and for the plant under consideration a limit of  $750^\circ\text{C}$  had to be maintained during the functioning of the oxidizer. This was the main reason for a reliable evaluation of the radiation exchanges and the establishment of the wall temperatures under steady operation.

The contaminated waste gas stream enters one of the three beds (e.g. bed A). It flows through a ceramic bed so that heat is exchanged between the bed structure and the gases. This heat originated in the combustion of the organic materials carried along by the flow heat is transferred from the ceramic medium to the gas stream. It exits the bed and enters the combustion-oxidation chamber at a temperature that approaches the final operating temperature of the oxidation chamber. The burning of the organic materials generates heat that contributes to the reheating of the ceramic matrix of the exhaust path. The entrance and exhaust path of the emitted gasses varies periodically.

The burning reheat complements the energy requirements in order to sustain the high temperature needs for the oxidation to proceed. The heating process was supplemented by an external burner. The exhaust of the stream entering matrix A exhausts through one of the other two matrices (B or C), reheating them for the following step in the oxidation process. The matrix that remained inactive is undergoing a purging from any mass that may have accumulated on the ceramic surfaces. The entire sequence is modified periodically with a time period of 1 minute. Hence, all matrices become active over a period of 3 minutes.

At the completion of each section, the ceramic matrix employed as entrance is purged by high pressure air from any solid matter deposited on the ceramic walls. This air injection acts as a matrix coolant. The cycle is repeated cooling one bed, heating another, and purging the third.

Since the complete cycle of operation takes three minutes but the malodorous gas requires only 1 minute to transverse the distance from entrance to exhaust at the plant chimney, the energy balance equations are averaged for this 1 minute.

The present paper is a validation of the of thermal zones method proposed by H. Hottel [3] alongside the model proposed by R.J. Tucker [2] for an actual operating unit. The influence of the concentrations resulting from the oxidation process on the thermal radiation was investigated and documented.

Similar data were published by Leckner [5] who employed regression analysis to evaluate the emissivity parameters from the figures provided by Hottel [3].

The solution of the thermal balance equations provided the magnitudes of the temperatures for each zone (surface or gas) into which each chamber was divided. The solution algorithm was stable, and the corresponding matrix determinant was symmetrical, a fact that leads to a straightforward and fast solution.

The values of the calculated temperatures proved to be in agreement with the corresponding values provided by the thermocouple measurements in the plant under consideration to within 98-99%.

### **3. Theoretical Analysis**

The first step of the analysis involved the division of the actual chamber into a number of zones, as illustrated in Figure 3.

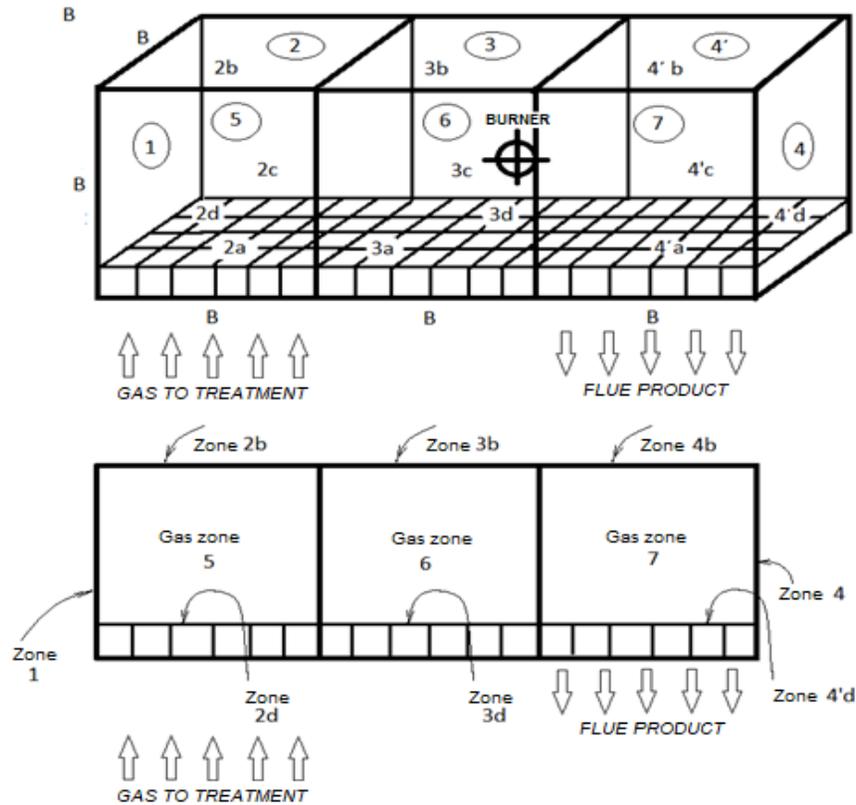


Figure 3: The division of the oxidizer facility into smaller zones.

