A novel method for determining the internal recycled dust load in kraft recovery boilers

MATHEUS ANTUNES GUIMARÃES, HONGHI TRAN, AND MARCELO CARDOSO

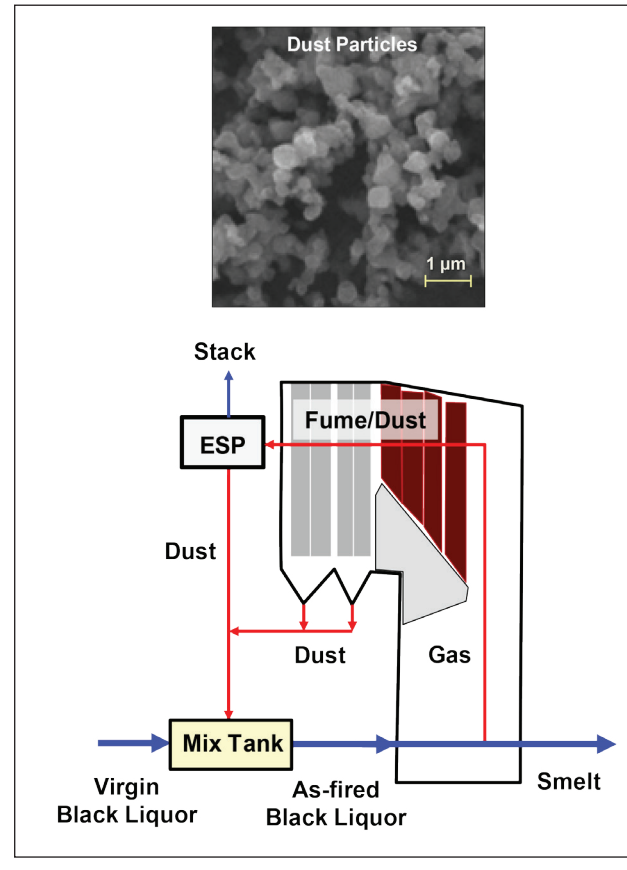
ABSTRACT: In kraft recovery boiler operation, fly ash or dust generated from black liquor combustion is mixed with the virgin black liquor in a mix tank and returned to the boiler with the as-fired black liquor. This internal recycled dust stream varies widely from boiler to boiler and from time to time and can have a great impact on the as-fired black liquor flow and properties and, ultimately, on the boiler thermal performance. A new method has been developed to quickly and accurately determine the amount of internal recycled dust in recovery boilers. The method is based on the difference between the total organic carbon content of the virgin black liquor and that of the as-fired black liquor. Tests using the method were performed on recovery boilers at three of Fibria's mills in Brazil. The results show that while the specific virgin black liquor solids produced at these mills were about the same, the internal recycled dust load varied widely, from as low as 4 wt% of as-fired black liquor solids fired in the boiler at one mill to as high as 15 wt% at another mill. Instead of total organic carbon values, heating values may also be used, but the result is not as accurate.

Application: Mills can use a newly developed method to quickly and reliably determine the amount of internal recycled dust in recovery boilers.

In kraft recovery boilers, the hot flue gas from black liquor combustion gives off heat as it passes through a series of heat transfer tube surfaces in the upper boiler to produce steam. The cooling causes the vapors of alkali compounds in the flue gas to condense and form fumes (**Fig. 1**). This, together with a small amount of physically entrained carryover, forms a stream of fly ash or dust that is collected by ash hoppers and electrostatic precipitators (ESP) [1]. A small portion of the dust stream ends up forming deposits on the tube surfaces, which are occasionally knocked off by sootblowers and fall to the char bed or to ash hoppers. Only a small amount (<0.5%) of the dust is lost with the stack gas as particulate emissions.

The collected dust is mixed with the strong (or virgin) black liquor, typically in a mix tank, and returned to the boiler with the as-fired black liquor. Because this dust stream originates from the as-fired black liquor, and eventually returns to it, it is conventionally known as internal recycled dust (IRD). The IRD typically accounts for about 5 wt% of the total black liquor dry solids (BLDS) fired in the boiler; however, it may vary from 1 wt% to 10 wt% depending on many factors, including liquor firing load, bed temperature, boiler floor surface area, and whether a sootblower in the generating bank or in the economizer is activated [2–7].

