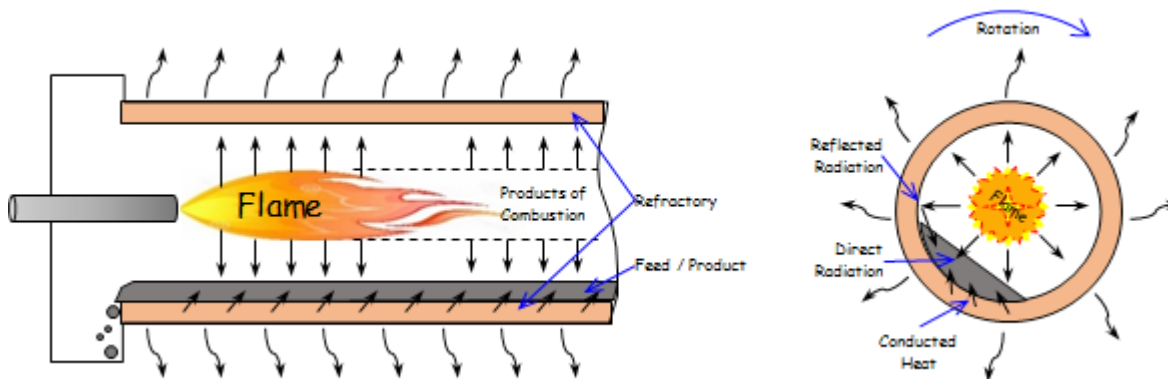




Masterclass: FUELS, FLAMES AND RADIATION

What are we trying to achieve when firing fuel in a rotary kiln? Simple really, we want to heat the product to the desired temperature with as much of the heat going to the product and as little as possible leaving with the flue gas, whilst minimizing the generation of NOx. There are three modes of heat transfer: Radiation, Convection and Conduction. The most significant of these in a high temperature rotary kiln is radiation, accounting for 95% of the heat transferred with the remainder transferred via convection.



We can simplify the situation if we say the energy from combustion (E_{Comb}) heats the products of combustion, raising the sensible heat of the combustion gases (E_{Sens}) and radiating heat from the combustion gases in the flame to the product and bricks (E_{Rad}). This can be expressed as follows:

$$E_{\text{Comb}} \text{ Energy from combustion} > E_{\text{Sens}} \text{ Heating of flame/gases} + E_{\text{Rad}} \text{ Heat Radiated from the flame to the product}$$

$$E_{\text{Comb}} > \dot{m} \cdot C_p (T_f - T_1) + A(T_f^4 - T_p^4)$$

Where:

- \dot{m} = Mass flow of combustion products
- C_p = Mean specific heat of the combustion products
- T_f = Average flame temperature, K
- T_1 = Temperature of fuel and air prior to heating, K
- σ = Stefan-Boltzmann Constant, $5.6703 \cdot 10^{-8} \text{ W/m}^2\text{K}^4$
- A = Area (essentially constant)
- ϵ = Emissivity
- T_p = Average product temperature, K



Whilst the equation above looks complex, it is important to understand it as a number of conclusions can be drawn from it.

1. The maximum flame temperature occurs when the E_{Rad} term is zero meaning that all the combustion energy goes into heating the gaseous products of combustion.

$$T_f = \frac{\left(E_{Comb} - \overset{0}{\widehat{E}_{Rad}} \right)}{\dot{m}C_p} + T_1$$

2. This is referred to as the adiabatic flame temperature. The adiabatic flame temperature for a number of fuels is shown here in Table 1. As you can see, fuels with higher Carbon: Hydrogen ratios tend to also have higher flame temperatures.

3. The maximum flame temperature also occurs when there is just the right amount of air for combustion, ie. there is no excess air (excess air coefficient is 1). If the flue gas products mass flow, \dot{m} , is increased by increasing the excess air co-efficient above 1, then the flame temperature is reduced as some of the energy from combustion is going into heating the additional air. If \dot{m} is reduced, such that the excess air coefficient is less than 1 and there is insufficient air for complete combustion, then the amount of energy released will be reduced, resulting in a lower flame temperature also. The effect of excess air on the adiabatic flame temperature for methane combustion in air is shown here in Figure 1. Due to less than perfect mixing in the real world, a small amount of excess air, say 10%, is required to ensure that complete combustion is achieved and the heat available to the product maximized.

4. Preheating of the fuel and air for combustion, T_1 , also contributes to increasing the flame temperature. Given the quantity of air required for complete combustion is in the order of 9-10 times the quantity of fuel, preheating of the combustion air results in a much larger increase in flame temperature than preheating of fuel. The impact on flame temperature from preheating combustion air is shown here in figure 2.

