

Surface temperature measurement of a burning black liquor droplet using two-colour optical pyrometry

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Abstract

This paper reports on the implementation of two-colour optical pyrometry to measure the distribution of surface temperature of a burning black liquor droplet in a flat flame environment. The black liquor was burned in the flame provided by the flat flame burner at two flame conditions, fuel lean ($\phi_{bg} = 0.8$), and fuel rich ($\phi_{bg} = 1.25$). Two identical digital single-lens reflex (SLR) cameras were used to allow the simultaneous measurement of the surface temperature and particle size. This provides an opportunity for more reliable measurements of surface temperature for black liquor than has previously been available.

Keywords: Surface temperature, Two-colour optical pyrometry, Black liquor.

1. Introduction

Black liquor is a complex and important source of renewable fuel in the pulp and paper industry. It consists of both organic components of wood, mainly lignin, and inorganic components derived from sodium based pulping chemicals. The sodium can be bound to both organic and inorganic compounds [1]. During black liquor combustion the organically bound sodium, which is associated with the phenolic hydroxyl and carboxyl compounds, decomposes and converts to Na_2CO_3 [1]. The purpose of burning black liquor in a kraft recovery boiler is to recover both the pulping chemicals and the heat generated from the black liquor combustion, which is converted to electricity to power the pulp mill through a steam turbine. The black liquor is sprayed into a recovery boiler, typically as droplets from 0.5–5 mm in diameter [2].

Combustion of a single droplet of black liquor combustion can be divided into the four stages of drying, devolatilisation, char combustion and smelt oxidation [3]. Black liquor swells significantly during the devolatilisation stage, by 10–60 times in volume [4], due to gas evolution within the highly viscous droplet [2]. The drying and devolatilisation stages of combustion may overlap due to large temperature gradient within the swollen droplet (Biot number > 1) [2, 5]. During the char combustion stage, char is oxidised by reaction with H_2O , CO_2 and O_2 , and by the reduction of Na_2CO_3 and Na_2SO_4 [2]. A molten bead of smelt, consisting of inorganic components (mainly Na_2CO_3 and Na_2S), is formed at the end of the char combustion stage and the oxidation of Na_2S can occur if O_2 is available [2]. Details of the black liquor combustion

by measuring swelling and surface temperature simultaneously at each stage of the combustion are required to provide an insight to support the development of reliable models.

Two-colour optical pyrometry has been well-established and widely used to measure the surface temperature at a single point on burning coal particles [6–10]. The technique was further improved by Stenberg et al. [11] to measure the surface temperature of a burning black liquor droplet in a hot, radiating environment. It was then adapted by Frederick et al. [12] to study the influence of oxygen on the surface temperatures of a burning black liquor particle, again at a single point. Increasing the oxygen concentration in a N_2/O_2 gaseous environment increases the surface temperature of the droplet during the char combustion stage. At lower oxygen concentrations, the surface temperature of the droplet during the char combustion stage was found to be constant [12]. However, the average surface temperature was found to reach as high as 300°C above the furnace temperature for droplets burned in air [12]. Later, the swelling, mass loss and the surface and internal temperatures of a burning black liquor droplet were measured simultaneously by Ip et al. [13]. A digital video camera fitted with two infra-red filters was used to measure the surface temperature by detecting the radiation emitted from the burning black liquor droplet at two wavelengths. This technique requires the grey emissivity (ϵ) of the droplet to be assumed. Nevertheless, it provided two-dimensional imaging of the surface temperature of a burning black liquor droplet. A non-uniform distribution of the surface temperature of the burning droplet was observed, along with a large temperature difference between the surface and internal temperatures throughout the combustion stages. However, no statistical

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information of the distribution of the surface temperature during the black liquor combustion is available at low oxygen concentration and reducing conditions (e.g. by the use of probability density functions, PDFs).

Furthermore, measurements of black liquor droplet surface temperature within a flat flame environment at either fuel-rich or fuel lean conditions have not been previously reported. The aims of the present investigation are: i) to measure the surface temperature under a fuel-rich and a fuel-lean condition; and ii) to assess the distribution of surface temperature.

2. Methodology

A sample of black liquor obtained from a Swedish pulp mill was used for the measurements. A consistent quantity droplet of black liquor (10 mg) was carefully applied to a loop (3 mm diameter) of a platinum wire (0.5 mm diameter). The loop and the black liquor droplet was placed 10 mm \pm 1 mm above the tip of a flat flame burner, using a retort stand. The black liquor was burned in the flame provided by the flat flame burner at two flame conditions, fuel lean ($\Phi_{bg} = 0.8$), and fuel rich ($\Phi_{bg} = 1.25$). Here the symbol Φ_{bg} denotes the equivalence ratio of the burner gases alone, which were held constant throughout a given experiment, and ignores the contribution of the black liquor droplet to the fuel, which varies throughout the experiment.

