# CRITICAL EVALUATION OF THE OXYGEN-ENHANCED COMBUSTION APPLICATIONS IN INDUSTRIAL HEATING SYSTEMS

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***Abstract.*** *Most industrial heating processes require substantial amounts of energy, which are commonly generated through combustion such as hydrocarbons fuels as natural gas or oil. Most combustion systems use air as the oxidant. These systems can be enhanced using an oxidant that contains a higher volume of oxygen than the one that is found in the air. This is known as oxygen-enhanced combustion. The methodology can bring benefits to the heat transfer, available heat, productivity, decreases the pollutant emission, increases the thermal efficiency as improvement of the ignition characteristics. Glass, metals and ceramic industries in the world already use this process. The present work brings a critical evaluation of the use of this technique, identifying important points, especially in the transfer of the heat and pollutant's emission, for application of this technique in the industry of petroleum and its chain, which oxygen enrichment is not used too much.*

***Keywords:*** *Oxygen-Enhanced Combustion, Oxygen Enrichment.*

## 1. INTRODUCTION

The efficiency energetic control in industrial equipments was always a relevant subject in the industrial activity. Amongst them, the industrial burners present themselves as an equipment type of big significance, once this is used in many others, as boilers, gas turbines, ovens; amongst others.

Its utilization is distributed in many industries sectors, like in the fields of oil, gas, petrochemical, steel and automobile in special. Another important aspect is that the burn uses the process of combustion for the energy generation. According to Turns (1996), approximately 89% of the used energy in the United States was proceeding from sources of fuel combustion in 1989.

In the current situation of Brazil, which the production and the use of oil, natural gas and alcohol is in full expansion, the increase of the potentiality and the control of the industrial burners became an important point to the optimization and development of more efficient energetic equipment and with lesser impact to the ambient.

In this context, researches that were elaborated through projects with new methodologies and new processes of combustion control are well coming to the information promotion to the scientific community and for the technological development. Amongst these researches, the industrial application of the air combustion with oxygen enrichment appears in the last years (Oxygen Enhanced Combustion - OEC), with the recent technologies of oxygen production, it propitiated a bigger competitiveness of the oxygen utilization for applications in industrial combustion.

Baukal Jr. (1998) commented that the lowest levels of the enrichment- volumetric fractions of oxygen ($O_2$) in the air of combustion below of 30% - are used in applications of retrofit normally, which only small modifications are necessary in the existing equipment and expressive benefits are gotten with the significant increase of the production tax in processes of heating with small levels of enrichment. In the majority of the cases, burners can operate successfully using air of combustion enriched with $O_2$ up to 28%, without modifications in the equipment.

Also, Baukal Jr. (1998) informed that many industrial processes of heating can all be improved through the substitution of part or total air with oxygen of high pureness. Typical applications include heating of metals and fusing; fusing of glasses and calcification. In the report of the Gas Research Institute, the following applications had been identified as possible candidates to the OEC: processes that have high temperatures of exhausts, low thermal efficiency, because of the limitations of the heat transference typically, limitations in the income that can be benefited with the transference of additional heat, without adverse effect in the quality of the product and there are gases of exhaustion with particularities, with high emission of $NO_x$, and volume limitations of the exhaustion gases.

The present work presents the benefits and the potential problems of the enrichment use of the combustion with oxygen, making a critical evaluation of this use in heating processes, and its possible application in the industry of oil and its derivatives.

## 2. ENERGETIC ASPECTS IN THE OEC UTILIZATION

The enrichment methods used in industrial processes of the industries as the glass and ceramics sectors are presented by Baukal Jr, and it's divided in four basic processes: (1) through the addition of oxygen in the airflow admitted in the burner (enrichment air), (2) through the injection of $O_2$ directly in the generated flame of the fuel with air ($O_2$ Lancing), (3) substituting the air of combustion for pure oxygen (Oxy/Fuel) and (4) providing separately oxygen and air for the combustion, related to Air-Oxy/Fuel normally. The four methodologies are presented in Figure 1.