The parameters in the above figure refer to:

Surfaces 1, 4, 2d, 3d, 4d' (squares with a side equal to a length B)

Surface 2 (consists of the square surfaces 2a, 2b, 2c, each with a side equal to a length B)

Surface 3 (consists of the square surfaces 3a, 3b, 3c, each with a side equal to a length B)

Surface 4'd (consists of the square surfaces 4'a, 4'b, 4'c, each with a side equal to a length B)

The enclosed gaseous volume 5 (essentially the cube No. 5 (sides 1, 2a, 2b, 2c, 2d), with sides equal to a length B)

The enclosed gaseous volume 6 (essentially the cube No. 6 (sides 3a, 3b, 3c, 3d), with sides equal to a length B)

The enclosed gaseous volume 7 (essentially the cube No. 7 (sides 4'a, 4'b, 4'c, 4'd), with sides equal to a length B)

The analysis process involved initially the definition of the composition of the gaseous components that react with the thermal radiation, i.e. Carbon Dioxide (CO<sub>2</sub>) and Water Vapor (H<sub>2</sub>O). This evaluation was based upon the corresponding measurements on the exhaust gaseous mixture entering the chimney inlet. These two elements transformed the mixture into a grey gas, as indicated by the zonal method. The remaining gaseous elements (mainly Nitrogen (N<sub>2</sub>) and oxygen (O<sub>2</sub>)) were assumed to exhibit a tiny interaction with the thermal radiation. Once the mixture composition was fixed it was possible to determine the radiation absorption coefficients and the corresponding mean beam lengths of the mixture (from the partial pressures of the gaseous elements) inside the combustion chamber.

The evaluation of the elemental partial pressures was based upon Dalton's law and the measured gaseous concentrations. These pressures were combined with the mean beam lengths of the radiation exchanges among the chamber wall surfaces in order to evaluate the free parameter known as "the wave length"  $P \times L$  (atm x ft).

The prediction of the average spatial distribution of the gas temperatures inside the chamber space and the temperature and heat-flux distribution on the walls of the combustion chamber whose geometry and size as well as the enclosed gas properties are specified is presented in the following analysis:

It was assumed that the gaseous mixture inside the chamber was equivalent to a mixture of two grey gases (Carbon Dioxide (CO<sub>2</sub>) and water steam (H<sub>2</sub>O)) as well as a neutral gas (Nitrogen (N<sub>2</sub>)). The total emissivity of this gaseous mixture may be evaluated by the following relationship:

$$e_g = \alpha_{g,1}(1 - e^{-K_1 L}) + \alpha_{g,2}(1 - e^{-K_2 L}) \quad (1)$$

Where

$e_{gi}$  = emissivity

$a_{gi}$  = absorption coefficient

$K$  = attenuation coefficient

$L$  = mean beam length

The emissivity for each of the active exhaust gases  $i$  (water vapor ( $i=1$ ) and carbon dioxide ( $i=2$ )) was taken from the data provided in Reference [3] as functions of the corresponding values of the wavelength parameters  $P_w L_m$  and  $P_{CO_2} L_m$ .

The actual in situ measurements of the gaseous and the wall temperatures were conducted by a specialized company (ENCO LTD), which provided as well the gaseous concentrations and the corresponding partial pressures for the running conditions of the facility. As reported above, these data provided the basis for the evaluation of the free parameters ( $p_i L$ ) needed for the final evaluation of the gaseous emissivity for an assumed constant gaseous temperature equal to 750°C inside the entire chamber. The emissivity evaluation was based on the experimental data provided by the relevant charts in figures fig 6.11 (page 232), fig 6.9 (page 229), fig 6.12 (page 233) of Reference [3], with the constant temperature of the enclosed gases inside the chamber transformed into the Rankine scale, i.e.  $T = 1841$  °R<sub>a</sub>. Actually the emissivity parameter was evaluated by the following relationship:

$$\epsilon_g = \epsilon_{gw} + \epsilon_{gco2} - \Delta\epsilon \quad (2)$$

Where

$\Delta\epsilon$  = The wavelength overlap parameter

These charts apply for a chamber pressurized to a pressure equal to that of the surrounding atmosphere (i.e. 1 atm). When the chamber pressure differs from the atmospheric (in the plant under consideration it was regulated so that it was maintained steady at a magnitude of 0.4 atm) it

was necessary to readjust the emissivities determined above by introducing correction coefficients  $C_{H_2O}$  and  $C_{CO_2}$ , which multiplied the corresponding two emissivities.

