Flue Gas Recirculation

Flue gas recirculation is a method of reducing NOx. NOx is a criteria pollutant. NOx comprises two main species: nitric oxide (NO) and nitrogen dioxide (NO_2). One method of reducing NOx in boilers is to recirculate flue gas from the exhaust stack into the windbox. (See Figure 1.) The Faber VPSSS Burner uses a separate *mixing plenum* (also called a *mixing box*) to mix the recirculated flue gas with the combustion air to assure a homogenous mixture to the boiler windbox.

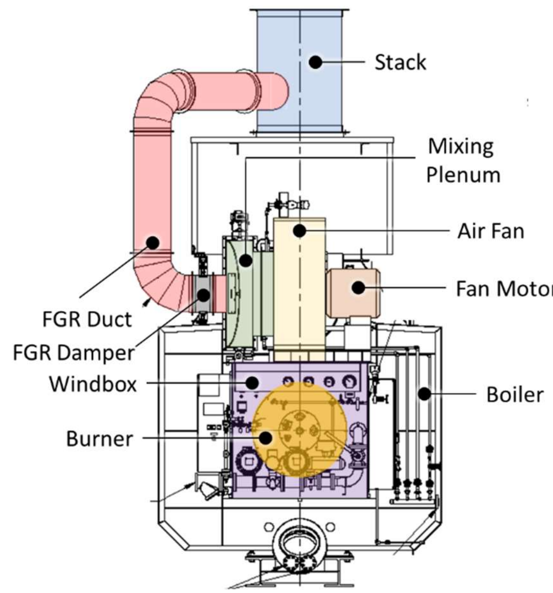

Figure 1, Faber VPSSS Burner in a Boiler Equipped with FGR. A portion of flue gas from the boiler stack (blue) flows through the FGR duct (red) and into a mixing plenum (green). The combustion air fan (yellow) driven by a fan motor (brown) draws air through the mixing plenum to mix it with the flue gas there. An FGR damper (gray) governs the amount of flue gas admitted to the mixing plenum. The mixture of flue gas and air exits to the windbox (violet) surrounding the burner (orange). Note that in this view the air inlet on the backside of the mixing plenum is not visible.

In boiler environments, NOx is nearly all NO. To understand how FGR reduces NOx, consider how NO is formed. Fuels such as natural gas contain no nitrogen bound in the fuel structure. That means that all of the nitrogen used to make NOx must come from the combustion air itself. Equation (1) is known as the shorter *Zeldovich* mechanism. It shows the essential features of nitric oxide formation in combustion systems.

$$\mathrm{N_2 + O \;=\; NO + N} \qquad (1)$$

$$\underline{\mathrm{N + O_2 = \;NO + O}} \qquad \underline{(2)}$$

$$\mathrm{N_2 + O_2 = 2NO} \qquad (3)$$

Oxygen is normally diatomic, comprising two atoms of oxygen bound together by a double bond, $\mathrm{O=O}$, also written as O_2. At high temperatures (such as those found in flames), some O_2 will dissociate to form two oxygen atoms, which is why the mechanism is also called the *thermal NOx* mechanism. Oxygen atoms have high energy and can even attack a normally stable nitrogen (N_2) molecule as shown in Equation (1). Equation (1) is known as the *rate limiting* step. It paces the reaction because the diatomic $\mathrm{N \equiv N}$ triple bond is very difficult to break. However, a favorable collision with an oxygen atom can do the job, generating a nitric oxide molecule (NO) and a nitrogen atom (N) per Equation (1). The nitrogen atom is very reactive and will easily attack a nearby oxygen molecule to produce another molecule of NO, leaving an oxygen atom to replenish the cycle as shown in Equation (2). This second reaction is must faster than the first, again indicating that the slower reaction (1) will pace the process. Adding Equations (1) and (2) yields (3), which is the overall reaction. Since Equation (1) is rate limiting, we may write a kinetic expression for it as $\frac{\mathrm{d[NO]}}{\mathrm{d}t} = k_f[\mathrm{N_2}][\mathrm{O}] - k_r[\mathrm{NO}][\mathrm{N}]$ where the brackets indicate concentrations of the enclosed species, k_f and k_r are the forward and reverse kinetic rate constants, and t is time. The differential expression, $\frac{\mathrm{d[NO]}}{\mathrm{d}t}$, is the rate of nitric oxide production in concentration units per time.