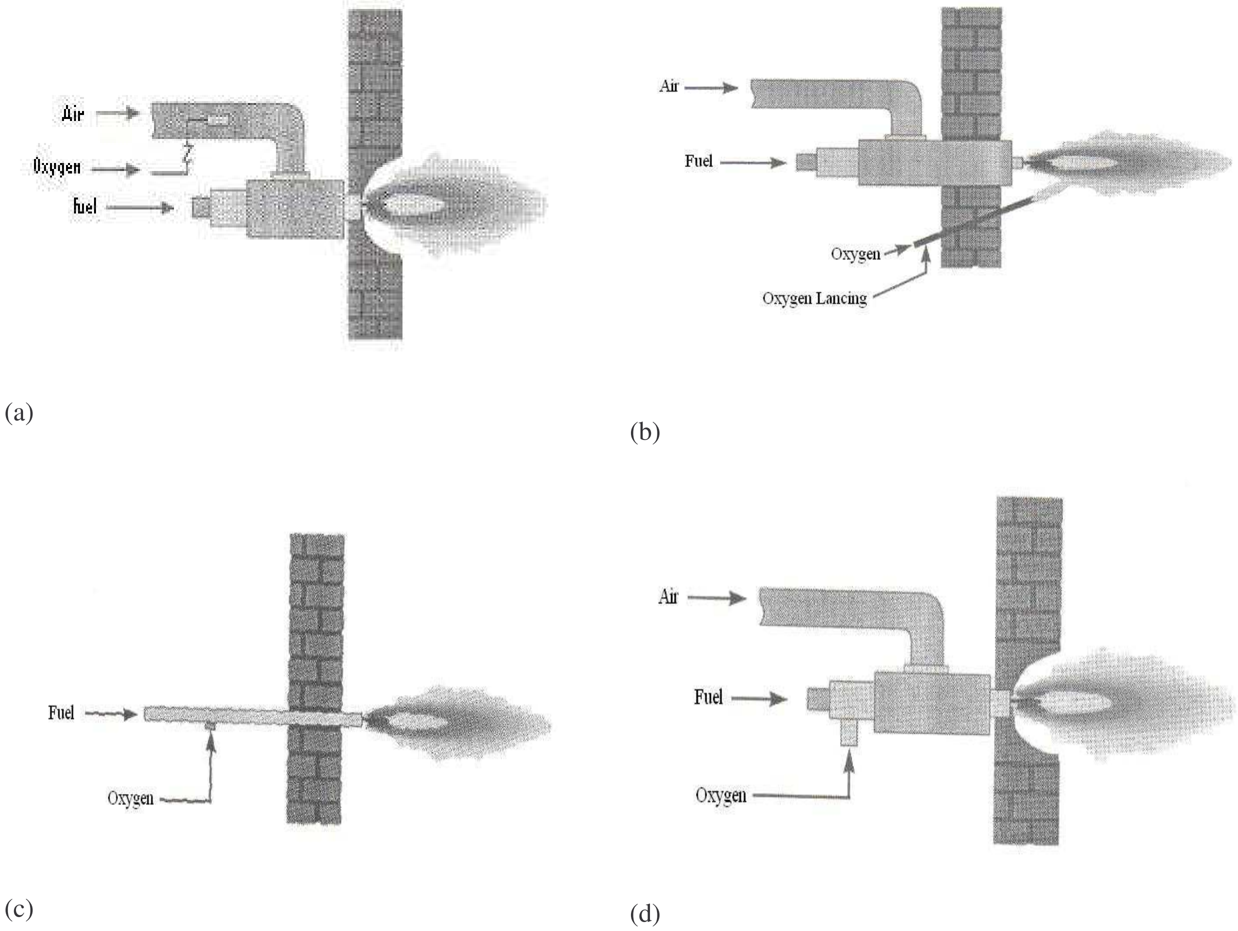


Figure 1: Enrichment Methodology with $O_2$: (a) Air Enrichment; (b) $O_2$ Lancing; (c) Oxy/Fuel; (d) Air-Oxy/Fuel (Source: Baukal Jr., 1998).

