Flame length in lime kilns with a separate noncondensible gas burner

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ABSTRACT: Using an acid-alkali visualization technique, we studied the flame length in a lime kiln with a separate noncondensible gas (NCG) burner, as a function of the combined Craya-Curtet number (combined Ct) and excess air. The combined Ct and excess air are the dominant parameters affecting the flame length, shape, and temperature. The flame length increases with an increase in the combined Ct and a decrease in excess air. We developed an empirical equation for calculating the flame length. The NCG effect is accounted for in this equation.

Application: New criteria for predicting the length of the flame in the lime kiln and how it changes with combined Ct and excess air will allow operators and engineers to monitor and continuously control fluctuations in flame length. This can stabilize and enhance the efficiency of kiln operation.

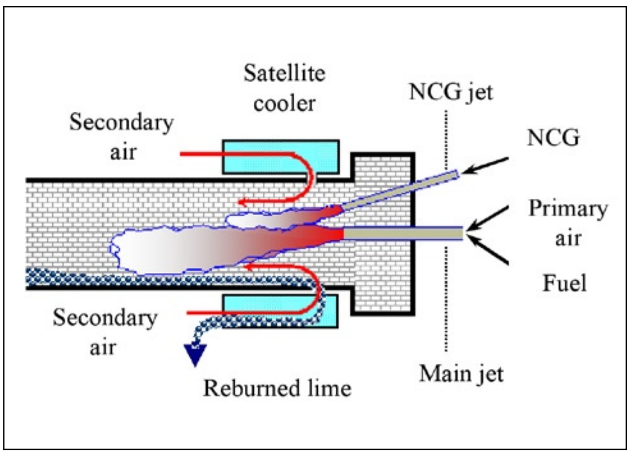
The efficiency of a lime kiln in converting lime mud into lime depends on how effectively the heat from the burner flame can be transferred to the lime mud particles as they move through the kiln. Since the burner is the only source of heat in the kiln, the flame patterns it produces (such as flame length, shape, and intensity) are critical to kiln operation and performance. The flame pattern affects the rate of heat transfer and, subsequently, product lime quality, TRS emissions, and refractory life. An unstable flame causes a wide fluctuation of gas temperatures, allowing the calcined lime mud particles to recarbonate to form hard rings on the refractory lining in the middle of the kiln [1].

The interaction between the main burner flame and NCG burner flame has been studied using a water/dye flow visualization technique [2]. We found that the mixing and interaction between the two jets is strongly influenced by the Craya-Curtet number (Ct). Although it was possible to obtain information about the flame width, we could not use the technique to determine the flame length itself, an important characteristic directly related to temperature distribution and heat transfer in the kiln [3]. In this study, we used an acid-alkali visualization technique to investigate the effect of operating parameters on the flame length.

Although acid-alkali visualization has been used previously to simulate flames [4, 5], the results were qualitative and the effect of Ct on the flame length was not fully investigated. It was shown that the ratio between the acid and alkali concentrations (or excess acid) closely relates to the excess air in the kiln, while the alkali jet length corresponds to the flame length in the kiln [4]. The excess acid is defined as the amount of acid remaining after the complete neutralization of the alkali jet. Therefore, we developed a methodology to simulate the flame length as a function of the Ct and the excess air.

For a given burner design and kiln geometry, flame length is influenced by (1) fuel type and flow rate, (2) ratio of primary combustion air to secondary combustion air, (3) flow rate and nature of waste gases, and (4) asymmetry of the burners.

Asymmetry is an important factor affecting flame characteristics. Burners are usually off-center because of the burner orientation and long lance. A greater degree of asymmetry may be experienced in kilns that burn waste streams such as NCG, stripper off-gas (SOG), and tall oil, using a separate burner. In such kilns, the flame patterns of the main-burner are distorted to a degree that can be large, depending on how the NCG burner is positioned and operated (**Fig. 1**). In addition, all kilns are somewhat asymmetric due to the presence of the solids bed, and to the uneven formation of ring deposits on the kiln walls. Since it was difficult to characterize the effects of asymmetry on flame length and patterns, the work performed to date has focused on symmetrical geometries [6, 7].