Tavares and Tran [4] conducted a systematic field study on fume formation in a recovery boiler by (1) analyzing the thermal images of the char bed to obtain bed temperature distribution profiles, (2) using the profiles to calculate the amount



1. Dust particles and internal recycled dust stream.

of fume formed thermodynamically and equating the amount with the IRD load, and (3) calibrating the calculated dust load against the actual dust load determined independently through a material balance around the mix tank over a 4-month period. The study showed that the increasing char bed temperatures increased the internal IRD load, and that at the same average bed temperature, a bed with a poor temperature distribution generated twice as much IRD as a bed with a good temperature distribution.

In another study, Tamminen et al. [6,7] developed an online recovery boiler dust analyzer and used it to measure the amount and composition of dust in the flue gas in two recovery boilers. The analyzer operated by continuously collecting the flue gas dust sample, dissolving it in water, and analyzing the flowing water potentiometrically for ion concentrations. They found that at full liquor firing loads, the average dust loads in these two recovery boilers were 6 wt% and 7 wt% as-fired BLDS, respectively. Their data showed that the amount of dust increased with an increase in liquor firing load and in furnace floor surface area, and that the majority of the fume (90%–95%) was formed from in-flight burning of black liquor droplets; only 5%–10% came from the char bed.

As more and more kraft pulp mills have adopted high-solids firing practices in recent years, many recovery boilers operate at a high bed temperature. This inevitably results in an increase in fume formation, and hence in IRD load. While wide variations in IRD load can have a great impact on the as-fired black liquor mass flow, composition, heating value, steam production, and ultimately on the boiler thermal performance, there is no simple and reliable means of directly measuring this dust stream. As a result, not many mills know how large a recycled dust stream is circulating around their recovery boilers.

In this paper, we first review the principles of several methods that have been used to estimate the amount of IRD. We then discuss the results of a systematic study conducted on recovery boilers at three kraft pulp mills within Fibria Celulose SA. The study was part of a larger effort to develop a simple method that could be used to reliably determine IRD load in recovery boilers, and then use it to investigate key boiler operating variables that lead to high IRD dust loads.

COMMON METHODS

Mass balance method

As-fired black liquor is the virgin black liquor that has been mixed with dust collected from ESPs and ash hoppers. Therefore, the amount of IRD is essentially the mass difference between the virgin black liquor and the as-fired black liquor. Customarily, IRD is expressed as the percentage, on a mass basis, of the as-fired BLDS (Eq. [1]):

$$\text{IRD} = \frac{M_{\text{As-fired}} - M_{\text{Virgin}}}{M_{\text{As-fired}}} \times 100 \quad (1)$$

where $M_{\text{As-fired}}$ and M_{Virgin} are the mass flow rates of as-fired and virgin BLDS, respectively. Most kraft pulp mills monitor the volume flow rates and solids content of the as-fired black liquor online and use these values to calculate the mass flow rate, $M_{\text{As-fired}}$, assuming a black liquor density value. Although the liquor density changes with solids content [8], some mills use only one fixed value for a wide range of their solids contents. This inherently results in an error in the $M_{\text{As-fired}}$ calculation, particularly during the time when there is a wide variation in liquor solids content and IRD load. A more proper way to calculate as-fired black liquor mass flow rates must take into account the change in liquor density with solids content. Furthermore, most mills do not continuously measure the volume flow rate and/or solids content of virgin black liquor, so M_{Virgin} is usually not available. As a result, although Eq. (1) is simple, it cannot be used readily.

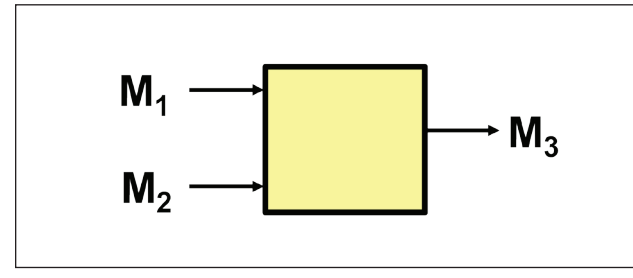
Dust dissolution method

Several mills measure the amount of IRD on a daily basis by directing the precipitator dust screw feeder to a small, dedicated tank filled with a fixed amount of water for a fixed period and analyzing the concentration and composition of the dissolved dust in the tank solution. The analysis results are then used to back-calculate the amount of IRD. The principle of this method is similar to that of the online recovery boiler dust analyzer used by Tamminen et al. [6,7] mentioned above, except that it operates on a much larger scale. While the method is relatively accurate as it deals directly with the dust stream, the procedure is complicated and the equipment involved is rather costly and requires frequent maintenance. As a result, it has not been widely adopted.