For the systems that operate with direct addition of oxygen in the airflow (enrichment air), and depending on the level of enrichment, the combustion equipment does not need to suffer significant alterations, the molar fraction is given in the following form:

$$\Omega = (O_2 \text{ fraction in volume in the oxidized})/(\text{total volume of the oxidized}) \quad (1)$$

For bigger agreement, atmospheric air possess $\Omega = 0.21$ or 21%. An airflow enriched with 10% of oxygen means that in this case $\Omega$ possess a value of 0.31 or 31%.

In a preliminary analysis, the mechanism of airflow with oxygen enrichment presented in the figure 1 (a) is presented as the adaptable and simplest methodology to the existing systems of industrial combustion for the power generation (thermoelectric), for low levels of enrichment does not demand great structural changes to its implantation. However, new studies must be done to verify the interface of the implementation of the energy performance with the generated ambient impact with the implantation of the OEC in these systems.

Amongst the energy benefits of the OEC use, we can detach - as described by Baukal Jr - the productivity increase, improvement of the flame characteristics, lesser volume of the combustion gases, greater efficiency in the heat transfer, improvement on the product quality, reduction of the fuel consumption, raw material and the costs of new equipments or the possibility to increase the existing equipment production.

Referring to the increase of the productivity, the author commented that in heating processes, the thermal radiation is the way to transfer the dominant heat. The radiation depends on the absolute temperature of the fourth power order [$Q = Q(T^4)$]. The greater temperatures, which are associated to the OEC, increase the radiation of the flame, increasing the heat transfer; it is implemented with the OEC through radiation and through the increase of the concentrations of $CO_2$ and $H_2O$ in special; they are participant gases in the transference of the heat through radiation - which produce greater taxes of raw material processing in the combustion chamber. Like that, more raw material can be processed in an existing system, or new systems will be lesser to reach the same production. Thus less energy will be necessary to produce the same amount of production.

The increase of the costs with the adoption of the OEC in combustion existing system is less usually, comparing to the capital costs used in the expansion of existing systems and acquisition of new equipments for the increase of the production.

Baukal, C.E. and Gebhart, B. (1997) studied the influence of the OEC in flames with natural gas. The thermal radiation was drastically implemented with the removal of the $N_2$ of the oxidant.

With the use of oxygen in substitution to the air, more energy remains in the chamber for processing one determined load, in substitution to the loss of energy caused by the discarded enthalpy in the chimneys through the $N_2$, which only absorbs energy in the combustion. With the increase of the available heat in the chamber, the productivity is raised by having less loss of energy through the chimneys, and, minor fuel consumption will be obtained consequently.

On the economic aspect, the energy benefits bring reduction of costs with new equipments that were resulting from the greatest productivity of the equipments and from the improvement in the transference of the heat with the OEC. If the equipments are more efficient, these will be lesser and will demand fewer spaces, becoming more competitive in relation to the equipments with air as oxidant. The increase of the production of the existing equipment is caused by the productivity increase, already commented above.

Another important point is the reduction of the costs with raw material, since the utilization of the OEC reduces the speed of the gases draining for needing a lesser outflow of comparative oxidant to the systems with air. This allows minor drags of impurities, which can provide a lesser cost with cleanness systems and laundering of raw material, reducing, therefore, the cost with raw material. Also another factor to be considered is starting from the greatest productivity of the systems with OEC, lesser amount of raw material will be necessary to get the specified end item, what reduces the cost with these materials.

Being all these energy aspects benefic, why not use this technology in the industry of oil and its derivatives? Does it involve the aspects of market price of the oxygen? Is there any concern with the increase of expenses in the implementation of changes for the use of this technology? Or, is it distrust because of the few information about potential problems that can occur in the systems of the sector simply? These questions need to be argued to evaluate the viability of the technology in the sector. This sector must be analyzing this technology for our implementation on burners that can bring economic and environmental savings.

Through what was displayed above, through the fact of the greater energy efficiency, the OEC must be faced through the industry of oil and other industrial segments, as an important technological implementation for the guarantee of the energy efficiency, diminishing the fuel consumption, and, with this, the technology becomes a factor to contribute to the reduction of emissions and global warming. The ambient aspects of the OEC are presented in the following.