1. Schematic of the lime kiln with separate NCG burner.

It is important to understand how flame length is affected by kiln geometry near the firing hood, by kiln operating parameters, and by the way waste gases are burned in the kiln. The objective of our work is to study flame length as a function of flow conditions, NCG burner orientation, and operating parameters.

SCALING CRITERIA

To compare the results produced from the experimental apparatus to a lime kiln, we used the Ct [8], a scaling parameter that incorporates the most important design and operating parameters related to flames in lime kilns. For a single jet, Ct is defined as:

$$Ct = U_k \Big/ \left(U_d^2 - 0.5U_k^2\right)^{\frac{1}{2}} \tag{1}$$

where U_k is the kinematic velocity and U_d is the dynamic velocity, which can be defined by:

$$U_k = \left(r_1^2 U_1 + \left(r_2^2 - r_1^2\right) U_2\right) \Big/ r_2^2 \tag{2}$$

$$U_d^2 = \frac{\left[r_1^2 U_1^2 + \left(r_2^2 - r_1^2\right) U_2^2\right]}{r_2^2} - 0.5\, U_2^2 \tag{3}$$

U_1 and r_1 are, respectively, the nozzle exit velocity and radius of the main jet; U_2 and r_2 are, respectively, the inlet velocity of the secondary stream (secondary air in the case of the kiln) and the confining duct (kiln shell) radius.

The Ct was modified in this work to include the effect of the separate NCG burner. The modified parameter is defined as:

$$\text{combined } Ct = U'_k \Big/ \left(U'^2_d - 0.5U'^2_k\right)^{\frac{1}{2}} \tag{4}$$

The modified dynamic (U'_d) and kinematic (U'_k) velocities are defined as:

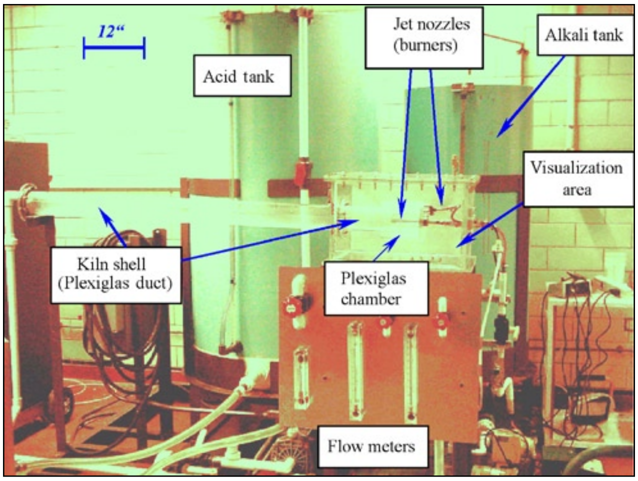
$$U'_k = \left(r_1^2 U_1 + r_3^2 U_3 + \left(r_2^2 - r_1^2 - r_3^2\right) U_2\right) \Big/ r_2^2 \tag{5}$$

$$U'^2_d = \frac{\left[r_1^2 U_1^2 + r_3^2 U_3^2 + \left(r_2^2 - r_1^2 - r_3^2\right) U_2^2\right]}{r_2^2} - 0.5\, U_2^2 \tag{6}$$

where U_3 and r_3 are, respectively, the NCG nozzle exit velocity and radius.

EXPERIMENTAL PROCEDURE

It is difficult to characterize the flame pattern in an operating lime kiln, because of the high temperature and the dusty environment near the firing hood, the sliding and tumbling motion of the lime, and the inaccessibility of the burner flame. In this study, we used flow visualization with an acid-alkali technique to simulate flame patterns.