In mills equipped with an ash treatment system to preferentially remove chloride (Cl) and potassium (K) from recovery boiler precipitator ash [9], the amount of ash may be known through the material balance around the ash treatment system. However, this method is limited only to mills where the ash comes from one boiler and all is treated.

THEORETICAL CONSIDERATION

The amount of IRD can be determined by performing a material balance around the recovery boiler. Consider a system involving three streams, in which stream 1 mixes with stream 2 to form stream 3, as shown in **Fig. 2**. M_1, M_2, and M_3 are the mass flows of streams 1, 2, and 3, respectively (Eq. [2]):



2. System with three streams.

$$M_1 + M_2 = M_3 \quad (2)$$

In Eqs. (3) and (4), if "a" and "b" are two particular species in stream 1, stream 2, and stream 3, then:

$$M_1C_{a1} + M_2C_{a2} = M_3Ca_3 \quad (3)$$

and

$$M_1C_{b1} + M_2C_{b2} = M_3C_{b3} \quad (4)$$

where C_{a1}, C_{a2}, and C_{a3} are concentrations, in wt%, of "a" in streams 1, 2, and 3, respectively, and C_{b1}, C_{b2}, and C_{b3} are concentrations, in wt%, of "b" in streams 1, 2, and 3, respectively. Rearranging the equations yields Eq. (5):

$$\frac{M_2}{M_3} = \frac{C_{a1}-C_{a3}}{C_{a1}-C_{a2}} \quad (5)$$

We now consider a case around a recovery boiler as shown in **Fig. 3**, where $M_{Virgin\ BL}$, M_{Dust}, $M_{As\text{-}fired\ BL}$, M_{Smelt}, and M_{Stack}, respectively, represent the mass flows of virgin black liquor, precipitator dust, as-fired black liquor, smelt, and stack gas.

Applying Eqs. (1)–(5) to the black liquor mix tank, the amount of IRD, expressed as % as-fired black liquor, can be calculated (Eq. [6]):

$$IRD = \frac{C_{a\ Virgin\ BL} - C_{a\ As\text{-}Fired\ BL}}{C_{a\ Virgin\ BL} - C_{a\ Dust}} \times 100 \quad (6)$$

where $C_{a\ As\text{-}fired\ BL}$, $C_{a\ Virgin\ BL}$, and $C_{a\ Dust}$, respectively, are concentrations in wt% of species "a" in as-fired black liquor, virgin black liquor, and precipitator dust. Equation (6) suggests there is no need to have the mass flow rates of various streams for the calculation of IRD. In theory, only the concentrations of one species or element (e.g., carbon, hydrogen, oxygen, sodium, potassium, sulfur, or chlorine) in as-fired black liquor, virgin black liquor, and precipitator dust are needed.

Although this equation allows the use of any one component present in the as-fired black liquor, virgin black liquor and precipitator dust to calculate the internal recycled dust, the choice of such component, sampling locations, and sampling time can all have an impact on the accuracy of the calculated results. Both virgin and as-fired black liquors should be collected at the liquor storage tank outlet where they have supposedly been well mixed.

