

A Novel Method of Waste Heat Recovery from High Temperature Furnaces

Arvind Atreya, Department of Mechanical Engineering, University of Michigan

ABSTRACT

One of the largest heat losses in high temperature furnaces is the loss of flue gas enthalpy. Currently, up to 60% of the heating value of natural gas (or any other fuel) used in high temperature furnaces is lost via the flue gases. Here the benefits and technology of recirculating the hot flue gases back into the furnace to avoid the large heat loss and supplementing the flue gases with oxygen to maintain the desired oxygen concentration are discussed. The energy-savings benefits are derived from two factors: (i) recirculating the hot flue gases back into the furnace, and (ii) a reduction in the mass of flue gases due to the use of oxygen. In addition to these energy benefits, environmental benefits are derived from a reduction in NO_x production. In fact, flue gas recirculation (FGR) is a common method used to control NO_x in engines and furnaces. The simple heat recovery device described in this paper can: (i) economically capture greater than 50% of the energy lost via the exhaust gases, (ii) provide a long trouble-free operational life of the heat recovery device at a significantly reduced installation cost, (iii) provide a method to control NO_x produced by the furnace by FGR recirculation, (iv) increase furnace gas radiation and hence productivity, (v) can be profitably employed even with the high temperature recuperator, (vi) can be profitably used with 100% oxygen furnaces, and (vii) will work with both batch and continuous furnaces.

Introduction

Many high-temperature industrial production processes (for metals, glass, etc.) consume large quantities of fuel and produce large amounts of high temperature exhaust gases that are often wasted. While numerous types of equipment have been developed to recover and reuse this waste heat, they are expensive, require maintenance and have drawbacks. Most waste heat recovery methods transfer heat from the high temperature effluent stream to a lower temperature input stream. The most widely used waste-heat recovery devices are recuperators and regenerators. Recuperators are heat exchangers that recover heat from hot exhaust gases and transfer it to the incoming cold combustion air across tubes or plates. These tubes and plates get fouled and damaged by the high-temperature gases over time. Fouling requires periodic cleaning of the heat transfer surfaces and to prevent damage, the flue gases are often diluted by cold air before passing through the recuperator. Thus, only a fraction of the exhaust enthalpy is recovered. Typically, only 5% to 30% savings are possible (DOE, 2001). Regenerative heat exchangers, on the other hand, are basically rechargeable heat storage devices. Essentially, an insulated container absorbs and stores large amounts of thermal energy that can be later used to heat combustion air passing through it. Clearly, regenerators operate intermittently and high-temperature heat storage material (such as ceramic balls) must be used. The difficulty is that the intermittent operation requires maintenance and ceramic balls need to be periodically cleaned to reduce pressure drop across the regenerator. Both these heat recovery methods increase the combustion temperature and hence the production of NO_x and other pollutants.

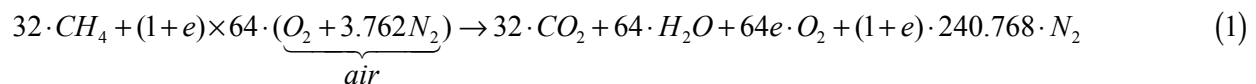
Recently, novel combustion technologies that provide significant energy savings and pollutant emission reductions have been developed for industrial furnaces. These may be classified as homogeneous combustion. Examples include Flameless Oxidation (FLOX), High Temperature Air Combustion (HiTAC), and low temperature gradient (MILD) combustion. These have been developed primarily in Europe and Japan (Wüning J. A. and Wüning J. G., 1997; Katsuki M. and Hasegawa T., 1998). The essential conditions for achieving these combustion conditions are: (i) air & gas mixture temperatures must be above the auto ignition temperature (~ 1200K), and (ii) fuel and oxidant must be sufficiently diluted before they react. Both these conditions can be achieved by high recirculation of hot exhaust products. The question is how to inexpensively accomplish this in existing furnace burners? New furnaces can, of course, be designed with internal flue gas recirculation (Atreya A., 2004).

The objective of this paper is to outline a method for both recovering the high-temperature waste heat and substantially diluting the oxidizer and fuel with hot flue gases by a maintenance-free inexpensive device. In addition, through the use of oxygen-enriched air, further efficiency gains are obtained due to the reduction in the mass flow rate of exhaust gases.