The determination of the correction factors  $C_{H_2O}$  and  $C_{CO_2}$  was based on experimental data provided in charts (fig.13.56 and fig13.57 in Rathore, Kapuno [6]).

The gas absorptivity and emissivity of the entire mixture were evaluated in a similar manner as the weighted sum of the corresponding contributions for each particular grey gas, i.e.

$$\epsilon_g = \sum_0^n [a_g, n(Tg)](1 - e^{-knPL}) \tag{3}$$

$$\alpha_g = \sum_0^n [a_s, n(Ts)](1 - e^{-knPL}) \tag{4}$$

Where

$\epsilon_g$ =emissivity

$a_g$ =coefficient of gas absorption

$a_s$ =coefficient of surface absorption

The emissivity-pL relationship for the gaseous mixture may be depicted as the weighted sum of the particular contributions of the gray gases participating in it and this relationship can be expressed as

$$\epsilon_g = \sum a_{g,i} (1 - e^{-k_i pL}) \tag{5}$$

In other words  $\epsilon_g$  is an increasing function of pL with an upper limit unity for a large value of the pL parameter. In this limit

$$\sum a_{g,i} = 1 \tag{6}$$

Hence all  $\epsilon_g$  values are positive.

For  $K = 0$  there exists no active grey gas component inside the mixture. For non-zero values of  $K$ , it may be shown that

$$\sum_{i=1}^n a_{g,i} = 1 - a_{g0} \tag{7}$$

$$\sum_{i=1}^n a_{g,i} - \epsilon_g = a_{g,1} e^{-k_1 pL} + a_{g,2} e^{-k_2 pL} + \dots + a_{g,n} e^{-k_n pL} \tag{8}$$

$$k_1 > k_2 \dots k_n \tag{9}$$

$$\epsilon_g = a_{g0}(1 - e^{-0pL}) + a_{g,1}(1 - e^{-k_1 pL}) = a_{g,1}(1 - e^{-k_1 pL}) = a_{g,1} (1 - e^{-K_1 pL}) \tag{10}$$

Defining the  $pL_m$  and  $2pL_m$  values in the above equation, results into the following relations

$$\epsilon_{g,Lm} = a_{g,1}(1 - e^{-k_1 pL_m}) \quad \epsilon_{g,2Lm} = a_{g,1}(1 - e^{-2k_1 pL_m}) \tag{11}$$

$$a_{g,1} = \frac{\epsilon_g \epsilon_{g,Lm}}{2\epsilon_{g,Lm} - \epsilon_{g,2Lm}} e^{-k_1 p L_m} = \frac{\epsilon_{g,2Lm} - \epsilon_{g,Lm}}{\epsilon_{g,Lm}} \quad (12)$$

$$k_1 p L_m = \ln \left[ \frac{\epsilon_{g,Lm}}{\epsilon_{g,2Lm} - \epsilon_{g,Lm}} \right] \quad (13)$$

by replacing the product  $k_1 p = K$

$$K_1 = \frac{1}{L_m} \ln \left[ \frac{\epsilon_{g,Lm}}{\epsilon_{g,2Lm} - \epsilon_{g,Lm}} \right] \quad (14)$$

For the chamber under consideration,  $K_1$  becomes

$$K_1 = \frac{1}{L_m} \ln \left[ \frac{\epsilon_{g,Lm}}{\epsilon_{g,2Lm} - \epsilon_{g,Lm}} \right] = 0.143 \quad [15a]$$

For wavelength of a double magnitude

$$K_2 = \frac{1}{2L_m} \ln \left[ \frac{\epsilon_{g,2Lm}}{\epsilon_{g,4Lm} - \epsilon_{g,2Lm}} \right] = 0.0908 \quad (16)$$