However, we may make two immediate simplifications. The first that we may neglect the reverse reaction because molecular nitrogen is about 8,000 times more abundant than nitric oxide, thus the reverse reaction plays little part in the kinetics. Second, because molecular oxygen is many thousands of times more abundant that its atomic form, one may assume atomic oxygen to be in partial equilibrium with its molecular cousin: $2[\mathrm{O}] \rightleftharpoons [\mathrm{O}_2]$. That allows one to write $[\mathrm{O}] = \mathrm{K}[\mathrm{O}_2]^{\frac{1}{2}}$, where K is an equilibrium constant. This results in a simpler kinetic express: $\frac{\mathrm{d}[\mathrm{NO}]}{\mathrm{dt}} = k_f K[\mathrm{N}_2][\mathrm{O}_2]^{\frac{1}{2}}$. The combined constant, $k_f K$, is a function of absolute temperature (T): $k_f K = Ae^{-\frac{b}{T}}$, where A and b are experimentally determined constants. This leads to $\mathrm{d}[\mathrm{NO}] = Ae^{-\frac{b}{T}}[\mathrm{N}_2]\sqrt{[\mathrm{O}_2]}\mathrm{d}t$. We may integrate the expression to yield its final form, where A is placed outside the integral since it is constant, and also $[N_2]$ since its concentration barely changes over the combustion reaction.

$$[\mathrm{NO}] = A[\mathrm{N}_2]\int e^{-\frac{b}{T}}[\mathrm{O}_2]^{\frac{1}{2}}\mathrm{d}t \tag{4}$$

Equation (4) tells us that there are three ways to reduce thermal NOx; first, by reducing the temperature; second, by reducing the oxygen concentration; and third, by reducing the time of exposure under these conditions. FGR reduces NOx in all three ways. First, the addition of flue decreases the oxygen concentration. Second, the heat lost in the FGR duct cools a portion of the flue gas admitted to the combustion zone. Finally, the increased mass flow shortens the time to which the reactants are exposed to the flame.

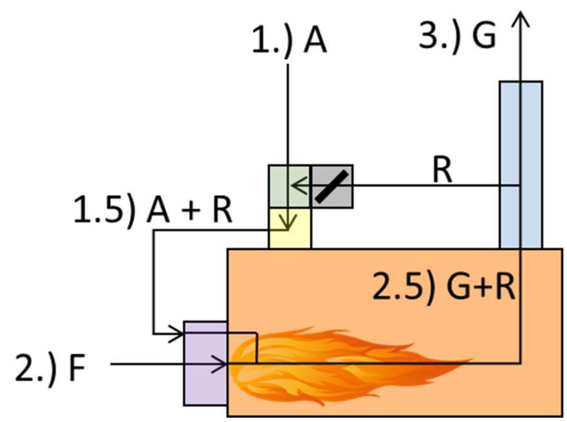

Figure 2, Mass Balance on a Boiler. Air at Station 1 enters the mixing plenum (green) and mixes with some portion flue gas (R) drawn from the stack (blue) and regulated by an FGR damper (gray). The combustion air fan (yellow) pulls the mixture from the mixing plenum and pushes it to the burner windbox (violet). Fuel at Station 2 enters through the burner nozzles. The burner combusts the mixture of fuel, air, and recirculated flue gas in the firebox (orange) to produce flue gas at Station 2.5. The flue gas (G) exits the stack at Station 3 after it has the recirculated component (R) subtracted from its flow.

Mass Balance for FGR

Regarding this latter point, consider the schematic of Figure 2. An overall mass balance requires that Air (A) entering the system at Station 1 and Fuel (F) entering the system at Station 2 must equal the mass of flue gas (G) that exits at Station 3.