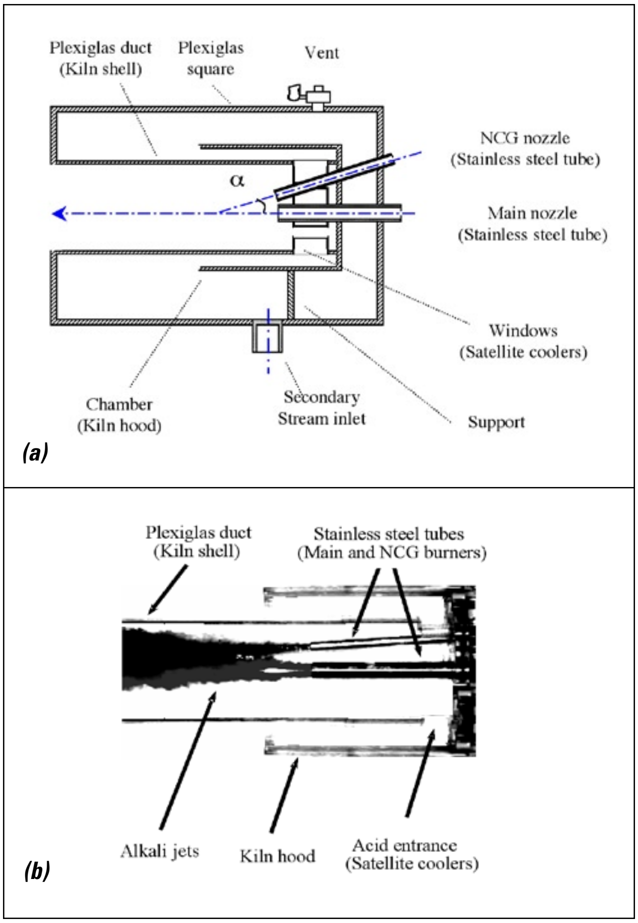


2. Flow visualization apparatus.

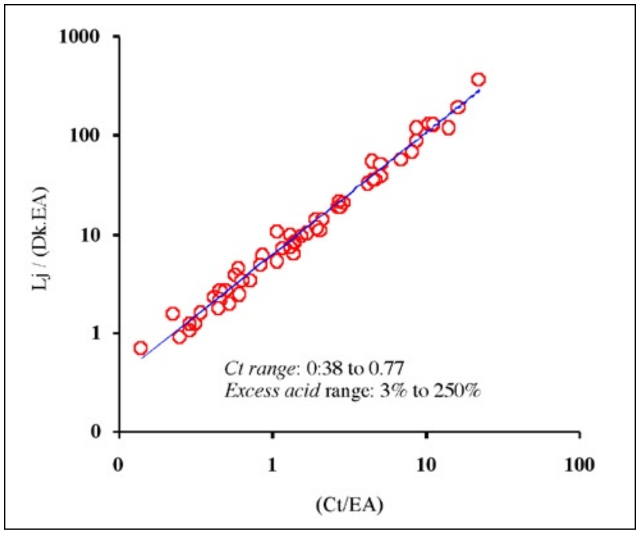
The experimental apparatus (**Fig. 2**) uses acid and alkali to simulate the flame patterns in the kiln. The rate of combustion in the lime kiln is controlled by the mixing between the fuel and the combustion air [9]. This is represented in the laboratory by the mixing between the alkali jet and the acid stream. Although this is an approximate isothermal simulation technique, the results can be extended to the non-isothermal case of burner flames when appropriately corrected for combustion effects [7]. The apparatus consists of two storage tanks, a flow control system, and a model-burner section. One tank is used for acid storage and the other for alkali storage. The model burner (**Fig. 3**), consists of two stainless steel tubes, a Plexiglas chamber and a Plexiglas duct to represent the burners, the firing hood and the kiln shell respectively.

We mixed a 0.005 mole/L alkali solution with a pH indicator (phenolphthalein) in the alkali tank to give the solution a pink color. The alkali solution was pumped through two stainless steel nozzles; while a 0.01 mole/L acid solution was pumped from the acid tank through the Plexiglas duct. As the alkali solution exits the nozzle, it expands and mixes with the acid solution. The acid neutralizes the alkali. As the pH of the solution drops below 7; the solution becomes colorless, clearly distinguishing the jet (pink) from the rest of the flow (no color). The flow rate of the alkali jets was constant during the experiments, while the flow rate of the acid was changed corresponding to different Ct and combined Ct values, and excess acid. For each experiment, the jet was filmed with a standard video camera, and the time-average jet length was estimated. A new alkali solution (with concentration between 0.005 – 0.020 mole/L) was used for each set of experiments.