The mean beam length was defined by H. Hottel [3] to represent the radius of an equivalent hemisphere so that the incident radiation flow at the center of the hemispherical base equals the average radiation flux incident to the surfaces surrounding the gas volume. According to this Reference this flux may be given by ((fig. 7.1, page 257) H. Hottel [3])

$$Q_{\lambda i/k} = 1 - e^{-\alpha_{\lambda} L_e} \quad (17)$$

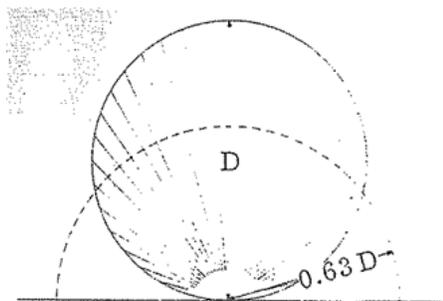


Figure 4: Mean beam length for a sphere according to Hottel [3].

The determination of the mean beam length for every combustion chamber is fundamental for the calculation of the heat radiation exchange between the isothermal zones on which the combustion chamber is divided. This representation allows for the implementation of the theory of thermal zones. The volume of the combustion chamber under consideration is equal to

$$V = (2d + 3d + 4d) \times (2d) \times (2d)$$

and since  $2d = 3d = 4d$ , the volume becomes equal to

$$V = 3 \times (2d)^3.$$

The surface of the combustion chamber is equal to  
 $A = 3 \times 2dx2dx2 + 2 \times 2dx2d + 3 \times 2dx2dx2 = 14x(2d)^2$

According to Hottel [3], the mean beam length is equal to  
 $L_m = 0.88 \times 4xV/A = 0.88 \times 4x3(2d)^3/14(2d)^2 = 0.739(2d)$

Which reduces into  
 $L_m = 0.739(2d)$  (18)

The combustion chamber, as depicted in fig. (3), was divided into 11 isothermal surface or gaseous zones. This way it was possible to identify the total exchange area between the thermal zones as follows:

Evaluate the direct-heat exchange among the zonal areas ( $\overline{ss}, \overline{sg}, \overline{gg}$ ), one set for each of the n values of the parameter K, as explained above.

Evaluate the total-exchange area of the values of  $\overline{S_i S_j}$ ,  $\overline{G_i S_j}$  and,  $\overline{G_i G_j}$   
 Employ equations (19) to evaluate  $W_j$  where  $j=1,2,3,4,5,6,7,8,9,10,11$

$$\begin{bmatrix}
 s_1 s_1 - \frac{A_1}{\rho_1} & s_1 s_2 & s_1 s_3 & s_1 s_4 & \dots & \dots & s_1 s_n \\
 s_2 s_1 & s_2 s_2 - \frac{A_2}{\rho_2} & s_2 s_3 & s_2 s_4 & \dots & \dots & s_2 s_n \\
 s_3 s_1 & s_3 s_2 & s_3 s_3 - \frac{A_3}{\rho_3} & s_3 s_4 & \dots & \dots & s_3 s_n \\
 s_4 s_1 & s_4 s_2 & s_4 s_3 & s_4 s_4 - \frac{A_4}{\rho_4} & \dots & \dots & s_4 s_n \\
 \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
 \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
 s_n s_1 & s_n s_2 & s_n s_3 & s_n s_4 & \dots & \dots & s_n s_n - \frac{A_n}{\rho_n}
 \end{bmatrix}
 \begin{bmatrix}
 W_1 \\
 W_2 \\
 W_3 \\
 W_4 \\
 \dots \\
 \dots \\
 W_n
 \end{bmatrix}
 =
 \begin{bmatrix}
 \frac{-A_1 \epsilon_1}{\rho_1} E_{s,1} & -s_1 g_1 E_{g,1} & -s_1 g_2 E_{g,2} & -s_1 g_3 E_{g,3} & -s_1 g_4 E_{g,4} & \dots & -s_1 g_m E_{g,m} \\
 \frac{-A_2 \epsilon_2}{\rho_2} E_{s,2} & -s_2 g_1 E_{g,1} & -s_2 g_2 E_{g,2} & -s_2 g_3 E_{g,3} & -s_2 g_4 E_{g,4} & \dots & -s_2 g_m E_{g,m} \\
 \frac{-A_3 \epsilon_3}{\rho_3} E_{s,3} & -s_3 g_1 E_{g,1} & -s_3 g_2 E_{g,2} & -s_3 g_3 E_{g,3} & -s_3 g_4 E_{g,4} & \dots & -s_3 g_m E_{g,m} \\
 \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
 \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
 \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
 \frac{-A_n \epsilon_n}{\rho_n} E_{s,n} & -s_n g_1 E_{g,1} & -s_n g_2 E_{g,2} & -s_n g_3 E_{g,3} & -s_n g_4 E_{g,4} & \dots & -s_n g_m E_{g,m}
 \end{bmatrix}
 \quad (19)$$

where  $W_i$  is the leaving flux density from each of zone.