The Problem and the Method

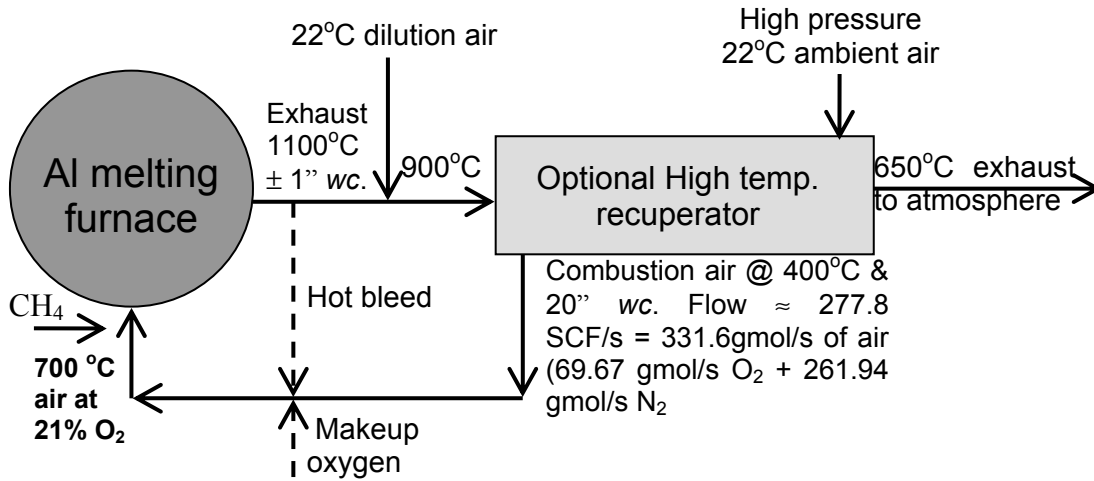
The problem is best illustrated by a real-life example. Consider a typical recuperated aluminum melting furnace schematically shown in Figure 1. In this example the furnace exhaust is at ~1100°C (= T_{ex}) and the exhaust pressure is close to atmospheric [it ranges between ± 0.1 " *wc* (water column)]. We will assume 0" *wc* or atmospheric pressure for the illustrative calculations shown below. The exhaust, however, is too hot to be directly used in the high temperature recuperator so it is diluted by room air to reduce its temperature to 900°C. One notes that while the combustion air is preheated to 400°C, the exhaust at 650°C still carries a substantial amount of enthalpy even after dilution by ambient air. This implies that only a small fraction of the exhaust enthalpy (at 1100°C) is recirculated and of course 32 gmol/s of CH₄ is not preheated or diluted. The main idea behind this paper is to directly use the 1100°C exhaust to preheat and dilute both the incoming fuel and air. As shown in figure 1, hot bleed can be mixed with air (cold or preheated by the recuperator) and fuel (not shown in the schematic). For air, makeup oxygen will have to be used but since the stream is preheated, oxygen concentration substantially less than 21% is needed at the burner inlet. In fact, 21% oxygen will result in unnecessarily high temperatures and NO_x. It is also possible to use pure oxygen instead of air to increase the amount of hot bleed. It is easy to see that in the limit with pure oxygen only 101.67 gmol/s (instead of 363.61 gmol/s) will have to be exhausted to maintain steady state – a 72% gain that can be further increased if 101.67 gmol/s of exhaust is used to preheat the incoming pure oxygen by a recuperator.

To further illustrate the method, let us first calculate the amount of hot bleed required to produce 331.61 gmol/s of reconstituted "air" at 21% O₂ & 700°C, as shown in figure 1. Consider the reaction equation with 32 gmol/s of fuel (CH₄) flow rate used in the furnace with $e(\times 100\%)$



as excess air fraction. It is useful to note the following easy conversion: 1gmol/s of methane (natural gas) \cong 3MSCF/hr. It is also convenient to use gram moles in these calculations because

Figure 1: Aluminum Melting Furnace Example



in this reaction the number of moles is conserved. From the data given in Figure 1, $e = 0.08794$ or 8.794% excess air. Now the following balances can be used:

Oxygen balance (assuming 21% O_2 in reconstituted "air"):

$$0.21 \times [X(\text{gmol/s of bleed}) + Y(\text{gmol/s } O_2 \text{ added})] = (\%O_2 \text{ in exhaust}) \times X + Y; \text{ or } Y = 0.2461 \times X \quad (2)$$

Energy balance (assuming constant specific heats):

$$X(\text{gmol/s}) \times 42.74(\text{J/gmolK}) \times (1100 - 700) = Y \times 33 \times (700 - 20) + (331.61 - X - Y) \times 33 \times (700 - 400) \quad (3)$$

Equations (2) & (3) are solved to find X & Y, giving: $X = 137.305 \text{ gmol/s}$; $Y = 33.79 \text{ gmol/s}$; and air = 160.515 gmol/s.