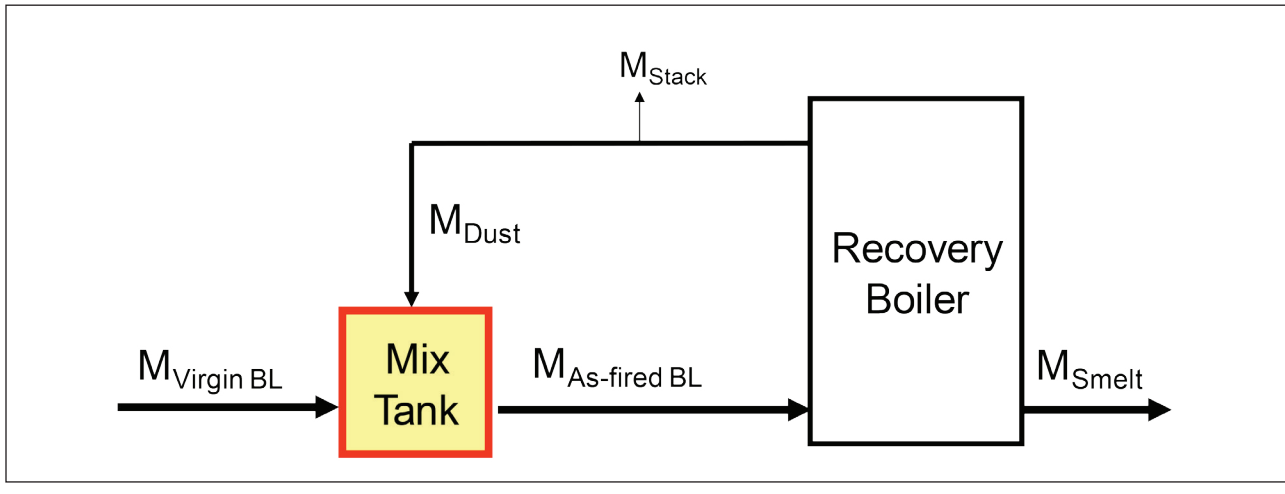
Collecting a representative dust sample is not as easy a task as it may seem to be; dust and black liquor are often not well mixed and the dust composition can vary widely with boiler operation. For instance, boilers fired with high-solids liquors tend to produce not only more dust, but also dust that contains more carbonate, chloride, and potassium and less sulfate and hence, more sodium than boilers fired with low-solids liquors. Consequently, if sodium is used as the element of interest in Eq. (6), the change in dust composition can lead to an error in the calculation of IRD load.

Also, the amount and composition of dust collected after a precipitator discharge cycle may be different from that collected during the discharge cycle. They may also vary greatly depending on whether a sootblower in the generating bank and/or the economizer region is activated during the time of sampling. These variations can have a great effect on the as-fired black liquor composition and hence, the accuracy of IRD calculation.

PROPOSED METHOD

Choosing a component that is present in a large amount only in the virgin and as-fired black liquors and not in the dust can help minimize the system error and eliminate the need for dust analysis. In this case, since $C_{a\ Dust} = 0$, Eq. (6) can be simplified as Eq. (7):

$$IRD = \frac{C_{a\ Virgin\ BL} - C_{a\ As\text{-}Fired\ BL}}{C_{a\ Virgin\ BL}} \times 100 \quad (7)$$



3. Flows around mix tank and recovery boiler

4. Total organic carbon analyzer.

One component that is abundant in both black liquor and dust streams is carbon (C). In dust, C is present mostly as carbonate (i.e., sodium carbonate and potassium carbonate). In black liquor, however, it is bound mostly with organic compounds, which can be easily determined using a commercial total organic carbon (TOC) analyzer. Thus, by choosing TOC as the component of interest, Eq. (7) becomes Eq. (8):

$$IRD = \frac{TOC_{Virgin\ BL} - TOC_{As\text{-}Fired\ BL}}{TOC_{Virgin\ BL}} \times 100 \quad (8)$$

where TOC_{Virgin} and $TOC_{As\text{-}fired}$ are the TOC contents of virgin and as-fired black liquors, respectively. Knowing the TOC contents in these liquors, the amount of internal recycle dust can be readily calculated.

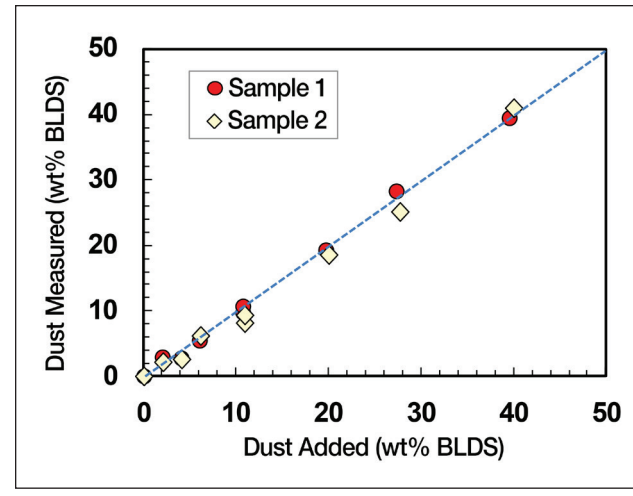
METHOD VALIDATION

Reproducibility tests

To evaluate the validity and accuracy of the proposed method, experiments were conducted to determine the reproducibility of the TOC analyzer used in this study. The analyzer was a Model TOC-V CPN (Shimadzu Corp.; Kyoto, Japan) available at mill 1 (**Fig. 4**). The analysis was performed on two sets of virgin and as-fired black liquor samples collected from two Fibria kraft pulp mills (mill 1 and mill 2). The virgin black liquor was collected from the weak black liquor tank to the evaporation plant, while the as-fired liquor was collected from the liquor feed tank to the boiler. Each liquor sample was divided into 10 subsamples that were dried at 105°C for 12 h. The subsamples were then analyzed for their TOC contents.

