



OPTIMIZATION OF THE OPERATIONAL PARAMETERS FOR THE FURNACE OF A THREE BED REGENERATIVE OXIDIZER THAT NEUTRILIZES GASEUS POLLUTANTS

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Abstract:

The purpose of this work is to correlate the excess oxidant-air with the percentage of CO₂ in the combustion chamber waste gas of a three-bed regenerative thermal oxidizer unit for the elimination of gaseous pollutants in a given capacity.

Keywords: Three Bed Thermal Regenerative Oxidizer; Chemistry of Combustion; Emission Pollutants.

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1. Introduction

It has been used by us for the neutralization of malodorous gases coming from productive industrial processes or even waste water treatment plant. (see European Patent Application. EPO 1409924 **Patent N. Pittas** [1] this issue is globally known and it is caused by every waste treatment plant after 2-3 months of operation and by every industrial unit that releases maleodorous and pollutant gases.

There are various techniques such as scrubber chemicals and other biologicals and active carbonate beds as well or a combination of the above for solving this bad smell problem effectively, but the efficiency varies between 8-12%, as it comes from the operational experience of the units. It is a very low percentage of neutralization of bad smell in comparison to the problem that is created to the surrounding residents and the workers as well (health problems and property devaluation).

The operation of these units with different dynamics, that we installed in industry, with identical use for this purpose, had excellent results in reducing the maleodorous air pollutants and the aim is now, to optimize the function of these units for a further reduction of atmospherical pollution. The limitation concerning the emission of waste gas is very strict globally, about the cleaning waste gas systems. In the particular unit, the following numbers were measured in waste gas. Concentration COT in chimney $\leq 20 \text{ mg/Nm}^3$

$$\begin{array}{l} \ll \quad \text{NO}_x \quad \ll \quad \ll \quad \leq 50 \text{ mg/Nm}^3 \\ \ll \quad \text{CO} \quad \ll \quad \ll \quad \leq 100 \text{ mg/Nm}^3 \end{array}$$

Specifically, the existing European legislation sets a much higher limit in the numbers of usual waste gas concentration.

In order to succeed this, because the temperature of the combustion chamber is about 750 °C, and heat transfer is transferred completely through thermal radiation, we use the model of thermal zone of H. Hottel [2] in order to define the thermal flows and temperatures in the combustion chamber, so as to get clear the correlation between radiation and composition of waste gases.

In this way is established theoretically the operation of the unit and become clear the details that need to be taken in consideration for the functional optimization of the units.

In addition, developing the theoretical foundation of the thermal layers model, and by resulting is the same theoretical and measured values, we end up in certification of H. Hottel [2] theory.

In specific, the measured percentage of composition of waste gas, leads to the calculation of **partial pressure** per waste gas, through Dalton's law.

We assume that waste gases (vapor and carbon dioxide) are grey and follow Lambert's law.

The theoretical model of this mixture of waste gas is composed of vapor, CO₂ and a pure gas.

From the approved diagrams of H. Hottel [2] and the use of regression analysis we define the emitting functions of vapor and carbon dioxide depending on the track width PL regression analysis in each gas being under standard temperature after we have first specified the mean beam length of combustion chamber. Accordingly, we define the overlap and after we have elaborated the equations that express the model, we end up in the function that associates the emissivity of each gas with the thermal absorption coefficient.

Furthermore, we determine the correction coefficients of emissivity through other diagrams because the combustion chamber works in sub pressure and all numbers should be adjusted in a different pressure of 1 atmosphere in which all H. Hottel [1] diagrams are calculated. In this way we have determined the emissivity of the waste gas mixture for a PL track width.

In order to estimate the absorption coefficient, the whole procedure must be repeated for double geometrical length.

Subsequently, we replace in the equation that connects the emissivity of waste gas mixture with absorption coefficient. The absorption coefficient is directly connected with thermal radiation through R. J. Tucker [3] equation but H. Hottel[2] diagrams as well, which results that the increasing composition of waste gas evokes in absorption coefficient reduction and this leads to increase of thermal radiation and gets the max value for $K=0$, where K is the absorption coefficient.