Energy savings with the recuperator: The amount of 22°C dilution air required before the recuperator to bring the temperature to 900°C for $(363.61 - 137.305 = 226.305) \text{ gmol/s}$ of exhaust flow is calculated by the energy balance as follows: $226.305 \times 42.74 \times (1100 - 900) = Z(\text{gmol/s of cold air}) \times 33 \times (900 - 22)$; or $Z = 66.77 \text{ gmol/s}$ instead of 107.27 gmol/s.

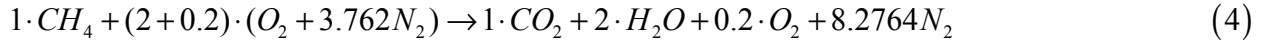
Thus, savings = $137.305 \times 42.74 \times (650 - 22) + (107.27 - 66.77) \times 33 \times (650 - 22) = 4525 \text{ KJ/s} = 15.45 \text{ MMBtu/hour}$. At \$10/MMBtu, this represents (\$154.5/hr – cost of oxygen) over and above the recuperator savings.

Energy savings without the recuperator: Without the recuperator the energy balance becomes: $X(\text{gmol/s}) \times 42.74(\text{J/gmolK}) \times (1100 - 700) = (331.61 - X) \times 33 \times (700 - 22)$. This gives: $X = 188.21$; $Y = 46.32$. Thus, savings = $188.21 \times 42.74 \times (1100 - 22) = 8685 \text{ KJ/s} = 29.66 \text{ MMBtu/hour}$. At \$10/MMBtu, this represents (\$296.6/hr – cost of oxygen).

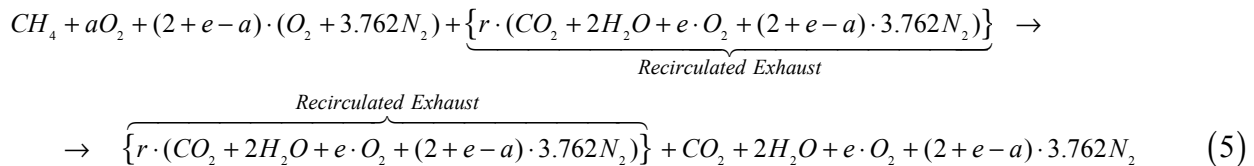
These savings will result in a reduction in fuel and oxygen usage. Thus, the above flow rate calculations will have to be modified and, in fact, the reduction in fuel and oxygen consumption has to be determined iteratively. For the present case without the recuperator and without iterative calculations, the reduction in fuel consumption = $29.66 \text{ MMBtu/hr} \times (1 \text{ MSCF/hr} / 1 \text{ MMBtu/hr}) \cdot (1 \text{ gmol/s} / 3 \text{ MSCF/hr}) = (29.66/3) = 9.89 \text{ gmol/s}$. Thus, the new fuel consumption = 22.11 gmol/s and the total required oxygen is 48.11 gmol/s. If all the oxygen is supplied by air the required air flow rate is 229.1 gmol/s. If the amount of oxygen in the exhaust is kept the same, the oxygen balance above does not change but the energy balance becomes:

$X(\text{gmol/s}) \times 42.74(\text{J/gmolK}) \times (1100 - 700) = (229.1 - X) \times 33 \times (700 - 22)$, yielding $X = 129.87 \text{ gmol/s}$; $Y = 31.96 \text{ gmol/s}$ and air = 67.27 gmol/s . While further iterations are needed, the oxygen requirement has fallen from $Y = 46.32 \text{ gmol/s}$ to $Y = 31.96 \text{ gmol/s}$ increasing the total savings.

To generalize the above calculations first consider the reaction equation:



Where, a typical 10% excess air, $e = 0.1$, and 1 gmol/s of fuel flow rate is used. This gives 11.4764 gmol/s of exhaust/mole of CH_4 with 1.74% O_2 on a wet basis. It is important to note that 8.2764 gmol/s of hot N_2 simply carries away the exhaust enthalpy and does not participate in the reaction. If pure oxygen is used instead and the same 1.74% O_2 in the exhaust is desired, then the equation becomes: $1 \cdot \text{CH}_4 + 1.0266 \times 2 \cdot \text{O}_2 \rightarrow 1 \cdot \text{CO}_2 + 2 \cdot \text{H}_2\text{O} + 0.0532 \cdot \text{O}_2$. Clearly, to maintain steady state we must exhaust at least 3.0532 gmol/s per gmol of CH_4 even if 100% oxygen is used. This, of course, carries away enthalpy that can be recovered only by a heat exchanger but it is 26.6% if air was used, saving ~73.4% of exhaust energy at the same exhaust temperature. Further, a 73.4% reduction in the lost enthalpy would require significantly less fuel as shown above and hence the actual exhaust is even lower than 3.0532 gmol/s. This reduction in the exhaust flow rate will reduce the gas circulation inside the furnace that may not be desirable. However, it does not prohibit the general condition illustrated by the reaction equation (5) to maintain approximately the same amount of exhaust as in equation (4) to control the flow conditions inside the furnace and maintain approximately the same amount of O_2 in the exhaust on a wet basis and yet exhaust only $(3+e)$ gmol/s when 100% O_2 is used (i.e. $a = 2+e$).