## 3. ENVIRONMENTAL ASPECTS OF THE OEC UTILIZATION

One of the main points of the ambient benefit with the use of the OEC is the reduction of the exhaustion gases volume, since the enrichment with $O_2$ involves the nitrogen removal in the oxidant chain basically. Compared to the systems that use atmospheric air, the OEC will reduce the volume of inserted exhausts in the atmosphere significantly, depending on the oxygen fraction in the used oxidant. With the greatest availability of oxygen in the oxidant, it’s going to have lesser fuel consumption; the combustion processes become more efficient and less pollutant consequently.

Baukal Jr. (1998) also presents aspects about the emission of pollutants that are presented in the following.

### 3.1. $NO_x$

Baukal Jr. (1998) informs that the $NO_x$ refers to the nitrogen oxides. These generally include the monoxides of nitrogen also known as acid nitric, and nitrogen dioxide ($NO_2$). They can also include oxide nitrous ($N_2O$), also known as gas of the laugh, as also, less common nitrogen and oxygen combinations, as $N_2O_4$. In good part of the heating applications with high temperature, the majority of the $NO_x$, which was found in the exhausts in the chimneys, is in the form of NO.

The NO is poisonous for the human beings and it can cause irritation in the eyes and skin, nauseas, migraine and gradual loss of conscience. A long exposition to the NO can be fatal. Others negative effects caused by the $NO_x$ are summarized through its effect in the environment. One of these effects is the acid rain production, which aid in the destruction of trees, plants and plantations, besides causing damages in building. Another important effect, caused basically by the $NO_2$ is the production of the mist effect (smog), where photochemistry effects are caused in the atmosphere through the contact of the solar light with molecules of $NO_2$ and fuels not burnt. However, the same NO possess vital importance in the human being physiology. Recent researches point to the aid of the digestion and regulator of the sanguineous pressure to the action as messenger in the nervous system.

The use of the OEC produces contradictory effects in the formation of $NO_x$ (basically NO). There are two effects that compete in the production of the NO in the systems with OEC. As the concentration of $O_2$ increases in the chain of the oxidant, the temperature of the flame tends to increase, and this speeds up the formation of $NO_x$, caused by the exponential dependence of the thermal $NO_x$ reactions with the temperature. However, in greater levels of enrichment (from about 70%), the concentration of $N_2$ diminishes drastically and the formation of $NO_x$ falls consequently.

The formation of $NO_x$ also can be affected by the project of burners. New researches must be implemented for a greatest agreement of the effect caused in the configurations of the burners in the $NO_x$ formation.

About this aspect, to have the real effect of the OEC influence on the formation of $NO_x$ in low levels of enrichment, it is necessary to connect the effect of the temperature increase to the heat transmission through radiation, once, as it's going to be described later, the formation of the soot is implemented in certain regions of the flame in most part of the cases, diminishing its temperature, and the emission of $NO_x$ consequently. For this, new information must be raised for the best agreement of this connecting process between the soot, thermal radiation and the formation of $NO_x$.

### 5.2. CO

The formation of the CO with the OEC tends to be reduced with the increase of the grade in the volume of the oxygen in the oxidant. The OEC promotes a more complete burning of the fuel hindering the CO formation. The CO formation is connected to the formation of the NO through chemical effect. In reducing atmospheres, the CO formation is preferential in relation to the NO.

### 3.3. Volatile Organic Compounds (VOC)

The VOC are generally aliphatic molecules with small weight and aromatic hydrocarbons with alcohols, ketones, esters and aldehydes. Typical VOC includes benzene, acetaldehyde, and toluene. It is expected that the VOCs emissions diminish with the OEC, as resulted of the increase of the temperatures of the flame, the lesser dilution and increase of the residence time in the combustion chamber. The destruction and removal efficiency of the VOCs have increased with the OEC drastically. In burnt municipal of solid residues, the VOC emissions had diminished through the use of low levels of enrichment with $O_2$ in the air of combustion, as described for Strauss et al. (1988).

### 3.4. $SO_x$

Sulphur oxides, usually related as $SO_x$ possess great importance in the emissions of the industrial combustion systems. According to Baukal Jr. (1998), the use of the OEC has not brought changes in the emissions of $SO_x$ normally. However, as seen previously, since the volume of exhaustion gases is reduced with the use of the OEC, the emission of $SO_x$ will be lesser in comparison to the systems that use atmospheric air as oxidant.