Two temperatures were measured in the present investigation, namely the gas flame temperature of the burner gases, T_{gf} , and surface temperature, T_s , of a burning black liquor droplet. The T_{gf} was measured at a height of 35 mm above the wire, without the black liquor, by a 0.5 mm diameter Type-R (Pt/Pt-13% Rh) thermocouple. The T_{gf} for $\Phi_{bg} = 0.8$ and 1.25 were 1600°C and 1725°C, respectively. A separate measurement was performed with the droplet burning, and the presence of combustion was found to influence the gas temperature by no more than $\pm 20^\circ\text{C}$ over the axial range $5 < Z < 40$ mm, where Z is the height above the wire. The measurement of T_{gf} was corrected for radiation losses from the thermocouple using the radiation correction equation of Brohez et al. [14]. The correction was typically 300°C and the uncertainties were calculated to be $\pm 50^\circ\text{C}$.

The T_s measurement was determined by the two-colour pyrometry technique following van Eyk et al. [10]. Simultaneous and synchronised images of the history of a burning black liquor droplet were obtained by each of two similar models of camera (Canon 400D). A narrow bandpass interference filter of 532.5 nm (λ_1) was placed in front of the camera lens and a 632 nm (λ_2) filter on the other camera lens. In addition, a 50/50 beam-splitter was placed in front of the cameras to achieve equal distance from each of the two cameras to the black liquor droplet as shown in Fig. 1 and an identical field of view.

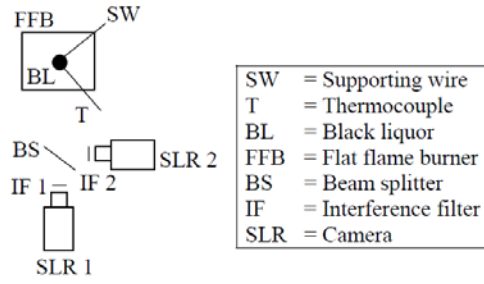


Fig. 1. The experimental apparatus (plan view) used to image temperature by the planar two-colour optical pyrometry during the combustion of a black liquor droplet.

This technique measures the relative emission intensity at two wavelengths and relates the ratio to the temperature of the source. Wien's law approximation, as shown in Eq. (1), is selected as it relates to the emission intensity (E_λ) of a black body to the wavelength (λ) and absolute surface temperature (T_s).

$$E_{\lambda_i} = -C_1 \lambda_i^{-5} \varepsilon_{\lambda_i} \exp\left(-\frac{C_2}{\lambda_i T_s}\right) \quad (1)$$

where ε_λ is emissivity of the solid surface at λ_i and C_1 and C_2 are first and second Planck's constants. The relationship between T_s and the ratio of two emission intensities, E_{λ_1} and E_{λ_2} , at wavelengths, λ_1 and λ_2 , respectively, is as shown in (2).

$$T_s = \frac{-C_2 \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)}{\ln \left(\frac{\varepsilon_{\lambda_1} \lambda_2^5 / E_{\lambda_1}}{\varepsilon_{\lambda_2} \lambda_1^5 / E_{\lambda_2}} \right)} \quad (2)$$

Two-dimensional images of the particle radiation at the two wavelengths were captured in greyscale at the shutter speed of 1 Hz. The ratio of corresponding spectral emissivity of the black liquor droplet, $\varepsilon_{\lambda_1}/\varepsilon_{\lambda_2}$, can be assumed to approximately 1, since that the wavelengths were chosen sufficiently close to each other. A calibration of the ratio $E_{532.5}/E_{632}$ as a function of temperature was required due to the dependence of the intensities collected by each camera on the response of each CCD array to wavelength and the transmission through each interference filter. The calibration was obtained from the average ratio of the radiation emitted from the two instantaneous images at the bead of a thermocouple in the flame environment. The range of the surface temperature measurement on the thermocouple, used to measure the T_{gf} , based on the optical settings was found to vary from 940–1350°C to obtain a linear relationship for the value of $E_{532.5}/E_{632}$ from (2). The uncertainties of the surface temperature measurement using (2) were calculated to be $\pm 3\%$ ($\pm 30^\circ\text{C}$). For each image (both cameras) of the edges of burning black liquor droplet was carefully selected on a frame-by-frame basis, since the shape of the droplet varies with time,

so that the instantaneous image at 532.5 nm matches that at 632 nm. The surface temperature of the droplet was then measured for each pixel within the droplet at a resolution of $0.04 \times 0.04 \text{ mm}^2$.