The factor 'r' is chosen to maintain roughly the same flow rate as with air ($a=0$) but it may be arbitrarily chosen because it only governs the amount of flue gas recirculation. It will be chosen by the method used for recirculation. Also note that in addition to maintaining the circulation in the furnace, there is a substantial heat transfer advantage of having high volumes of hot radiating gases like CO_2 and H_2O in the furnace.

In the method illustrated below, fuel preheat and dilution is not included because it is similar to the oxidizer preheat and dilution. Furthermore, for equation (5) the mechanism used to recirculate the exhaust gas into the furnace is irrelevant. However, fuel preheat and dilution is important because it promotes homogeneous combustion and soot formation that is later oxidized in the furnace. This is important for obtaining the Radiative Homogeneous Combustion (RHC) condition inside the furnace. The pollutant reduction and productivity benefits of RHC are described below.

Representative calculations are done assuming stoichiometric conditions, i.e. $e=0$, to avoid algebraic complications and with 'r' moles of exhaust gases recirculated. The maximum moles of O_2 added under stoichiometric conditions per mole of CH_4 are 2 (i.e. $a=2$). To maintain the same flow rate for the burner, and the maximum value of $r = 2.508$ to replace all 7.524 moles of N_2 . However, if lower $\text{O}_2\%$ (20%) is desired for NO_x control, then the maximum value of $r = 8/3 = 2.667$. An even lower oxygen concentration ~18.2% may be desirable because the reactants are preheated to 1800°F. Under these conditions equation (5) becomes:

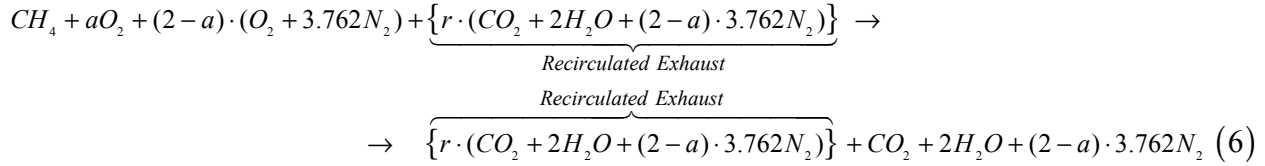
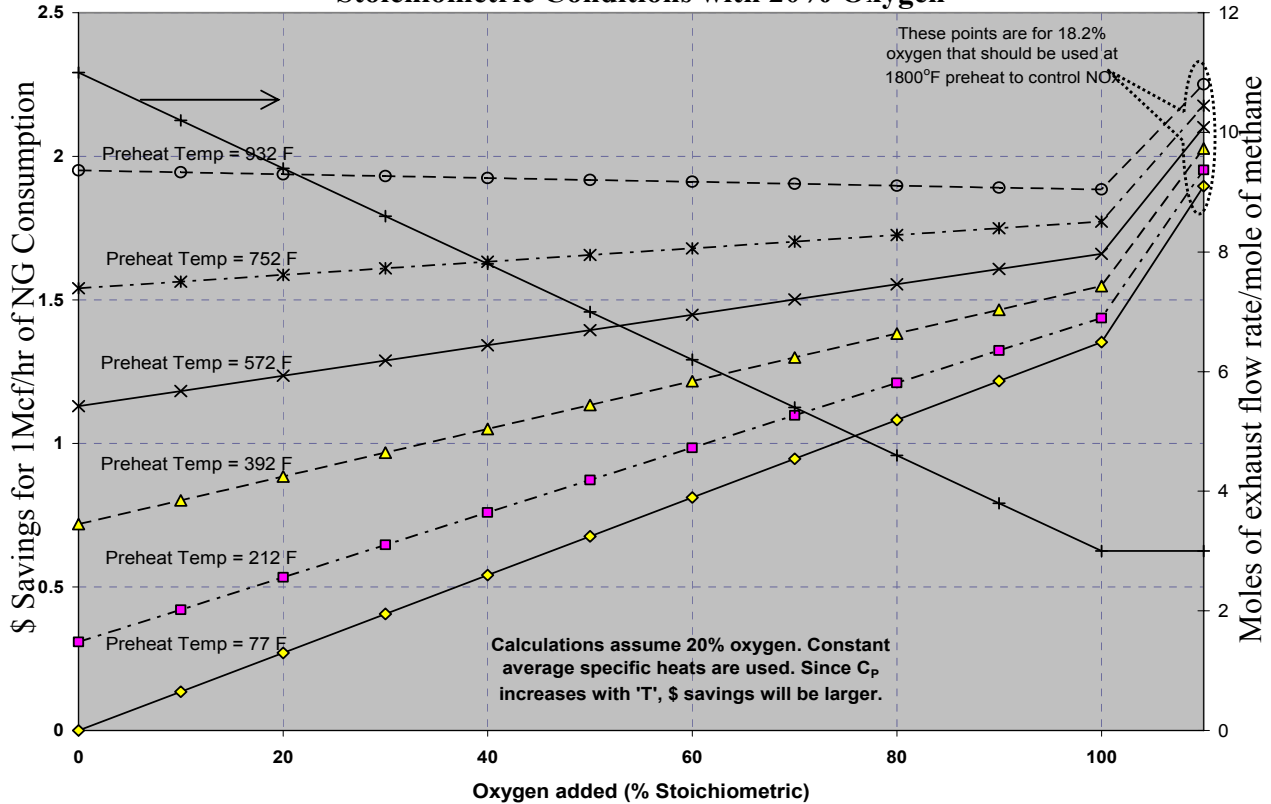