To specify the thermal flows inside the combustion chamber, we first have to define the thermal radiation which falls, is absorbed and partially reflected for numerous times on the walls and the molecules of gases in the chamber, the possible exchange ways as well.

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 is to calculate the thermal balance of each zone and measure the emitted power per thermal zone. Therein after, with Stefan Boltzmann law, calculate the corresponding temperatures.

1.1. Short Description Three Bed Thermal Regenerative Oxidizer

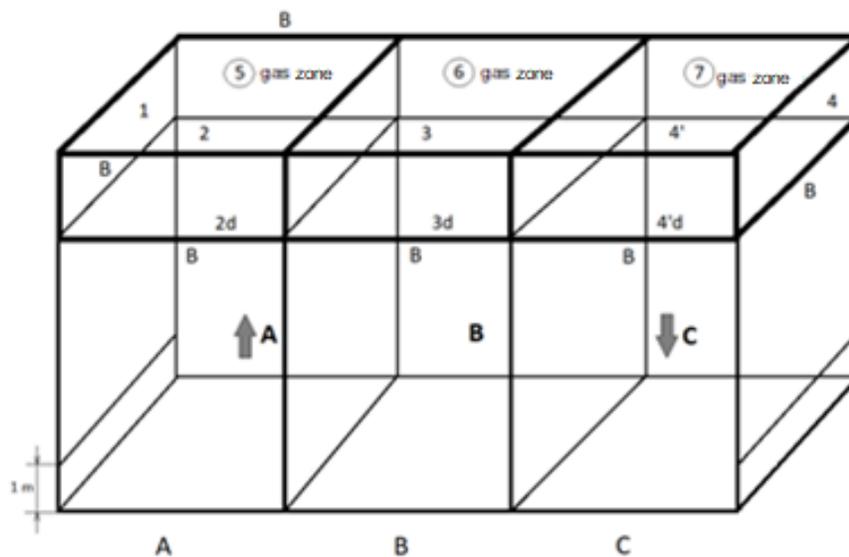


Figure 1: Tree bed thermal regenerative oxidizer

During the normal operation these ceramic beds contain stored heat from previous operating cycle. The contaminated waste gas stream enters one of the three beds (e.g bed A). As this travel through the ceramic bed 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.

A standard gas fired burner is then used to raise the temperature of the now preheated waste stream to the final operating temperature.

The hot combustion of gasses then exits the RTO through one of the remaining beds (e.g bed C), transferring most of their heat to the ceramic heat transfer medium for recovery in a reverse cycle. During this reverse cycle, waste gas is diverted to enter through the third bed (e.g. 3) and exits through bed B.

Bed B was purged during the previous cycle.

At the same time, fresh air is used to purge residual gases remaining in bed A into the combustion chamber for destruction of their VOCs.

Cycle are then repeated alternately cooling one bed, heating another, and purging the third.

Since the complete cycle of operation during three minutes, and for maleodorous gas to crossing the bed A after the combustion chamber and then the bed C and after exit in the chimney require one minute. We will adapted our calculations in time 1 min.

The obtain results of calculation must be identical if the entry and the exit of maleodorous gas change.

The present paper is a validation of the thermal radiation of thermal zones on H. Hottel[2] model alongside R.J. Tucker [3]model, in an realtime operating unit. The effect of thermal radiation on chemical composition of waste gases is investigated and documented.

With the use of experimental data of H. Hottel [2] diagrams and LECKNER [4] equations concerning the emissivity, as also the experimental data of H. Hottel [2] and R. J. Tucker [3] diagrams concerning the total exchange areas between thermal zones the final purpose is to define the thermal radiation exchange between the zones and the achievement of thermal equilibrium for every thermal zone.

Solving the equation system of thermal balance obtain the values of temperatures of each zone (surface or gas) in which the combustion chamber is divided. The equation system is stable, and the determinant are symmetrical a fact that leads to a simpler solution.