The images from the SLR cameras as described above were also used to measure the history of droplet diameter and estimate the duration of the drying, devolatilisation, char consumption and smelt coalescence stages. The time for drying was determined from the moment at which the burner was lit until the onset of the visible diffusion flame or soot at the droplet. The devolatilisation stage was determined from the onset of the diffusion flame until its disappearance. The char consumption time was determined from the moment at which the diffusion flame disappeared until the time when the char particle collapsed to form a molten droplet. Note that the term char consumption is used instead of char combustion because the char is consumed predominantly by CO_2 and H_2O in this flat flame environment. The composition of the combustion products, O_2 , H_2O , CO_2 and CO , from the gas burner for both stoichiometries was calculated using the Pre-Mixed Burner model in CHEMKIN 4.1 with GRI-Mech v3.0 [15]. The surface temperature of the droplet during the smelt oxidation stage, however, could not be detected due to the collapse of the smelt onto the loop of the wire.

3. Result and Discussion

Figure 2 presents typical images of the swelling and the temporal history of the combustion of black liquor using the interference filters of 532.5 nm (Fig. 2a) and 632 nm (Fig. 2b) and the surface temperature (Fig. 2c), derived from raw images as per (1), for $\Phi_{\text{bg}} = 0.8$ obtained from the SLR cameras. As expected, the intensity of the burning droplet at $E_{532.5}$ was found to be less than that at E_{632} . While the measurement obtained from the background surrounding the particle is very noisy, as expected due to the low signal, that obtained from inside the droplet boundary is only noisy in the regions where the surface temperature is relatively cold (Fig. 2c). In addition, the surface temperature of the burning droplet is clearly distinguished.

A non-uniform T_s distribution was observed during the drying stage ($t = 2$ s), as shown in Fig. 2c-I. During the devolatilisation, similar observations of non-uniform surface temperature and also large pores near to the wire were observed (Fig. 2c-II). As expected, soot was detected during this stage at the top right of Fig. 2c-II. During the early stage of char consumption, $t = 6-8$ s, the variation in T_s (Figs. 2c-III and 2c-IV) was observed to be smaller than that during the devolatilisation stage (Fig. 2c-II). However, the temperature at $t = 10$ s (Fig. 2c-V) just above the wire was found to be at least 100°C higher than that during the devolatilisation stage. At the end of the char consumption stage ($t = 12$ s), all the char had

collapsed to form into a smelt bead on the loop of the wire.

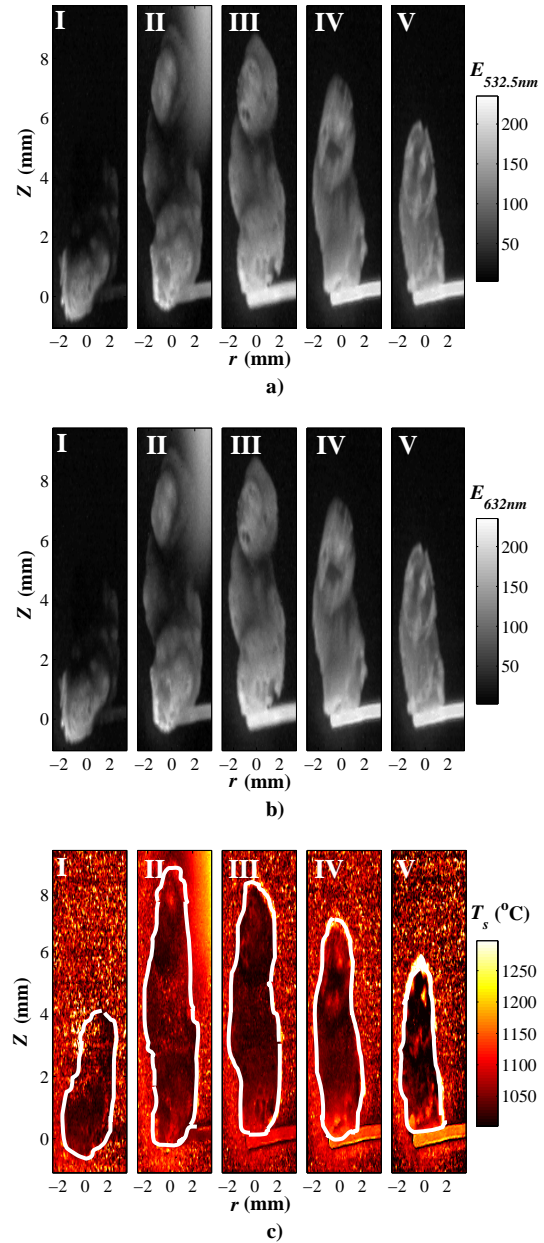


Fig. 2. Time history of images of a burning black liquor droplet for $\Phi_{\text{bg}} = 0.8$ a) raw image at 532.5 nm; b) raw image at 632 nm; and c) temperature derived from raw images as per Eq. (1) during (I) drying ($t = 2$ s), (II) devolatilisation ($t = 4$ s) and (III–V) char consumption ($t = 6-10$ s). White line = edge of droplet.