Figure 2: Net \$ Savings with NG = \$10/Mcf; O₂ = \$1.5/Mcf; Exhaust Temp = 2100°F; Stoichiometric Conditions with 20% Oxygen



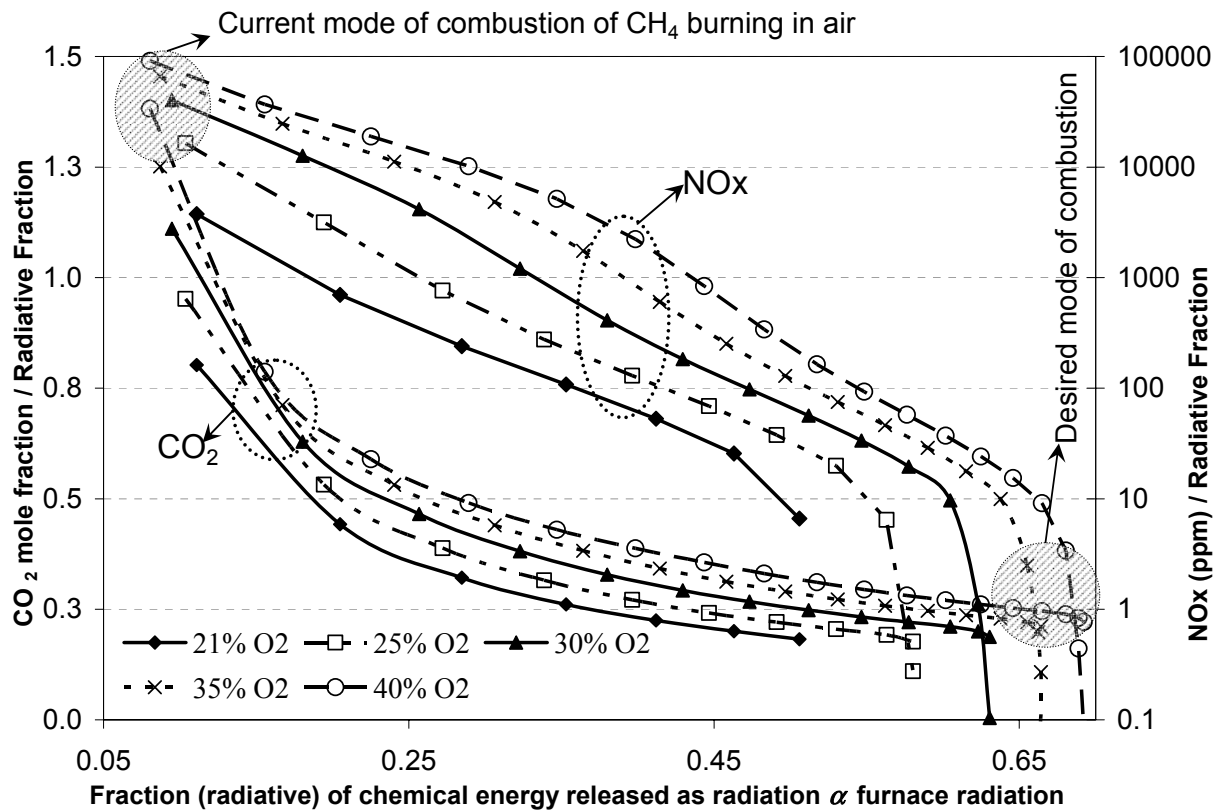
Savings calculations using these variables are shown in Figure 2 which accounts for the cost of oxygen. Thus, if fuel and air are not preheated (77°F) it saves ~\$1.5/hr per Mcf of natural gas by using 100% oxygen. On the other hand, if the fuel and air can be preheated to 1000°F, using 100% O₂ is economically neutral and may only be useful to increase radiation and hence the furnace productivity. Since the slope of all the lines is positive, it is clearly useful to both preheat and use oxygen enrichment. It is also important to note that the exhaust flow rate reduces substantially with oxygen enrichment and hence the size of the recuperator also reduces making it less expensive. A preheat to 572°F and use of 100% O₂ is very attractive yielding net savings of ~\$2/hr per Mcf of natural gas used.