$$\mathrm{A} + \mathrm{F} = \mathrm{G} \tag{5}$$

Now consider the inner loop of Figure 2. Some portion of flue gas (R) recirculates from the stack (blue) to the mixing plenum (green) drawn by the inlet side of the combustion air fan (yellow) and exits the fan at Station 1.5 and is pushed into the windbox (violet). Meanwhile, fuel (F) from Station 2 enters the firebox and burns with the surrounding air and flue gas. When the combustion is complete, all of the fuel has been oxidized to flue gas products (G). Therefore, internal to the firebox (orange) at Station 2.5, the total mass flow comprises the mass of the flue gas (G) plus the recirculated portion of the flue gas (R). Thus, if the flue gas damper (gray) is open, some flue gas will be sent in a circle. This will increase the mass flow in the firebox. This extra mass will be subtracted out of the stack before exiting. This allows the mass flow to increase in the firebox without affecting the total mass exiting the stack. Figure 3 shows the typical NOx reduction FGR provides. The ratio of NOx with FGR to that without FGR $\left(\frac{NOx}{NOx_0}\right)$ is a declining function of the flue gas recirculation rate. Equation (6) shows a NOx correlation formula that is often useful.

$$\frac{NOx}{NOx_0} = \frac{1}{\sqrt[r]{1 + m \cdot FGR_i}} \qquad (6)$$

Here r and m are constants and FGR_i is the ratio of recirculated flue gas based on the flowrate internal to the boiler (to be defined in greater detail presently). For the particular burner and boiler system shown in Figure 3, $r = 0.46$ and $m = 41.6$.

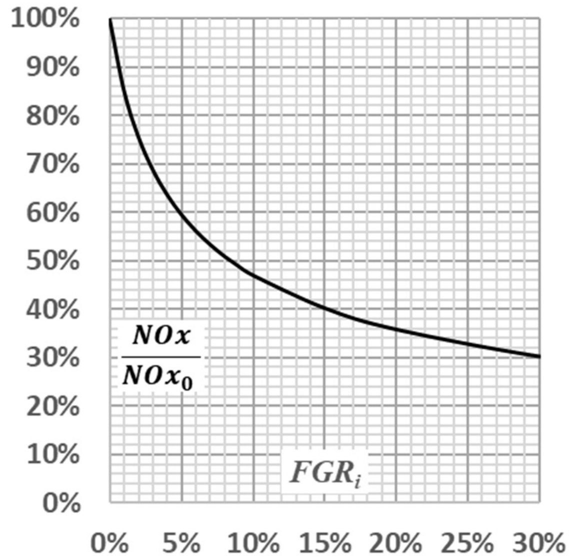

Figure 3, NOx Ratio as a function of FGR. NOx is a declining function of the flue gas recirculation rate.

If one knows the oxygen in the windbox and the flue gas, one may determine the amount of flue gas that is recirculating. The fraction of oxygen in the influent air (A), $y_{02,A}$, is 21% or 0.21. The fraction of oxygen $(y_{O2,R})$ of the wet recirculated flue gas (R) is identical to that found in the firebox (G+R) or even the stack (R) if measured on a wet basis; however, if the stack O_2 is measured on a dry basis, it must be corrected for moisture – see Equation (10). The windbox itself contains a mixture of air and wet flue gas at comprising an intermediate oxygen fraction $(y_{O2,R} < y_{O2,WB} < y_{O2,A})$.

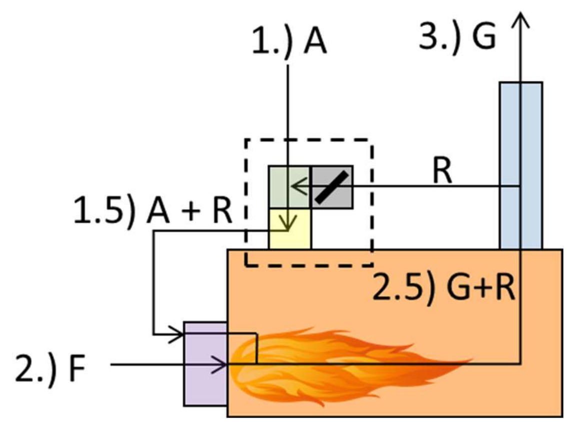

Figure 4, Mass Balance on the Mixing System. The system (dashed square) comprises an inlet damper (gray), mixing plenum (green) and fan (yellow). Flue gas (R) and air (A) enter the system and exit as a homogenous mixture to the windbox (violet).