$$\overline{G_i S_j} = \frac{A_j \epsilon_j}{\rho_j} \cdot g_{i,j} W_j \quad (20)$$

The equations

$$\overline{S_i S_j} = \frac{A_j \epsilon_j}{\rho_j} (s_{i,j} W_j - \delta_{ij} \epsilon_i) \quad (21)$$

$$\overline{G_i G_j} = g_i g_j + \sum_k s_{k,g} \overline{W_k} \quad (22)$$

(for each  $K_n$ ) provide the magnitudes for the parameters  $\overline{SS}$ ,  $\overline{GS}$  and,  $\overline{G_i G_j}$ , where these three parameters represent (i) the total radiation exchange area between the surface zones, (ii) the total radiation exchange area between the surface and the gas zones and (iii) the total radiation exchange area between the gas zone respectively.

The evaluation of the temperature field from the above group of equations, allowed the evaluation of  $\overline{SS}$ ,  $\overline{SG}$ ,  $\overline{GG}$  with the help of the relations

$$\overline{S_i S_j} = \sum_n [a_{s,n}(T_i)] (\overline{S_i S_j})_n, \quad \overline{S_i S_j} = \sum_n [a_{s,n}(T_j)] (\overline{S_i S_j})_n \quad (23)$$

for each zone –pair combination.

Similar expressions can be written with  $\overline{SG}$ ,  $\overline{GG}$  etc.. When temperature equilibrium is established among the chamber zones

$$\dot{Q}_{A_i} \leftrightarrow_{A_j} = E_{s,i} \overline{S_i S_j} - E_{s,j} \overline{S_i S_j} \quad (24)$$

From the second law requirement that the net radiative transport must be equal to zero when no temperature difference exists.  $\overline{S_i S_j}$  approaches  $\overline{S_i S_j}$  in the limit as  $E_i$  approaches  $E_j$ .

Formulate the total –energy balances on the zones of unknown temperature. When all  $\overline{SS}$ ,  $\overline{SG}$ ,  $\overline{GG}$  values are known and under the assumption that the combustion process is complete inside each gaseous zone (essentially the gaseous zones Nos. 5,6,7), the zonal energy conservation equations may be established:

For the surface zone  $A_i$ , the corresponding conservation equation becomes

$$\sum_i \overline{S_i S_j} E_{s,i} + \sum_j \overline{G_j S_i} E_{s,j} - A_i \epsilon_i E_i + h A_i (T_{g,c} - T_{s,i}) - U (T_{s,i} - T_a) = Q_{net,i} \quad (25)$$

The corresponding equation for the gaseous zone  $i$  becomes

$$\sum_j \overline{G_i G_j} E_{g,j} + \sum_j \overline{S_i S_j} E_{s,j} - \sum_n 4 a_{g,n} K_n V_i E_{g,i} + \dot{Q}_{c,i} = \dot{Q}_{u,gi} - \dot{Q}_{c,i} \quad (26)$$

Where

$\dot{Q}_{c,i}$  = the energy release rate, due to combustion in the gaseous zone No. 6

$\dot{Q}_{e,i}$  =the rate of decrease in sensible enthalpy of the gas inside the gaseous zone No. 6, flowing into the gaseous zone No. 7 and convection losses through the zone enclosing surfaces.

$\dot{Q}_{u,gi}$  =a transient term, due to any possible energy storage inside the zone bottom. For the present application this was assumed to be equal to zero.

In general, the above system of conservation equations is non-linear (due to the  $T^4$  dependence of the emitted thermal radiation). Once, however the temperature has been defined, the system transforms into a linear one. The final solution was made possible with the help of a repetitive procedure i.e. a (loop) by making assumptions for the zonal wall temperatures until the energy conservation equation solutions generated results similar to those of the initial assumptions. The outer wall convection losses were taken equal to those recorded by the experimental measurements, with the plant in full operation. This heat loss rate was found to be equal to 280kcal/m<sup>2</sup>.