The values of the resulting temperatures are close to 98-99% with the real-time measured values which are transferred to thermocouples and depicted on the control panel of the operating unit of thermal oxidizer in Lecheo Korinthos.



Figure 2: The three bed thermal regenerative oxidizer 22K LECHEO-KORINTHOS-ZOONOMI AEBE

This unit has been established in Lecheo since 2005 with excellent results, 100% success in neutralization of maleodorous waste gas, of a flow rate 22000Nm³/h total supply, coming from the fish feed manufacturing industry, ZOONOMI AEBE LECHEO KORINTHOS.

The basic geometry of the thermal three bed oxidizer is depicted in fig. 1, the combustion chamber and the longitudinal section of it as well, in fig.3, along with the measured fuel consumption and the chemical analysis of waste gases.

The values of measurements reported in this paper (hourly supply of waste gas for processing, consumption per hour and composition percentage) are real and measured in the operating unit in Lecheo Korinthos.

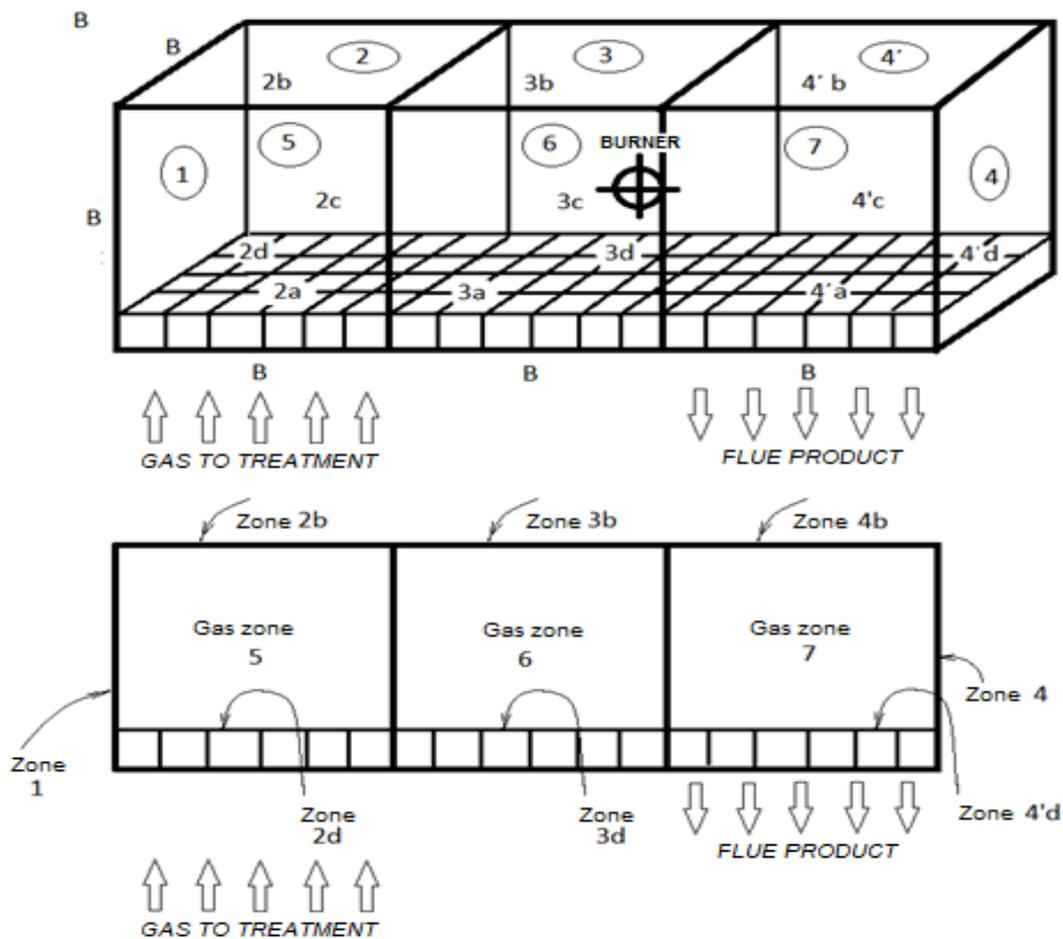


Figure 3: Chamber of combustion chamber-three bed thermal regenerative oxidizer and longitudinal section

Below exposed the values of temperature after 47 s for every thermal zone of the divided combustion chamber. When the entry is the bed A and the exit is the bed C.