Consider a mass balance on oxygen at the dotted system boundary shown in Figure 4. If the flowrate of air is $\dot{V}_A$ and that of the flue gas is $\dot{V}_R$ then the total flowrate exiting the system and traveling to the windbox $(\dot{V}_{WB})$ will be $\dot{V}_{WB} = \dot{V}_A + \dot{V}_R$, and the oxygen concentration of that mixture will be $y_{O2,WB}$. A mass balance on oxygen for the system gives $\dot{V}_A y_{02,A} + \dot{V}_R y_{O2,R} = (\dot{V}_A + \dot{V}_R) y_{O2,WB}$. Then $\frac{\dot{V}_R}{\dot{V}_A} = \frac{y_{O2,A} - y_{O2,WB}}{y_{O2,WB} - y_{O2,R}}$. A previous article showed how to calculate the air/fuel ratio (α) and wet-flue-gas/fuel ratio (ϕ_{wet}) knowing the H/C ratio of the fuel (ψ) and the wet oxygen content of the flue gas. Since $\alpha = \frac{\dot{V}_A}{\dot{V}_F}$, where $\dot{V}_F$ is the volumetric fuel flow rate, then $\frac{\dot{V}_R}{\dot{V}_F} = \alpha\frac{\dot{V}_R}{\dot{V}_A} = \alpha\frac{y_{O2,A}-y_{O2,WB}}{y_{O2,WB}-y_{O2,G}}$. Also, $\phi_{wet} = \frac{\dot{V}_G}{\dot{V}_F}$. We shall call $\frac{\dot{V}_R}{\dot{V}_G}$ the *external flue gas recirculation ratio*, $FGR_e = \frac{\dot{V}_R}{\dot{V}_G}$, because it is the ratio of flue gas recirculated to the flue gas exiting the boiler and stack. Likewise, we shall call $FGR_i = \frac{\dot{V}_R}{\dot{V}_G+\dot{V}_R}$ the *internal flue gas recirculation ratio* because it is based on the flue gas flow rate in the furnace relative to the flue-gas flow internal to the boiler. This is the more typical definition of FGR. Equation 7 compares each formulation in terms of the other.

$$FGR_e = \frac{FGR_i}{1 - FGR_i} \qquad FGR_i = \frac{FGR_e}{1 + FGR_e} \tag{7a, b}$$

Mathematically, FGR_i is bound between 0 and 1 while FGR_e is bound between 0 and ∞; however, in practical terms, FGR_i should be less than 30% to prevent combustion instability, and sometimes much lower depending on the burner. Equation (8) follows from the definitions of (7) and the previous equations.

$$FGR_e = \left(\frac{\alpha}{\phi_{wet}}\right)\left(\frac{y_{O2,A} - y_{O2,WB}}{y_{O2,WB} - y_{O2,R}}\right) \qquad FGR_i = \frac{1}{\left(\frac{\phi_{wet}}{\alpha}\right)\left(\frac{y_{O2,WB} - y_{O2,R}}{y_{O2,A} - y_{O2,WB}}\right) + 1} \tag{8a, b}$$

In the worst case $(\psi = 4, y_{O2,R} = 0\%)$, $\frac{\alpha}{\phi_{wet}} = 0.9$, and in the best case $(y_{O2,R} = 21\%)$, $\frac{\alpha}{\phi_{wet}} = 1.0$. Therefore, for any hydrocarbon, $0.9 \le \frac{\alpha}{\phi_{wet}} \le 1$; using $\frac{\alpha}{\phi_{wet}} \sim 1$ simplifies Equation (8) with a maximum absolute error of less than 2%. Figure 5 depicts the relation as an alignment chart.

$$FGR_e \approx \frac{y_{O2,A} - y_{O2,WB}}{y_{O2,WB} - y_{O2,R}} \qquad FGR_i \approx \frac{y_{O2,A} - y_{O2,WB}}{y_{O2,A} - y_{O2,R}} \tag{9a, b}$$

Notwithstanding, Equation (10) gives the exact formula for $\left(\frac{\phi_{wet}}{\alpha}\right)$ if desired.

$$\frac{\alpha}{\phi_{wet}} = \frac{4 + \psi(1 + y_{O2,R})}{4 + \psi(1 + y_{O2,A})} \tag{10}$$

If oxygen is measured on a dry basis, Equation (10) corrects it to a wet basis. The equation assumes that the system is leak tight or positive pressure and thus free of any air inleakage.

$$\frac{y_{O2,R}}{y_{O2,G,dry}} = \frac{0.79\psi + 4}{1.21\psi + 4} \tag{11}$$

Figures 6 and 7 illustrate Equation (8) graphically. The figures show that FGR_i is very nearly linear with windbox O_2 for a given ψ and $y_{O2,R}$.