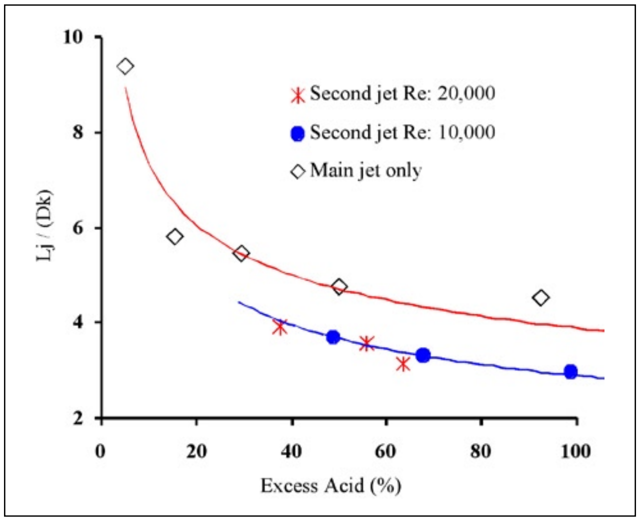
Using the method we developed, we examined the effect of the second jet orientation (angle α), Ct, combined Ct, and



3. Schematic of the model-burner section (a) and a photo of the section with jets shown (b).



4. Normalized length of main jet, Lj /(Dk.EA), as a function of CT and excess acid (Ct/EA).



5. Length of the two jets for Ct = 0.77. (Angle between the two nozzles is 0°).

excess acid on the flame length. The Ct and combined Ct range considered in this study covers the typical range used in lime kilns [2].

RESULTS AND DISCUSSION

Flame length with single jet (main jet only)

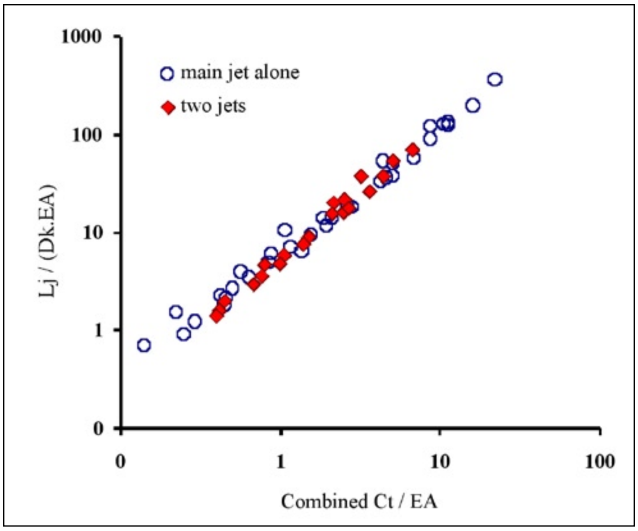
We compared the length of the main jet (Lj) to Ct and excess acid (EA, %). Ct summarizes the aerodynamic effects of the design and operating parameters, which directly affect the mixing between the acid stream (i.e., secondary stream) and the alkali jet. Ct is directly linked to the primary/secondary air ratio, the primary air to fuel ratio, the excess air and the size of the kiln and its burners, as these parameters are used in calculating the velocities (U_1 and U_2) in equations 2 and 3. The excess acid simulates the effect of the excess air in the lime kiln [4,5].

When the results are normalized, as presented in **Fig. 4**, the change in the alkali jet length divided by the excess acid (normalized jet length) becomes dependent only on "Ct divided by the excess acid (Ct/EA)". We did these experiments over a wide range of excess acid, and found that normalizing the jet length (dividing it by excess acid) makes it easy to represent the results in a single relationship. This presents the results in a useful form that is applicable to lime kilns.