### 3.5. $CO_2$

OEC can reduce the $CO_2$ emissions significantly, because of the increase of the available energy efficiency, which guarantees the same amount of energy with lesser fuel consumption. According to Farrell et al. (1996), the substitution of burners with air, through oxy-fuel equipment in processes of metal casting, generated a reduction of 55% in the $CO_2$ emission.

The reduction of the $CO_2$ emission is an important aspect to have a base of the relation cost/ benefit of the OEC implantation. With the aspects of the greenhouse effect, this factor must be written up in the financial and social profits generated with this reduction. The industrial sector must include in its evaluation of financial return, the aspects of the greenhouses gases reduction ahead the benefits generated for the society. This aspect can be a relevant factor for the use of this technology in the oil industry and derivatives.

### 3.6. Soot

The soot is a solid particular material with carbonic structure produced in the combustion, some of them possess appreciable amount of hydrogen, beyond other elements and composites that can be gotten from the original structure of the fuel

As Glassman (1987), the characteristics of the solids produced in the combustion differ in function of their conditions of formation. One of the most important difference is when the particle was formed in homogeneous reaction in the vapor phase, or as deposit on a solid surface (superficial growth), which can be located inside or close to the reaction zone.

According to Smiths (1981), the formation mechanisms of the soot are given by the pyrolysis of the fuel or pyrolysis in the presence of an oxidant, nucleation, superficial growth, coagulation and agglomeration.

Ideally, the soot is desired in the beginning of the flame to implement the heat transfer through thermal radiation and to be destroyed in the end of the flame to not be emitted to the atmosphere.

Baukal Jr. (1998) informs that the use of the OEC generally reduces the emission of the comparative soot to the burners with air. However, new projects of oxy/fuel equipments still presenting soot emission. It shows that there is an opened field for the study of the OEC in the formation of the soot and its exploitation as an important factor for the implementation of the energy performance of the burners, from its paper in the thermal radiation. Brookes and Moss (1999) had confirmed the close relation between the taxes of the soot production and the loss of the flame heat through radiation, through the study of computational model of the production prediction of the soot and thermal radiation.

Some studies of the enrichment influence through oxygen of the combustion air in the soot formation are presented in the following.

Lee et al. (2000) studied the influence of the diffuse flames enrichment of methanol/air through the $O_2$. The $O_2$ was injected in the airflow, enriching the air to 50 and 100% of $O_2$ in volume conditions, considering the air with a mixture of $N_2$ and $O_2$. The authors verified the reduction of the soot production in the two conditions of the enrichment, being the 100% condition the one that stimulated greater reduction. Zelepouga et al. (2000) also verified the influence of the enrichment with $O_2$ in the side of the air in diffuse laminar flames of methanol. On this time, the evaluation parameter was to the integrated radial concentration of the soot. The authors evidenced a reduction in the formation of the soot for volumetric grade of $O_2$ in the air of 35, 50 and 100%. The authors had also evidenced that the soot concentration would be lesser for flames with greater grades of $O_2$, because of the lesser lengths of the flame, and the fewer times of residence that would be available to the growth of the particle of the soot

In some works the variation of the $O_2$ grade in the side of the air was made in a such way that the $O_2$ grades were lesser than the value, which was found in the atmospheric air. This was obtained, considering the air as a mixture of $N_2$ and $O_2$, which there was a greater volumetric proportion in favor to the $N_2$. These works are giving in the following.

Glassman and Yaccarino (1980) studied the influence of the variation in the $O_2$ concentration in the side of the oxidant in the trend to the formation of the soot in ethene flames. The $O_2$ used grades were found about 9 and 50% (molar fraction). The authors verified that the trend of the soot formation was the minimum for the grade around 24%. To grades that were lesser than 24%, the decrease of the $O_2$ grade would increase the trend of the soot formation, while for higher grades than 24%, the decrease would diminish the trend. These trends were explained through the competition between the fuel pyrolysis tax and the oxidant of the soot in the domain of the process.