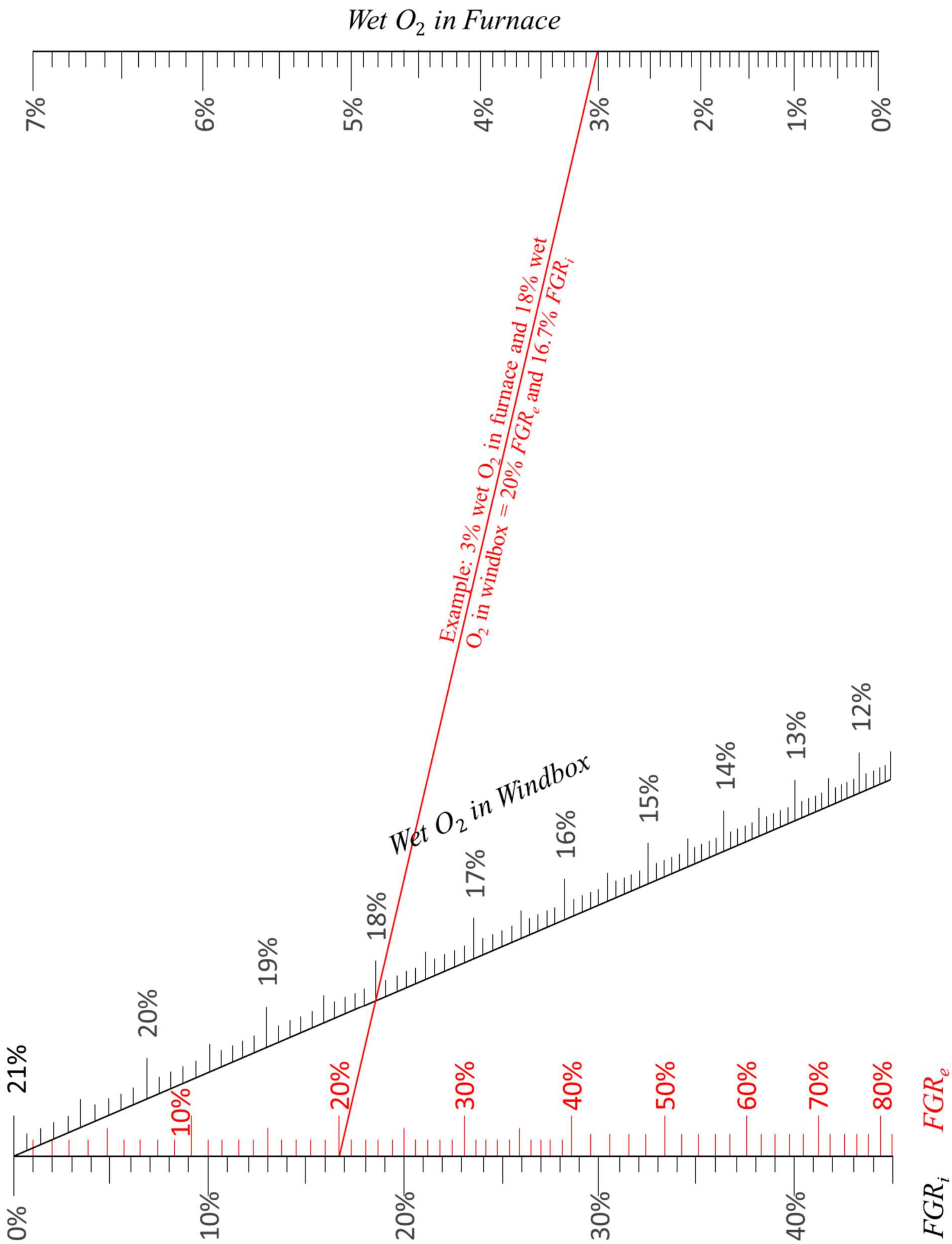

Figure 5, Alignment Chart to Calculate Flue Gas Recirculation as a Function of Wet Oxygen in Furnace and Windbox. Align wet oxygen in furnace and windbox to read % flue gas recirculation on an external (red) or internal basis as shown.