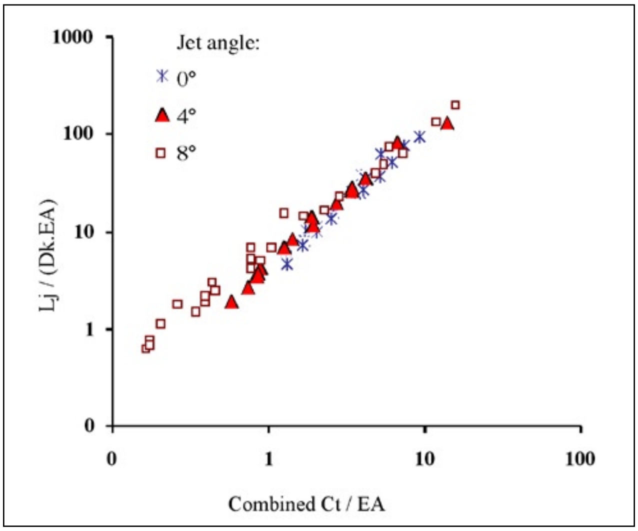
Figure 4 shows that the normalized jet length is a unique function of Ct/excess acid. The jet length increases with an increase in Ct due to the decrease in entrainment of acid [8]. Decreasing the excess acid increases the time for the alkali jet to be neutralized, leading to a longer jet. These results imply that the excess air is an important parameter to be considered when simulating the flame. Based on the similarity between jet length and flame length [4], the results suggest that Ct is a very important parameter in controlling the flame characteristics in kilns with a single burner, and that lime kilns might be controlled by monitoring Ct and the excess air.

Flame length with two jets

Figure 5 shows the length for the two jets as a function of excess acid, for a Ct value of 0.77. The same graph presents the results for single jet (main jet only) for comparison. The results show that the length of the two combined jets is short-



6. Normalized length for single jet and two jets. (Angle between the two nozzles is 0°).



7. Normalized length of the two jets for different angles.

er than the length of the main jet alone, probably due to enhanced mixing between the acid and alkali jets. The presence of the second jet seems to increase the demand for acid due to higher entrainment rates by the two jets, compared to a single jet, which is equivalent to reducing Ct. These results are consistent with previous work with jet simulation, where evidence of stronger mixing between the jets and secondary stream were noticed through longer recirculation zones [2].

In order to scale the results, we used the combined Ct. **Figure 6** shows the length of the two jets as a function of the combined Ct/excess acid. The results are consistent with the single jet case (Fig. 4). The length of the two jets increases with an increase in the combined Ct and a decrease in the excess acid. The combined Ct seems to be a good scaling parameter for the length of the two combined jets. These results suggest that the flame length depends mainly on the combined Ct and excess air. When burning NCG through a separate burner, the flame length could be controlled by monitoring these two parameters.

Effect of second jet orientation

Figure 7 shows the length of the two jets for three different angles of the second jet (0°, 4°, and 8°). The results show insignificant dependence on the angle. This indicates the angle of the second jet has little effect on the jet length, probably due to the small value of the angles of the second jet. The second jet is also weaker than the main jet, leading to a weak influence on the main jet. A dependence on angle may exist at larger angles, but this needs to be verified.

APPLICATION OF THE RESULTS

The results presented in this paper based on acid and alkali work are approximately isothermal, as there is no measurable temperature change as the jets expand. However, the situation is different in the lime kiln, as there is a temperature difference between the flame and secondary air. To apply this data to kiln conditions, we compared these results to existing models for flame length, such as the Magnussen's model [6]. The Magnussen formula is given by:

$$\frac{L_f}{r_2} = 10*\left(\frac{c_\infty}{c_T}\right)\left(\frac{1}{B}\right)^{1/2}\left(\frac{1-\left(\frac{m_{1o}}{m}\right)k}{1-\left(\frac{c_\infty}{c_T}\right)k}\right) \quad (7)$$

$$k = \frac{\left(0.425B^{1/2}-0.55\right)}{\left(0.425B^{1/2}-0.45-\frac{m_{1o}}{m}\right)} \quad (8)$$

In which r_2 is the diameter of the kiln, c_∞ is the concentration of jet materials at exit, c_T is the stoichiometric concentration of the fuel in the un-reacted mixture, m_{1o} is the mass flow rate of the jet at the exit of the nozzle, m is the total flow rate, and B is the Magnussen similarity parameter. Equation 7 is valid only for Ct < 0.82, which is the range applicable in the lime kilns. The parameters used in the equation to calculate the flame length were modified to take into account the effect of the second jet (or NCG separate burner in the case of the lime kiln). For a lime kiln, B is related to Ct by the following formula:

$$B = 0.5 + \left(\frac{1}{Ct}\right)^2 \quad (9)$$

Using the least-square method, the acid-alkali results were fitted into the following formula:

$$\frac{L_f}{Dk} = 17.4\left(\frac{(\text{combined Ct})^2}{\text{excess air}}\right)^{0.3} \quad (10)$$