Pollution Benefits of Radiative Homogeneous Combustion (RHC)

Thermodynamic representations like equations (5) & (6) hide the complexity of the actual chemical reactions that are needed to determine pollutant formation. Thus, RHC calculations are conducted using SANDIA's perfectly stirred reactor model with full CH₄ chemistry (GRImech-3.0), oxygen-enrichment and high flame radiation are presented in figure 3. An estimated reactant residence time of 0.5 seconds and stoichiometric conditions were assumed. In figure 3,

each pair of CO₂ and NO points is a separate calculation and it is for the same amount of CH₄ burning in “O₂-enriched air”. The abscissa is the fraction of chemical energy released as flame radiation and the two ordinates are CO₂ & NO produced per unit flame radiation. Assuming that the amount of radiation released is proportional to furnace productivity, CO₂ and NO production rates decrease substantially (CO₂ by a factor of five and NO by five orders of magnitude) for the same productivity and the same fuel consumption as the radiative fraction increases. The normal flame condition for CH₄ combustion is shown in this figure by the shaded circle in the top left hand corner and the desired flame condition is shown by the shaded circle in the bottom right hand corner. Our goal is to obtain the bottom right hand corner condition. This figure emphasizes the importance of homogeneous combustion and flame radiation in industrial furnaces to reduce both NO_x and greenhouse gases. These pollutant formation and productivity benefits are over and above the energy efficiency benefits shown in Figure 2.

Figure 3: Chemikin Calculations Using the Perfectly Stirred Reactor Model with GRI-Mech 3.0 for Stoichiometric Conditions & Residence Time = 0.5s



With so many benefits, an obvious question is: why is this simple solution currently not implemented? The reason is that it is not possible to recirculate the exhaust because the furnace exhaust pressure is typically between $\pm 1''$ of water column, whereas, the gas and air pressure at the burner is in excess of $20''$ of water column. Thus, high temperature exhaust has to be pressurized by a high temperature blower for recirculation. Such high temperature blowers are more expensive than high temperature recuperators and suffer from worse maintenance problems. A simple solution to this problem is presented below.