In our case the system of equations is as follows

ZONES	1	2	2d	3	3d	4	4'	4'd	5	6	7
1	-109.1	49.32	20.23	11.25	5.14	1.08	2.45	1.17	17.25	2.6	0.229
2	49.3	-222.9	57.6	31.99	17.34	2.48	7.24	3.79	49.4	17.9	0.607
2d	20.23	57.6	-146.57	19.79	4.37	1.17	3.98	2.46	32.79	3.48	0.31
3	11.025	31.28	19.38	-231.89	53.29	10.76	31.11	16.83	6.09	46.7	6.94
3d	5.03	16.94	4.24	53.29	-136.15	6.57	18.97	2.16	3.51	21.49	3.34
4	1.07	2.3	1.07	10.43	6.34	-107.6	47.35	20.88	0.21	2.35	15.38
4'	2.26	6.68	3.68	31.42	18.36	47.34	-220.2	58.52	0.45	6.6	46.2
4'd	1.07	3.8	1.57	15.88	2.05	19.84	56.27	-142.5	0.43	4.97	31.53
5	17.25	49.42	34.49	6.09	3.6	0.21	0.45	0.43	-133.1	15.17	10.94
6	2.63	7.96	3.69	46.75	22.3	2.33	2.54	4.92	15.17	-120.2	10.91
7	0.229	0.607	0.57	6.94	3.36	15.8	45.91	31.86	11.02	14.7	-131.9

$\begin{bmatrix} E1 \\ E2 \\ E2d \\ E3 \\ E3d \\ E4 \\ E4' \\ E4'd \\ E5 \\ E6 \\ E7 \end{bmatrix}$	=	$\begin{bmatrix} 466.2 \\ 1398.7 \\ 466.2 \\ 1398.3 \\ 466 \\ 466.3 \\ 1399.3 \\ 466.4 \\ 64338 \\ 8689.4 \\ -73927.6 \end{bmatrix}$	(25)
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$$E_i = \sigma T_i^4 \tag{26}$$

Where  $\sigma = 5.67 \cdot 10^{-8} \text{W/m}^2 \text{K}^4$

Replacing for the magnitudes of the  $E_i$  parameters (Where  $i=1,2,2d,3,3d,4, 4',4'd, 5,6,7$ ) it was possible to calculate the temperature  $T_i$  for each zone illustrated in figure 3.

The feeding of the chamber with malodorous gases alternated between the two outer zonal (A and C) inlets with a period of 60 seconds. The calculated zonal temperatures for a run, after 47 seconds from the start of a given pulse, are listed below against the recorded values on the plant control room, when the malodorous gases entered through inlet A and exited through exit C. The initial assumptions for the zonal temperatures were of the order of 650 °C.

The left column contains the measured temperature magnitudes, while the right column contains the calculated ones. As it is obvious, the agreement among these two data sets is excellent.

$T_1=724$ °C	$T_1=724$ °C
$T_2=719$ °C	$T_2=718.8$ °C
$T_{2d}=712$ °C	$T_{2d}=713.3$ °C
$T_3=730$ °C	$T_3=729.5$ °C
$T_{3d}=733$ °C	$T_{3d}=732.7$ °C
$T_4=755$ °C	$T_4=756.5$ °C
$T_{4'}=758$ °C	$T_{4'}=758$ °C
$T_{4'd}=745$ °C	$T_{4'd}=743.2$ °C
$T_5=673$ °C	$T_5=671.6$ °C
$T_6=710$ °C	$T_6=711.4$ °C
$T_7=802$ °C	$T_7=800$ °C

Hence, the present study may be considered as a validation of the thermal zones method proposed by Prof. H. Hottel [3] as well as the corresponding contribution by R.J. Tucker [4] since the data generated by the employment of the above method agreed very well with the results of the relative measurands in an actual plant. Moreover, the method generated data for evaluating the effectiveness of the added combustion in controlling the chemical composition of the malodorous gases, which proved to be very close to the measured values.

#### 4. Conclusions

The present study applies the zonal method proposed by Prof. Hottel [3] and the relevant contribution by R.J. Tucker [4] in calculating the temperature field inside a furnace in a three-bed regenerative oxidizer that neutralizes gaseous pollutants (malodorous gases) for a plant producing fish feed. The calculation process employed the thermal radiation exchange among a number of gaseous and wall zones composing the furnace (combustion chamber) structure by linearizing the nonlinear energy conservation equations for each zone. The calculated temperature results agreed exceptionally well with the corresponding measurements when the plant was in full operation, validating thus the accuracy of the method of zones proposed by the above two scientists.

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