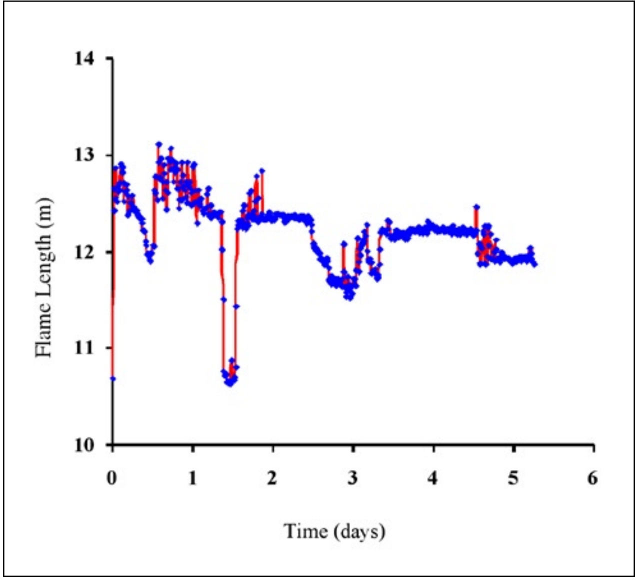
Since the acid-alkali results are isothermal, this equation had to be modified to account for the difference in the temperature in the lime kiln. The main effect of the temperature difference is a shorter flame than predicted based on the acid-alkali results [10, 11]. A correction was made using the ratio of the densities of the flame and secondary air [7, 12]. The flame length based on the acid-alkali results, for a typical lime kiln operating range, corrected for combustion is given by:

$$\frac{L_f}{Dk} = 17.4\left(\frac{(\text{combined Ct})^2}{\text{excess air}}\right)^{0.3}\sqrt{\frac{\rho_f}{\rho_{secondary}}} \quad (11)$$

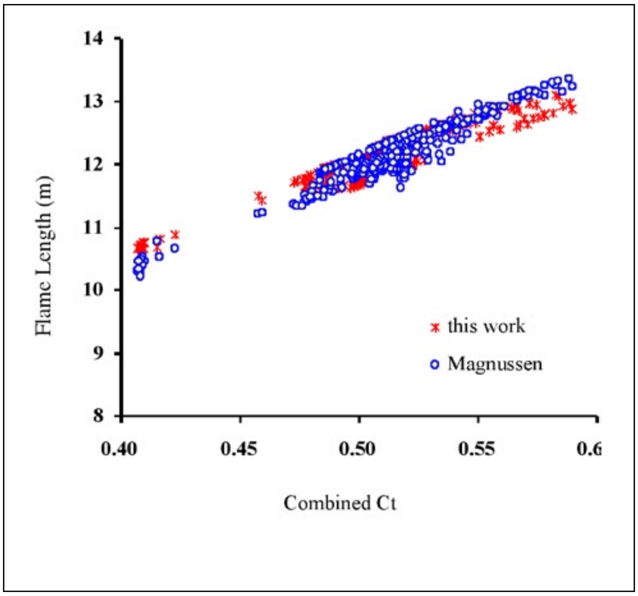
in which L_f is the flame length, D_k is the kiln diameter. ρ is density with subscripts *f* and *secondary* representing the flame and secondary air flow conditions, respectively. The densities are estimated fuel type and operating conditions in the lime kiln.

Operating data were collected from a Canadian kraft mill for a kiln burning NCG, every 15 minutes, over a period of one week. Using this data, the flame length was estimated using this equation and the Magnussen formula. The kiln was 3.5 m in internal diameter and burned natural gas through a 0.35 m diameter main burner. It had a separate NCG burner with a 0.23 m diameter.