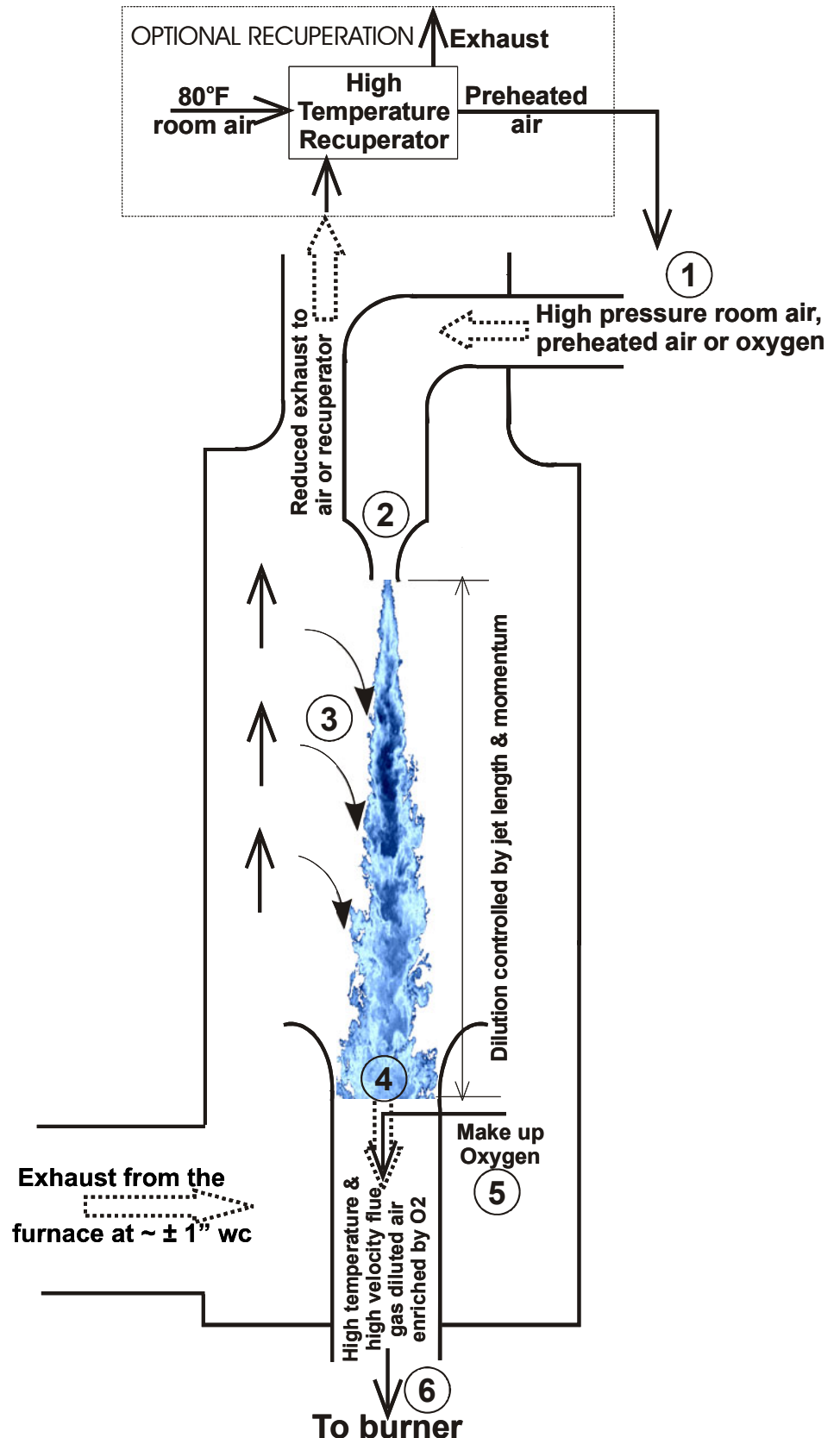
Proposed Solution

Figure 4 shows a schematic of a Flue Gas Recirculating (FGR) device. As shown, mixing in a high velocity jet automatically converts high pressure to high velocity and back to high pressure in the hot combustion air duct. Since, only cold air needs to be pressurized less expensive blowers can be used (in fact, the existing blower used for combustion air may be adequate). Also, no change in the existing system is required. An added advantage of this arrangement is that it is self cleaning. Under steady conditions, the amount of nitrogen circulated is reduced thus the exhaust mass flow rate is reduced increasing efficiency. This is done without increasing the concentration of oxygen in the flame zone and hence the flame temperature. In fact, it provides a method to control NO_x by FGR. A similar device can be used to dilute and preheat the fuel.

Description of the FGR Device

As shown in Figure 4, cold or preheated (by an existing recuperator) high pressure combustion air (or oxygen, if 100% oxygen is used) can be directly introduced into the FGR mixing device at location

Figure 4: Schematic of the Flue Gas Recirculating Device



(1). The FGR mixing device is simply a portion of the exhaust duct with a concentric injection nozzle and a combustion “air” accumulating duct. While the vertical configuration is shown, the device will work in any orientation of the duct. The injection nozzle (2) converts the high pressure of the air into a high velocity jet. This air jet expands at roughly 12° half-angle entraining the surrounding hot flue gases into it (3). The total mass flow rate of the jet increases while the injected momentum is conserved. The amount of flue gases entrained depends on the length of the exposed jet and the injected momentum. This problem has been well studied in the literature allowing us to choose suitable parameters (nozzle diameter, upstream pressure, the exposed jet length, and the diameter of the duct to the burner) for any implementation. For representative literature please see Ricou, F. P., and Spalding, D. B., 1961; Dowling, D. R., and Dimotakis, P. E., 1990; Donghee Han and M. G. Mungal, 2001, and references cited there in.

The suitably diluted, reduced velocity, and increased mass and temperature jet enters the accumulating duct (4) where the high velocity is converted back to the high pressure required by the existing burners. At this point, oxygen is added to the flue gas diluted air (5) to increase the oxygen concentration to the desired level (adequate amount of oxygen could also be added at (1) to avoid step (5)). This level depends on the amount of dilution and the gas temperature for NOx control. It is important to note that in the implementation of this device, no change in the existing burners or recuperators is required even when 100% oxygen is used.

