Effect of ring formation on burner flame stability in lime kilns

GIRISH MOHANAN, HONGHI TRAN, MARKUS BUSSMANN, AND RICHARD MANNING

ABSTRACT: Ring formation in lime kilns is a common problem in pulp mills. Unstable burner operation that causes wide temperature variations within the kiln has been shown to be a main contributor. As rings grow thicker and longer, they are expected to affect the burner flame pattern, alter the temperature distribution, and further aggravate the problem. This study systematically examines the effect of rings on burner operation as a function of primary air and ring characteristics, using a laboratory mock kiln. The results show that primary air greatly affects the burner flame pattern and stability. Without a ring, the flame is brighter and shorter, with an increase in primary air (PA) up to 17%, and blows out at 20% PA or higher. In the presence of a ring, the flame becomes unstable and blows out when the ring is placed near the burner, but it is more stable when the ring is placed away from the burner. Thick and long rings destabilize the flame more than thin and short rings.

Application: Pulp mill engineers may use the information in this study to help stabilize the lime kiln burner flame.

Ring formation in lime kilns is a persistent problem in many pulp mills, limiting the kiln production capacity, and in severe cases, resulting in unscheduled kiln shutdown for ring removal. As lime mud/lime solids slide and tumble through the kiln, they cover the refractory brick surface with a layer of dust. The deposited dust layer grows thicker with time and has a cross-section that resembles a ring. It has been postulated that in order for rings to form, particles must first adhere to the refractory surface to form deposits. The deposits must subsequently become hard to withstand the abrasiveness of the sliding and tumbling motion of the solids bed [1,2].

There are three distinct types of rings that are commonly observed. Mud rings typically form right after the chain section, due mainly to the high moisture and sodium contents of the lime mud. Mud rings are usually soft, but they can grow rapidly, completely blocking the kiln in a few hours. Mid-kiln rings form in the calcination zone, starting from the middle of the kiln to about 20 m (66 ft) from the kiln front end. The main hardening mechanism of mid-kiln rings is believed to be “recarbonation”, the reaction between the lime (CaO) particles deposited on the refractory surface and carbon dioxide (CO₂) in the kiln gas that occurs when the temperature of the particles drops below 750°C (1382°F) [2]. Front-end rings typically form near the kiln burner, particularly when the temperature in this area is excessively high, causing the deposited lime on the refractory brick surface to rapidly sinter. For kilns that burn high sulfur-containing fuels such as crude oil, non-condensable gases, petroleum coke, etc., the ringing problem can be further aggravated due to the formation of hard calcium sulfate (CaSO₄) deposits [3].

Of these types of rings, mid-kiln rings are the most common and also the most difficult type to tackle, due primarily to their inaccessibility from the outside during operation. Stabili-
profile in the kiln may help mills develop viable strategies to “break up” the cycle and minimize ring growth.

The objective of this study is to systematically investigate how ring formation affects the flame pattern and stability. In this paper, we will first describe the experimental setup and procedures used in the study, and then discuss the results obtained and the practical implications of the results.

**EXPERIMENTAL SETUP AND PROCEDURES**

Figure 2 shows the setup for a mock kiln used in this study. It consists of a miniature diffusion gas burner, a quartz glass tube, and an exhaust gas system. The entire assembly, 2.15 m (7 ft) long, is laid horizontally on three supporting bricks on a laboratory bench.

The miniature diffusion burner simulates actual burners used in lime kilns, although methane is used as fuel instead of natural gas. As shown in Fig. 3, the burner consists of a methane and primary air (PA) pre-mixed burner embedded concentrically in a chamber that mimics an actual kiln hood. Secondary air (SA) from a compressed air cylinder (not shown here) enters the chamber and passes through a series of 3 honeycomb flow straighteners. As it emerges from the chamber, the secondary air diffuses into the methane/PA mixture. The combustion is subsequently initiated using an electric igniter.

The quartz tube, 89 mm (3.5 ft) inner diameter (ID) x 1.83 m (6 ft) long, is connected to the diffusion burner at one end and the exhaust system at the other end. Quartz glass is used not only because it can withstand high temperatures, but also because it allows the burner flame inside to be visualized and documented with a high-resolution video camera (Fig. 4). The exhaust gas system is made of a simple 90° steel elbow connected to the quartz tube to direct the combustion gas to a laboratory fume hood located directly above. The exhaust gas can be readily purged from the system due to the high gas pressure in the mock kiln and the negative draft pulled by the fume hood.

The ring formation is simulated by placing a refractory cylinder in the quartz tube. The “ring” (the refractory cylinder) is carved from a piece of refractory brick and placed at various positions in the quartz tube by sliding it along the tube wall. The ring thickness, length, and position are defined as shown in Fig. 5.