The estimated flame length calculated from equation 11 is shown in **Fig. 8**, which shows how the flame apparently fluctuated during the week the data was collected. The estimated flame fluctuated mainly between 11 m and 13 m. Both the Magnussen Formula and our equation estimate the average flame length, and do not predict the variations related to flow turbulence. The variations in flame length, shown in Fig. 8, occur only because of the fluctuation in the different flow parameter used to estimate the flame length, such as the fuel flow rate and the excess air. The instantaneous flame length may fluctuate more than that shown in Fig. 8. A comparison with the Magnussen formula is presented in **Fig. 9**, which shows that the kiln operated at combined Ct between 0.45 and 0.60, and the flame length was in the range of 11 m to 13 m. The predictions of the equation agree with the Magnussen formula, which means that both can be used to estimate the flame length.



8. Estimated flame length in a lime kiln with NCG as estimated by equation 11.



9. Estimated flame length in a lime kiln with NCG. A comparison between Magnussen formula and this work (equation 11).

As shown in Fig. 8, the flame length varies between 12 m and 13 m in the first day of operation, and then drops to approximately 11.5 m in the second day (time = 1.5 days). By examining the operating data collected from the mill, we found that this drop in the flame length corresponds to a decrease in the secondary air flow leading to a lower combined Ct value. The stable flame length during the fourth and fifth day indicates minimal variations in the operating parameters. However, the instantaneous flame length is expected to fluctuate more, as explained earlier.

SUMMARY

We conducted a systematic study of burner flame patterns in lime kilns using an acid-alkali visualization technique. We investigated the interaction between the NCG flame and the main flame for a broad range of design and operating parameters. The results and implications of this study are summarized as follows:

1. the combined Craya-Curtet number and the excess air were the most important parameters affecting the flame length,
2. the flame length increased with an increase in combined Ct, and with a decrease in excess air, and
3. orienting the NCG burner at an angle between 0° and 8° had an insignificant effect on the flame length. **TJ**

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LITERATURE CITED

1. Tran, H., Mao X., and Barham, D., *J. Pulp Paper Sci.* 19(4): 167 (1993).
2. Aloqaily, A., et al., *J. Pulp Paper Sci.* 31(3): 137 (2005).
3. Gorog, J.P. and Adams, T.N., *TAPPI 1986 kraft recovery operations short course*, TAPPI PRESS, Atlanta.
4. Rhine, J.M. and Tucker, R.J., "Modeling of gas-fired furnaces and boilers and other industrial heating processes," British Gas technical monographs, London, 1991.
5. Ruhland, W., J. Inst. Fuel, 40(313): 69 (1967).
6. Magnussen, B.F., "Predictions of characteristics of enclosed turbulent jet flames," *14th Sym. Int. on Combust.*, 1973.
7. Thring, M.W. and Newby, M.P., "Combustion length of enclosed turbulent jet flames," *4th Sym. Int. on Combust.*, 1953.
8. Becker, H.A., Hottel, H.C., and Williams, G.C., "Mixing and flow in ducted turbulent jets," *9th Symp. Int. on Combust.*, 1963.
9. Moles, F.D., Watson, D., and Lain, P.B., J. Inst. Fuel, 1973 46 (389): 353 (1973).
10. Steward, F.R. and Guruz, A.G., Combust. Sci. Technol., 16(1-2): 29 (1977).
11. Sunavala, P.D., J. Sci. Industry Res., 20(B): 246 (1961).
12. Guruz, A.G., Guruz, H.K., and Osuwan, S., Combust. Sci. Tech., 9(3-4): 103 (1974).

INSIGHTS FROM THE AUTHORS

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We chose this area of research because flame length prediction is important in developing a control and optimization strategy for lime kilns, and a good strategy is essential for enhancing the efficiency of the kiln and reducing operating problems. Our research is a continuation of previous work on the effect of burning NCG on the flame characteristics in the lime kiln. It is different from other works because it focuses on the flame length predictions and practical significance of burning NCG in the kiln.

The most difficult aspect of our research was the issue of scales—how to simulate accurately with experimental setups, successfully scale the results to kiln operation, and validate them. Our results were scaled up using the scaling parameter defined in this work, the combined Craya-Curtet number, and validating it against known methods.

Our most interesting discovery was the definition of the combined Craya-Curtet number and how well it correlates with the characteristics of the flame in the kiln. In fact, it works very well.

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