Figure 3 presents the normalised probability distributions of T_s of one droplet for $\Phi_{\text{bg}} = 0.8$ and another droplet for $\Phi_{\text{bg}} = 1.25$. Here, $n(T_s)$, is defined as the number of pixels within each bin of $\Delta T = 10^\circ\text{C}$ over the range of resolution ($940-1350^\circ\text{C}$) and Σn is the total number pixels. We have defined the surface temperature which occurs at the maximum value of $n(T_s)/\Sigma n$, for each time, t , as the most probable surface temperature, $T_{s,\text{mod}}$. A non-uniform T_s of the burning black liquor droplet were found for both stoichiometries throughout the combustion stages, as is shown in Fig. 3. This is consistent with the study of Ip et al. [12], which the non-uniform T_s ranged from $1000-1400^\circ\text{C}$, in a closed furnace at 21% O_2 . The variation of the T_s distribution for Φ_{bg}

= 0.8 was found to be at least 100°C larger than that for $\phi_{bg} = 1.25$ (Fig. 3). The temperature distribution for $\phi_{bg} = 0.8$ and 1.25 is typically positively skewed rather than Gaussian. The positive skew implies that the mean value of the surface temperature is higher than the modal value. The range temperature distribution is from 940–1200°C for $\phi_{bg} = 0.8$ and 940–1130°C for $\phi_{bg} = 1.25$.

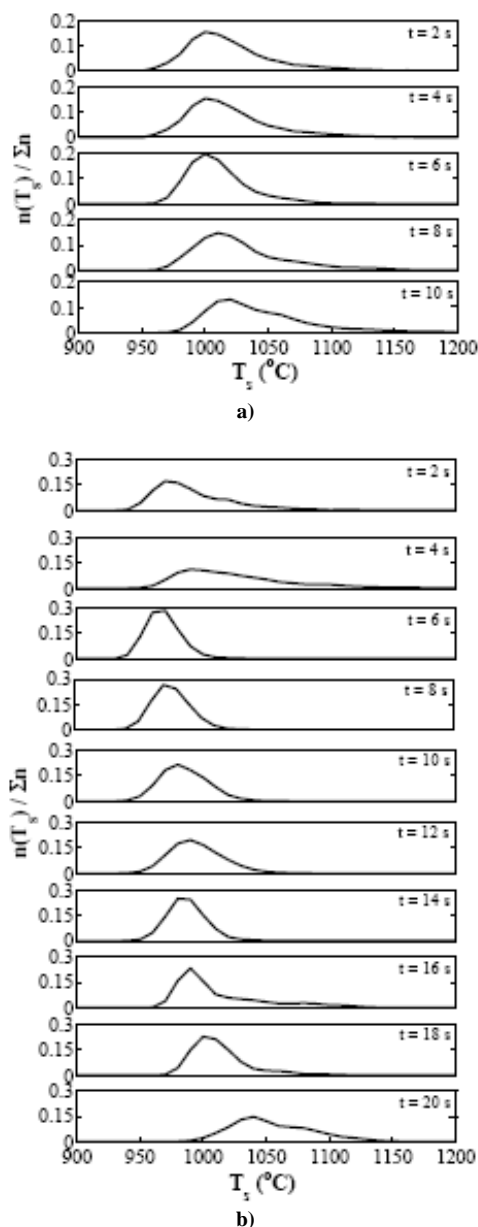


Fig. 3. Probability distribution of the T_s (solid lines) based on projected area of a burning black liquor droplet at a) $\phi_{bg} = 0.8$ and b) $\phi_{bg} = 1.25$.

4. Conclusion

The two-dimensional measurement of surface temperature of a burning black liquor droplet under a fuel lean and rich condition has been demonstrated for the first time. Large surface temperature variations over the range of 940–1200°C were measured under fuel lean condition and over the range 940–1130°C under fuel rich condition. The

average surface temperature under fuel lean condition is at least 100°C higher than that under fuel rich condition.

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6. References

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