The problem with this setup is that because the ring is made of refractory brick, it blocks the view of the burner flame. The setup is good only for short rings since the burner
flame is still visible. For long rings, however, the setup does not work well, as the burner flame cannot be seen once it goes inside the ring. In order to make the burner flame visible inside the ring, the long ring is made by inserting both ends of a smaller quartz tube concentrically into two short refractory cylinders, as shown in Fig. 6a. While the approach is not perfect, it does provide reasonably good insights on how a long ring may affect the burner flame (Fig. 6b).

In this study, methane was supplied through the fuel port of the premix burner at a flow rate of 6 liters per minute (L/min). The PA was fed to the burner through the air port of the premix burner at a flow rate varying between 10% and 25% of the total air. The SA was added into the air chamber through two opposing air ports. Both PA and SA flow rates were automatically controlled by means of two separate mass flow controllers. The methane flow rate was monitored and manually controlled using a rotameter.

The total air was the sum of the stoichiometrically required air and excess air (EA). Numerous trial runs showed that the optimum EA required for a stable burner flame operation of the mock kiln was about 10%. Depending on the goal of a specific test, the primary air was changed while keeping the total air constant at 10% EA. In other words, for tests where the primary air was increased (or decreased), the secondary air was automatically decreased (or increased) by the same amount so that the total air was the same, and the system was maintained at 10% EA. The three main ring characteristics examined were position, thickness, and length.

**RESULTS AND DISCUSSION**

**Effect of primary air**

Figure 7 shows the change in appearance of the burner flame with increasing primary air (expressed as % of total air) while burning 6 L/min of methane with 10% EA in the absence of a ring. At 0% PA (no primary air), the flame was yellow and long and appeared to be “lazy”. As the primary air was increased to 17% PA, the flame became increasingly brighter, shorter, bushier, and more intense. It eventually blew out at 20% PA. Tests were also carried out at 22% and 25% PA, and blowout occurred in both cases. This change in flame pattern with increased primary air resembles that of a Bunsen burner (or a propane welding torch) when more air is added to it, and it is consistent with that observed in a previous study using a pilot scale kiln [5] and that described by Adams [6].

4. Burner flame clearly visible through the quartz glass tube.

5. a=Ring thickness, b=Ring Length and c= Ring position
6. Experimental setup for investigating the effect of a long ring on burner flame pattern: a) setup schematic, and b) image of a burner flame passing through the ring.

7. Change in burner flame pattern with increasing primary air (methane flowrate = 6 L/min; excess air [EA] = 10%). Note: No flame (or blowout) at 20% primary air (PA) and higher.
Effect of ring position

Figure 8 shows how the burner flame, produced by burning 6 L/min methane at 15% PA and 10% EA, changed when a 2 cm thick, 2.5 cm long ring was placed in front of the burner. The flame immediately broke away from the burner tip and blew out in less than 1.3 s. The blowout was likely caused by the sudden blockage of the secondary air by the ring, which literally starved off the burner flame.

Under the same burning condition (6 L/min methane, 15% PA, and 10% EA), the flame was stable with no blowout when there was no ring (Fig. 7) or when the very same ring was placed at 50 cm away from the burner (Fig. 9).

Figure 10 summarizes results of a series of tests in which the effect of ring position on the burner flame was examined at different primary air flow rates between 17% and 22% PA. During each test, the burner flame was videoed for 60 s after it had stabilized. The video was divided into six 10 s-long clips; each clip contained 360 frames or images. The frames were then analyzed using an open image processing software, ImageJ, to determine the flame length. Since each data point shown in this figure was derived from 2160 frames, the error was small, about ±2.5% with a confidence of 95%.

In all cases, the flame length was zero (i.e., no flame or flame blowout) when the ring was placed right at the burner tip. At 17% PA, the flame was consistently 22 to 25 cm long when the ring was farther than 3 cm from the burner, suggesting that under such test conditions, ring position had no impact on flame stability. At 20% PA, the flame was somewhat shorter and stable when the ring was placed at 3 to 30 cm from the burner. It was less stable and blew out when the ring was placed at 30 to 40 cm, but became stable again when the ring was placed at 45 cm or farther from the burner. Similar results were obtained at 22% PA, except that in this case, the ring position where the flame blew out was only 15 to 40 cm to the burner—much closer than that at 20% PA.

Note from Fig. 7 that at 20% PA and higher, the flame blew out when there was no ring in the quartz tube. However, when there was a ring and it was placed at a right position, the flame was stabilized with no blowout, as shown in Fig. 10. One possible explanation for this observation is that at high
PA, the momentum of the methane/PA mixture is so great that it creates a significant low-pressure (vacuum) region that rapidly draws or recirculates the surrounding gas, mostly SA and combustion products (CO₂ and H₂O vapor) into the root of the flame. This, in turn, can cause the flame to extinguish. The presence of a ring can disturb the recirculation flow, making it harder for the combustion products to recirculate back to the root of the burner flame. This helps prevent the flame from extinguishing. Furthermore, since flame impingement on the ring can rapidly elevate the ring surface temperature, the extinguished flame can be reignited by the hot surface and stabilized. These burner flame characteristics are consistent with the so-called “flame puffing” phenomenon that is occasionally observed on a kiln platform when the flame suddenly blows out and rapidly relights.