Mixing Calculations

To conduct the illustrative calculations for the case shown in Figure 1, let us assume that at point (6) the required pressure is 20”wc. Applying the momentum equation to the control volume bounded by the horizontal planes at points (4) and (6) and the inner surface of the duct we have the net pressure force in the upward direction = $\Delta P \times A$. Where, $\Delta P = 20''wc = 4980 Pa$ given that the pressure in the surrounding exhaust plenum is nearly atmospheric. Assuming a duct area of (1 m radius) = πm^2 , we find the average gas velocity in the duct given that the duct carries 254.42 gmol/s of “air” with an average molecular weight of 27.5 g/mol. This gives a mass flow rate of 7 Kg/s and a density of 0.248 Kg/m³ at 1100°C. Thus, the volumetric flow rate is 28.23m³/s and the velocity is 9m/s.

Momentum balance gives the required V_4 :

$\Delta P = \rho_4 V_4^2 + \rho_{O_2} V_{O_2}^2 - \rho_6 V_6^2$; assuming $\rho_4 \approx \rho_6$ (700°C & ~ same composition); $\rho_{O_2} = M_{O_2} / \bar{M}_6 \cdot \rho_6$
 $\rho_{O_2} = 0.39374 \text{ Kg/m}^3$; $\rho_4 \approx \rho_6 = 0.33837$; we need to find V_{O_2} . The required oxygen flow rate (calculated above) = 35.54 gmol/s or = 1.1373 Kg/s. V_{O_2} can be arbitrarily chosen based on the oxygen injection nozzle diameter and is control parameter to maintain the burner inlet pressure. Choosing a velocity $V_{O_2} \sim 100\text{m/s}$ and assuming $V_6 = 25 \text{ m/s}$, we get $V_4 = 61 \text{ m/s}$ which seems reasonable. We need jet equations to go to point (2). From Ricou and Spalding, 1961, we get:

$$\text{Jet mass flowrate at } x = \dot{m}_x = 0.32 \times \frac{x}{d_0} \times \dot{m}_0 \times \left(\frac{\rho_\infty}{\rho_0} \right)^{1/2}; \rho_\infty = 0.24; \rho_0 = 1.2 \text{ \& } \dot{m}_0 = 2.156 \text{ Kg/s, or}$$

$$\dot{m}_x = 0.30854 \times \frac{x}{d_0}. \text{ For } \dot{m}_x = 6.127, \frac{x}{d_0} \approx 20. \text{ With } 12^\circ \text{ jet expansion, jet width at point 4} = 0.7\text{m}$$

Since the pressure remains constant in the jet, the integral of the stream wise momentum taken over the entire cross-sectional area must also remain constant. Hence, the jet exit

momentum at point (2) = total stream wise momentum at point (4), or $\dot{m}_0 \cdot V_2 = \dot{m}_4 \cdot V_4$, where, V_2 & V_4 are average velocities. Thus, $2.156 \times V_2 = 6.127 \times V_4$; or $V_2 = 173 \text{ m/s}$. $\rho_0 (\pi d_0^2 / 4) V_2 = 2.156 \Rightarrow d_0 = 0.115 \text{ m} \Rightarrow x = 20d_0 = 2.3 \text{ m}$. Hence, the accepting (or the burner inlet) air duct size is = 0.7m in diameter and the exposed jet length is 2.3 m which is very reasonable. The net savings generated for this case was calculated earlier from the energy balance as = (exhaust flow rate before – new exhaust flow rate) $\times C_p \times (T_{\text{exh}} - T_{\text{amb}})$.

Conclusions

In this paper a novel method of waste heat recovery from high temperature furnaces is presented. It is shown that substantial energy-savings are possible by the proposed method. These savings are derived from two factors: (i) recirculating the hot flue gases back into the furnace, and (ii) a reduction in the mass of flue gases due to the use of oxygen. In addition to these energy benefits, substantial environmental benefits are derived from a reduction in NOx and greenhouse gas production. This simple heat recovery device provides a long maintenance-free operational life at a significantly reduced installation cost and increases furnace radiation and hence productivity.

References

- Wünning J. A. and Wünning J. G., 1997, Flameless Oxidation To Reduce Thermal NO Formation, Vol. 23 *Prog. Energy Combust. Sci* 81-94.
- M. and Hasegawa T., 1998, The Science and Technology of Combustion in Highly Preheated Air, *Proceedings of the Twenty-Seventh (International) Symposium on Combustion*, 3135.
- [DOE] US Department of Energy. 2001. Process Heating Tip Sheet #8; DOE/GO-102005-2181.
- Ricou, F. P., and Spalding, D. B., 1961, *J. Fluid Mech.* 11:21–32.
- Dowling, D. R., and Dimotakis, P. E., 1990, *J. Fluid Mech.* 218:109–141.
- Donghee Han and M. G. Mungal, 2001, *Combustion and Flame* 124:370–386.
- Atreya, A., “Furnace Having Increased Energy Efficiency and Reduced Pollutant Formation,” U.S. Patent No. 7784-002187, 2004.