To the right column are the values of temperature become from the theoretical calculation and to the left the values depicted in the control panel of the unit.

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

In advance, the thermal equilibriums involve the wavelength through the absorption coefficient, which depends on the average geometrical length, which is also depended on the dimensions of the combustion chamber. In conclusion the results are general and give the opportunity to design and measure similar thermal regenerative oxidizers with every possible function and dimension, which will have identical temperature allocation inside the combustion chamber, same composition percentage but different fuel consumption depending on its power.

The thermal oxidizer we study, has a complex geometry and furthermore, the surfaces that combine it are of different material with different thermal endurance and thermal storage, a detail that results to different emissivity, something that makes it more complicated to analyze this specific oxidizer.

This project is a tool for every projectist in order to help dimensionalise the three bed thermal regenerative oxidizer with the emitting composition percentage of coming out waste gases, inside the regulation framework of the existing legislation.

The existing international bibliography does not contain a validation of the H. Hottel [2] - R.J. Tucker [3] method, about thermal zones in a complex combustion chamber such as the 3 bed regenerative oxidizer in a specific real time operating unit with measured data during operation. The aim of this paper is to optimize the functional parameters of the unit with the final goal, neutralization of maleodorous waste gases under process, with the minimum fuel consumption, and the chemical composition of the combustion products will not be a further burden on the environment. Accordingly, we need to correspond to the highly strict framework of criteria in European legislation about air pollutants and waste gases, by studying the effect of thermal radiation on the composition of gases.

2. Methodology

Initially, we need to calculate the emissivity of each gas that composes the waste gas mixture. Subsequently, construct a model of this waste gas mixture, so by adding the different emissivities of each gas and subtracting the overlap, we get the total emissivity of the mixture for a certain wavelength. Furthermore, the chamber is working in subpressure so we need to define the correcting coefficients with which we multiply the corresponding emissivities.

Finally, we work on the equations of the model of gas mixture which leads to a relation between the composition percentage of waste gas and the absorption coefficient of thermal radiation. The supreme parameter in thermal radiation exchange among thermal zones.

This work is part of a larger one which has as its object the fluid-thermal analysis, namely the determination of the heat fluxes and temperatures in each zone of the combustion chamber, three bed thermal regenerative oxidizer using the thermal radiation and given the composition of the flue gas and chamber pressure combustion.

For this reason, in addition to determining the thermal radiation incident to each wall, the volume of the gas (CO₂ or water vapor) is partially absorbed and partially reflected indefinitely, it is necessary to determine the emissivity of each gaseous component.

The total heat radiation exchanged between the surface zones and the gas volumes in each possible combination is then determined. Finally, thermal energy released by combustion, thermal losses and thermal convection for each energy balance of the surface or gas zone (in totally 11 zones) divided by the combustion chamber according to the thermal zones method is offset.

It is very important that the exact value of the oxidant so that combustion is mixed and burned for the safety of the thermal three bed oxidizer and, at the same time, the formation of flue gas within the framework of European legislation.

The regenerative three bed thermal oxidizers are the ideal type of oxidizers for neutralizing gaseous pollutants and use natural gas or LPG as a fuel.

First because it contains little or no presence of S in its composition and consequently no additional pollutant from its combustion is produced and released into the atmosphere.

The thermal oxidation method for breaking down the chemical bonds of the harmful organic compounds into a combustion chamber with a temperature of about 750°C and their conversion to water vapor and CO₂ is catalytic to completely neutralize the majority of the gaseous pollutants.

Because the complete cycle requires three minutes.