*Effect of ring thickness*
In lime kilns, rings become radially thicker and axially longer with time. They are therefore expected to have a different effect on the burner flame. In this series of tests, the effect of ring thickness on flame stability was examined using rings of three different thicknesses: 1.5 cm, 2 cm, and 2.5 cm. The burner was operated at 6 L/min methane, 10% EA, and at a constant PA flow rate.

**Figure 11** shows photos of the burner flame at 15% PA with different ring thicknesses placed at 15 cm from the burner. In all three cases, the flame appeared to be stable with no significant difference in flame characteristics.

**Figure 12** plots burner flame lengths at 15% PA versus ring positions for different ring thicknesses. Both 1.5 cm and 2 cm thick rings appeared to have no significant effect on the flame length, except that the 2 cm thick ring stabilized the flame when it was placed at 3 cm away from the burner. For the 2.5 cm thick ring, the flame was stable only when the ring was placed between 6 and 20 cm from the burner. These results suggest that while rings can help stabilize the burner flame, thick rings are not as effective as thin rings. This is understandable because thick rings have a smaller area through which the SA can pass, so they affect the flame stability more than thin rings.

*Effect of ring length*
In this series of tests, 2 cm-thick rings of three different lengths were used: 2.5 cm, 5.0 cm, and 7.5 cm. As with the
previous test series, the rings were placed at different positions inside the quartz tube and the burner flame characteristics at each position were recorded and analyzed. Figure 13 compares the interaction between the burner flame and the short (2.5 cm) ring and that between the burner flame and the long (7.5 cm) ring. The longer ring appeared to make the burner flame longer.

Figure 14 plots burner flame lengths at 15% PA versus ring positions for different ring lengths. The short ring (2.5 cm) had no significant effect on the flame length, which was stabilized when it was placed at 3 cm and 25 cm away from the burner. For longer rings (5 cm and 7.5 cm), the flame was longer and stable only when the ring was placed between 6 cm and 20 cm from the burner.

The possible explanation for this finding is that in the case of short rings, although the flame is initially disturbed, it can recover quickly once it has passed through the ring. In the case of long rings, however, it is more difficult for the flame to recover.
to pass, causing the flame pressure inside the ring to increase, and this likely results in an elongated flame.

**SUMMARY**

A laboratory study was conducted using a mock kiln to systematically investigate the effect of ring formation on the burner flame stability. Experiments were carried out by burning 6 L/min of methane mixed with various amounts of PA while keeping the total air constant at 10% EA. The ring characteristics investigated were position, thickness, and length. The results show that:

- PA is the main parameter that affects flame stability. In

the absence of a ring, the flame becomes brighter, shorter and more intense with an increase in PA up to 17%, and blows out at 20% PA or higher.
- In the presence of a ring, the flame is not stable when the ring is placed too close to the burner, but becomes stabilized when the ring is placed away from the burner.
- Thick rings are more susceptible to flame destabilization than thin rings. The effect of ring thickness on flame stability varies with ring position.
- Long rings destabilize and elongate the flame more than short rings.

13. Longer rings elongate the flame by reducing the volume available for combustion reaction (6 L/min methane, 15% PA, 10% EA).

14. Effect of ring length on flame stability (methane flowrate = 6 L/m, 15% PA, 10% EA).
This study clearly shows that ring formation can have a great effect on the flame shape and length. However, how it affects the gas and ring surface temperatures and the temperature distribution in the kiln is not clear. This is an interesting and important subject for future research. **TJ**

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**LITERATURE CITED**


**ABOUT THE AUTHORS**

We chose this topic to research to see if we could prove that as rings grow thicker and more massive with time, they can destabilize the burner flame and alter the temperature profile in the lime kiln. This study complements our previous research that showed how flame instability can lead to ring formation. This research is the other way around, investigating how ring formation may lead to flame instability.

The most difficult part of this study was how to characterize the burner performance under various operating conditions in the model kiln. We address the problem by clearly defining the flame length using an imaging computer program. It was interesting to discover that ring formation is a self-promoting process; once formed, it will likely get worse with time. It was also surprising to find that a minor change in burning conditions in the model kiln could abruptly change burner flame behavior.

Mills may use the information here to address the importance of stable process operation as a means to minimize the ringing problem. Our next step is to investigate how growth of rings may affect the temperature profile, both experimentally and with computational fluid dynamic modeling.

Mohanan is a graduate student and Tran is Frank Dottori Professor of Pulp & Paper Engineering in the Department of Chemical Engineering and Applied Chemistry at the University of Toronto, Toronto, ON, Canada. Bussmann is professor in the Department of Mechanical and Industrial Engineering at the University of Toronto, Toronto, ON, Canada. Manning is director and chief technology officer at KFS in High Wycombe, U.K. Email Tran at honghi.tran@utoronto.ca.