Du et al. (1990) examined the effect of the $O_2$ concentration in the side of the oxidant on the formation of the soot in propane and ethene flames. The authors concluded that there was an increase of the soot concentration with the variation of the $O_2$ concentration between 15 and 21%, and this effect was done because of the increase of the temperature, which was occurred in this variation.

Goldstein et al. (2002) verified the influence of the $O_2$ grade in the side of the oxidant in a daily pay-mixed flame. The authors used the immersed flame in the atmospheric air, and it was involved through a $N_2$ shield. It was verified that with the barrier of $N_2$, the soot formation in the flame was increased; fact that was explained through the lack of $O_2$, which was available to intensify the oxidation process.

Beltrame et al. (2001) examined the influence of the enrichment air with oxygen in flames in the methane countercurrent. The authors verified that the grade increase of the oxygen in the oxidant increased the soot formation. The grade band of the oxygen in the oxidant, which was tested in the work, was from 21 to 100%.

Santos et al. (2002) studied the influence of the enrichment oxygen of the combustion air in diffuse acetylene flames. The results suggest that the use in set of the variation of the $O_2$ grade of the air speed can represent an useful tool to control the soot, once depending on the speed and the grade of $O_2$ used, the soot formation can be implemented or not. The levels of enrichment with $O_2$ used were from 2 to 4%.

Wang, L. et al. (2005) evidenced that there is an increase on the formation and oxidation of the soot with the OEC use, caused by the increase of the flame temperature basically. They also verified that the radiation caused by the soot modifies the structure of the flame; it diminishes its temperature and reduces the emission of $NO_x$ substantially, especially in the zone of the flame top.

Evaluating the described aspects, the formation control of the soot can be an important factor for a more rational implementation of the OEC. With this control, the transferred thermal radiation in heating processes can be monitored, and the formation of $NO_x$ controlled consequently. This aspect can be a factor in the use of the technology, and its peculiarities must be more searched.

## 4. POTENCIAL PROBLEMS OF THE OEC UTILIZATION

The potential problems of the OEC utilization are presented by Baukal Jr: damages in the heat-resistance, which were caused by the improper heat distribution; heating not uniform; instability in the flames; increase of the pollutants emission - the $NO_x$ in special - and increase of the noise; possibility to have backfire (flashback) in daily pay-mixture burners.

All these aspects must be weighed up, associating to the energy and ambient aspects to take the decision of the OEC technology implantation.

## 5. CONCLUSIONS AND FUTURE PERSPECTIVIES

The majority of the industrial combustion processes uses the atmospheric air as oxidant. However, many processes can be improved using a richer oxidant in the oxygen than the combustion air, which can be obtained injecting oxygen in the oxidant chain. This is the principle of the combustion enriched with the oxygen that can promote productivity increase, increase of the thermal efficiency, lesser volume of combustion gases, among others benefits.

According to Greco, C. (1999) the industries must become more and more competitive in some time, through the constant search for lesser costs and greater productivity, and the OEC is a weapon, which the companies should not ignore. Adding to these two factors, the possibility of the emissions reduction is evident; the OEC offers many profit possibilities and advantages.

Baukal, Jr. (1998) concludes that lesser $O_2$ costs, which are connected to the ambient and to the operation benefits of the OEC, make this an attractive technology.

Through what was displayed in this work, through the fact of the greater energy efficiency, the OEC must be faced through the industry of oil and other industrial segments, as an important technological implementation for the guarantee of the energy efficiency, diminishing the fuel consumption, and, with this, the technology becomes a factor to contribute to the reduction of emissions and global warming.

The energy and environmental aspects, and the potential problems must be analyzed for the implantation of this technology. Inside of this work, it was verified that the beneficial aspects can assist the industries that use heating processes to increase its energy efficiency and to improve its balance of emissions. These two aspects are already enough to initiate technician-economic feasibility studies for the use of the technology in the industries of oil and its derivatives, industries with great energy consumption and of great ambient impact in special, this last one when associated to the greenhouse effect specially.

Researches must be done yet with the OEC use about the performance improvement of the burners – especially in oil and derivates industries –, about the processes of the heat transfer – basically for radiation heat process –, and about new technological applications of the processes effectiveness improvement.

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