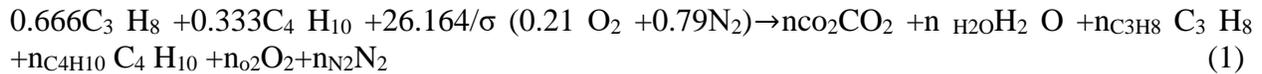
We will reduce our study in one minute, namely when the maleodorous flow passes the thermal regenerative oxidizer entering from the bed A into the combustion chamber and leaving the bed C and then the chimney.

We first calculate the chemical reaction of LPG and then calculate the moles of O₂ required for its stoichiometric combustion and consequently the amount of air required. Then we write the chemical reaction in its full form with the fuel mass to oxidant ratio is equal to the coefficient of the chemical reaction.

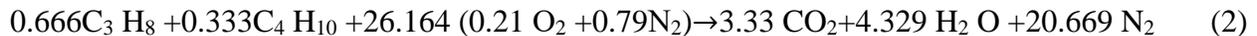
Knowing the hourly fuel consumption we calculate and write the actual chemical reaction that is being realized and as we know the chemical composition of the flue gases we express the concentration of CO₂ as a function of the excess of the oxidant equal to σ .

3. Chemical Reaction –Combustion LPG

The chemical equation of combustion of LPG because it consists of three parts of propane and a part of butane is the following



If $\sigma = 1$ the chemical reaction is stoichiometric then the above equation become



Stoichiometric combustion of one LPG with air requires a number of mol O_2 capable of oxidizing $0.666 \times 3 + 0.333 \times 4 = 1.998 + 1.332 = 3.33$ carbon atoms in CO_2 and $0.666 \times 8 + 0.333 \times 10 = 5.328 + 3.33 = 8.658$ H_2 atoms in water vapor.

For example, $3.33 \times 2 + 8.658 / 2 = 6.66 + 4.329 = 10.989$ O_2 atoms or $10.989 / 2 = 5.4945$ moles of molecular oxygen (O_2) are required for the oxidation.

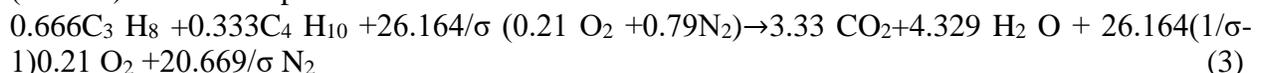
And because one mole of air contains 0.21 moles of molecular oxygen (O_2), $5.4945 / 0.21 = 26.164$ moles of air are required to have stoichiometric combustion

The molecular weight of LPG is equal to $0.666 (3 \times 12 + 8) + 0.333 (12 \times 4 + 10) = 48.61$ kg / mol
The molecular weight of the air is equal to $0.21 \times 32 + 0.79 \times 28 = 28.84$ Kg / mol and thus the stoichiometric ratio of the mass of the required fuel to the mass of the required oxidant is $48.61 \text{ Kg / mol} / 26.164 \text{ mol air} \times 28.84 \text{ kg} = 48.61 / 754.56 = 0.064$, i.e. about 15%.

But our own case is the full consumption of one of the reactants without the creation of intermediary products. << dissociation >> We have mixed fuel, namely LPG fuel, not only for economy but primarily for safety reasons. And that is why it is imposed < 1 .

The fuel is completely oxidized, but N_2 and O_2 remain, as measured by the carrier that carried out the measurements with an O_2 concentration of 19.8%, CO_2 of 0.6% and H_2O of 6%.