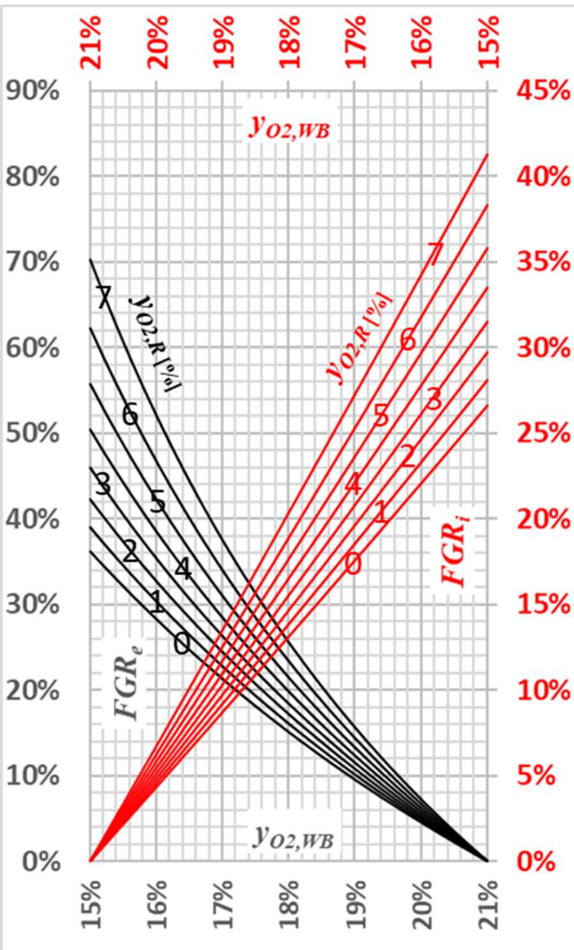

Figure 6, FGR for Natural Gas as a Function of Windbox O2 with Flue Gas O2 as a Parameter. E.g., $y_{O2,WB} = 16\%$ and $y_{O2,R} = 3\%$ gives $FGR_e = 35.4\%$ and $FGR_i = 26.1\%$.

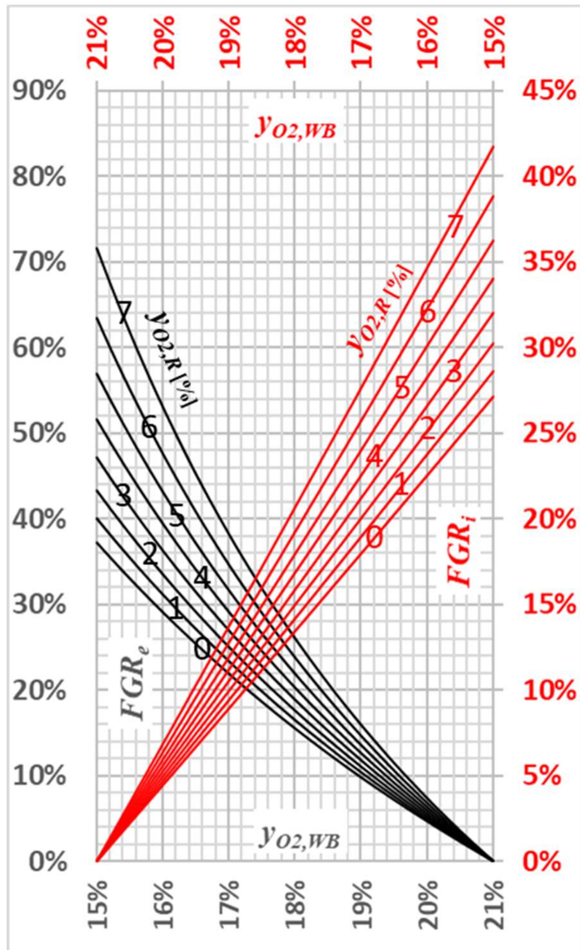

Figure 7, FGR for Fuel Oil as a Function of Windbox O2 with Flue Gas O2 as a Parameter. E.g., $y_{O2,WB} = 16\%$ and $y_{O2,R} = 3\%$ gives $FGR_e = 36.2\%$ and $FGR_i = 26.6\%$.