5. To maximise radiant heat transfer the difference in the flame and product temperature, must also be maximised. Put another way the temperature

$$\left(T_f^4 - T_p^4 \right)$$

of the product surface exposed to the flame, T_p , must be minimised. Therefore it is important that the product cascades rather than slides to ensure product from the core of the charge is brought to the surface and in contact with the bricks. As can be seen in Figure 2 the product takes up less than half the kiln circumference meaning that the bricks receive more of the direct radiation from the flame than the product. As a result the product receives more heat by conduction in contact with the bricks than by direct radiation from the flame. Therefore cooling of the bricks as they pass under the cascading product is important to help maximise heat transfer to the brick and in turn to the product.

Fuel	Flame Temperature (oC)
H2	2097
CH4	1950
C2H2	2262
C2H4	2088
C2H6	1986
C3H6	2061
C3H8	1988
C4H10	1973
CO	2108

Table 1: Adiabatic flame temperature for stoichiometric mixes of air/ fuel and oxygen/fuel.

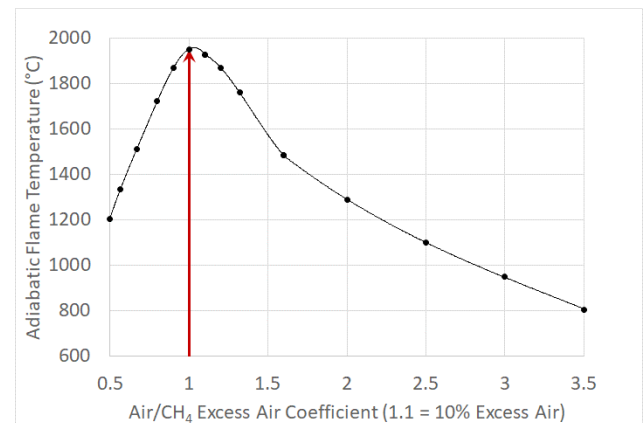


Fig 1

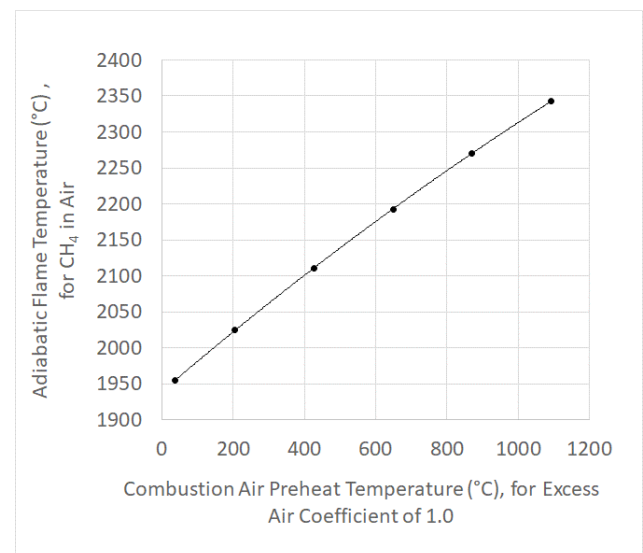


Fig 2

6. The area, A, for heat transfer is also important. This applies to both the area of product exposed to the radiant flame and the volume or size of the radiant flame itself. Kiln speed, refractory /coating surface condition, stickiness of product play a part in the area of the bed exposed to the flame as it climbs up the side of the kiln and cascades back down again. Also a wide, short flame near the tip of the burner will concentrate the heat transfer at the discharge end of the kiln where as a longer narrower flame will distribute the heat further into the kiln.

7. The flame emissivity, ϵ , also plays an important part. Increasing the emissivity of the flame can dramatically improve radiant heat transfer to the product and in turn reduce the flame temperature. One benefit of the reduced temperature for flames with high emissivity is lower thermal NOx emissions. To demonstrate this, consider a flame in a rotary kiln heating clinker to 1450°C. If we start with a luminous flame with $T_z=1750^\circ\text{C}$ and $\epsilon_1=0.95$ and then compare that to a non-luminous flame with $\epsilon_2=0.3$ we see the non-luminous flame would need a temperature of:

$$\epsilon_1 (T_{f1}^4 - T_p^4) = \epsilon_2 (T_{f2}^4 - T_p^4)$$

$$T_{f2} = \left(\frac{\epsilon_1}{\epsilon_2} (T_{f1}^4 - T_p^4) + T_p^4 \right)^{1/4}$$

$$T_{f2} = \left(\frac{0.95}{0.3} ((1750 + 273\text{K})^4 - (1450 + 273\text{K})^4) + (1450 + 273\text{K})^4 \right)^{1/4}$$

$$T_{f2} = 2413\text{K} = 2140^\circ\text{C}$$

In other words, the non-luminous flame temperature is about $2140 - 1750 = 390^\circ\text{C}$ higher than the luminous flame. This calculation is clearly over simplified but stands to show how flame emissivity affects the flame temperature.

Different fuels result in flames with different flame emissivities. A rough guide to flame emissivities for different fuels is:

- Coal $\epsilon > 0.95$
- Oil $\epsilon = 0.7 - 0.9$
- Gas $\epsilon = 0.3 - 0.6$

In the next Masterclass we'll explore practical methods for reducing NOx in rotary kiln flames.