More specifically 26.164 moles of O_2 are involved in the combustion, while the remaining 26.164 $(1/\sigma - 1)$ do not take part and therefore we have



To determine the composition of the molecular weight components or the moles of the flue gas mixture we will have

$$\text{Since } pv = nRT \text{ and } M = m/n = \frac{\sum_{i=1}^N m_i}{n} \quad (4)$$

Since the concentration of CO₂ in the waste gases is 0.6%, it follows from the above equation that $3.33 + 4.329 + 5.49 (1 / \sigma - 1) + 20.669 / \sigma$ mol of the combustion products contained 3.33 mol CO₂ and consequently to 100 mol 0.6 mol CO₂ from where $555 = 2.169 + 26.669 / \sigma$ (5)

results and the actual excess of air is equal to $\sigma = 0.048 = 1 / 20.8$ (6)

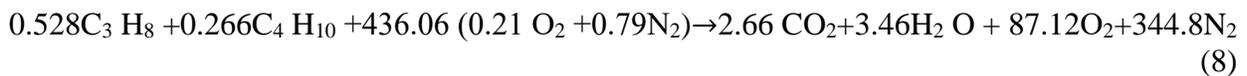
in the chemical reaction.

Thus, the ratio of fuel mass / oxidant mass = $1 / 20.8 = \sigma$ and therefore the chemical reaction is $0.666C_3 H_8 + 0.333C_4 H_{10} + 545.08 (0.21 O_2 + 0.79N_2) \rightarrow 3.33 CO_2 + 4.329 H_2 O + 108.9 O_2 + 430.6 N_2$ (7)

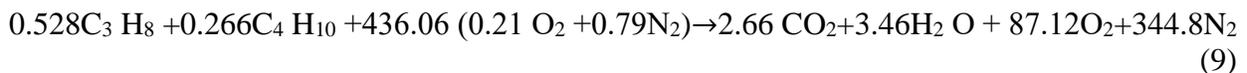
In this thermal three bed oxidizer unit operate for given capacity 22000 Nm³ / h of gas dips are being input for treatment with an inlet temperature T = 50 ° C and an outlet temperature of 110 ° C.

However, since LPG consumption in the thermal oxidizer rises hourly to $22.000Nm^3 / h \times 0.32kcal / ^\circ C \times (110-50) ^\circ C / 11500 kcal / ^\circ C kg = 22.000 \times 0.32 \times (110-50) / 11500 = 36.7kg/h$ LPG. Where 11500 kcal/⁰Ckg is the lowest calorific value of LPG. And because the molecular weight of LPG is equal to 45.8 kg, we will have $36.7 / 45.8 = 0.8mol / h$ LPG, therefore the actual chemical reaction that is taking place is the following.

We multiply both members of the above chemical equation by the ratio of 0.8 and thus the actual chemical equation that is realized is obtained.



With a total number of moles of products per hour equal to = $2.66 + 3.46 + 87.12 + 344.48 = 437.72$ moles / h.



The calculation of the excess of the oxidant in the RTO thermal oxidizers can be done only by the percentage of CO₂ in the waste gases because the percentages of water vapor and excess O₂ in the waste gases contain both water vapor and O₂ incoming gases to be treated and this leads to confusion.

From the last equation (9) it follows that

2.22 mol of CO₂ is contained in $2.22 + 2.89 + 17.477x (1 / \sigma - 1) \times 0.21 + 13.80 / \sigma$ mol of products when burning LPG (10)

The y mol of CO₂ will correspond to 100 mol of products and thus results

$2.22 / y = 1.44 + 17.6 / c / 100$ from where it occurs (11)
 $y = 222\sigma / 1.44\sigma + 17.46$

The y function must be between 0 and 1

$$0 < 0.222 \sigma / 1.44 \sigma + 17.46 < 1 \quad (12)$$

And σ takes values between it

$$0 < \sigma < 0.079$$

For $\sigma = 0.048$, $y = 0.6$ and this value corresponds to the percentage of CO₂ in the waste gases.

This value is identical to the measurements carried out by an independent carrier in the RTO operating unit

For $\sigma = 0.07$ $y = 0.88$ ie 0.88%

For $\sigma = 0.06$ $y = 0.75$ ie 0.75%

For $\sigma = 0.048$ $y = 0.6$ ie 0.6%

For $\sigma = 0.03$ $y = 0.38$ ie 0.38%

4. Conclusion

It follows from the above that increasing the excess of the oxidant-air in the mixture to be combusted reduces the percentage of CO₂ in the waste **gases**.

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