	Mill 1 Liquor		Mill 2 Liquor	
	Virgin	As-Fired	Virgin	As-Fired
Average of 10 samples, g/kg BLDS	317	302	314	291
Standard deviation, g/kg BLDS	3.1	4.6	4.3	12.5
Variation coefficient, %	1.0	1.5	1.4	4.3

I. Total organic carbon contents in virgin and as-fired black liquors from two kraft pulp mills.



5. Comparison between the amount of dust measured by the proposed total organic carbon method and the amount of dust initially added to the virgin black liquor samples.

Table I summarizes the TOC analysis results for these 10 subsamples. The reproducibility was good for mill 1 liquors and for mill 2 virgin liquor, with a small error (or variation coefficient) of ± 1%–1.5%. For mill 2 as-fired black liquor, however, the reproducibility seems to be poorer, with an error of ± 4.3%. The greater error for as-fired black liquor samples was likely due to their more heterogeneous nature compared to virgin black liquor samples

Calibration tests

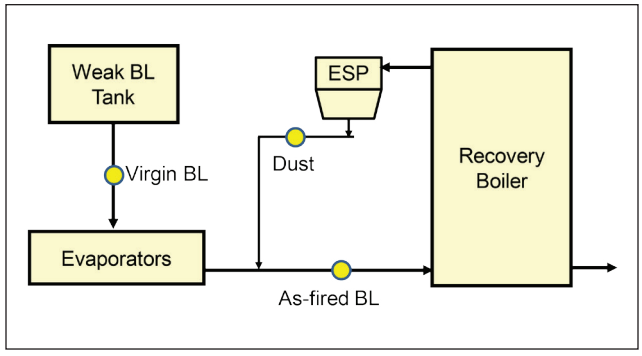
Calibration tests were performed to determine if the TOC analyzer could be used to determine the amount of precipitator dust in the as-fired black liquor. Two mill 1 virgin black liquor samples (with 17%–25% solids) collected on different days were used. Each sample was spiked with various amounts, 0–40 wt%, of mill 1 precipitator dust to produce well-mixed liquor-dust mixtures. The mixtures were dried at 105°C for 12 h and analyzed for TOC. The TOC values obtained for the virgin liquors and the mixtures were then used to calculate the amounts of dust added to the samples using Eq. (8).

Figure 5 compares the amount of dust in the mixtures determined by the proposed TOC method and the amount of dust added to the mill 1 virgin liquor samples collected on different dates. The data points are located either exactly on or close to the diagonal line of the graph, suggesting that the proposed method was accurate and the equipment was reliable.

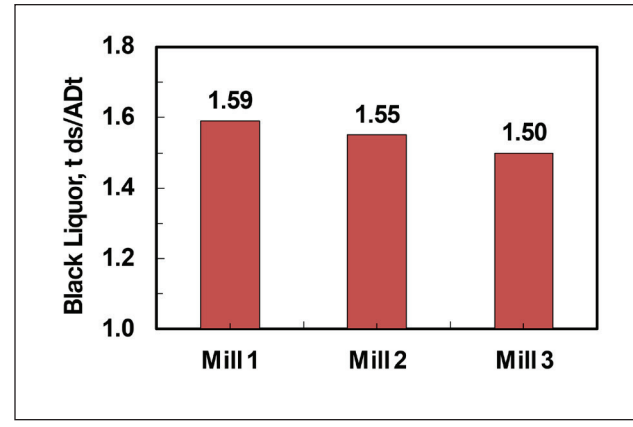
IRD MEASUREMENTS

The TOC method was used to determine the amount of IRD in recovery boilers at three Fibria mills (mills 1, 2, and 3). For each mill, five sets of samples (virgin black liquor, as-fired black liquor, and precipitator dust) were collected, and each set was collected on a different day.

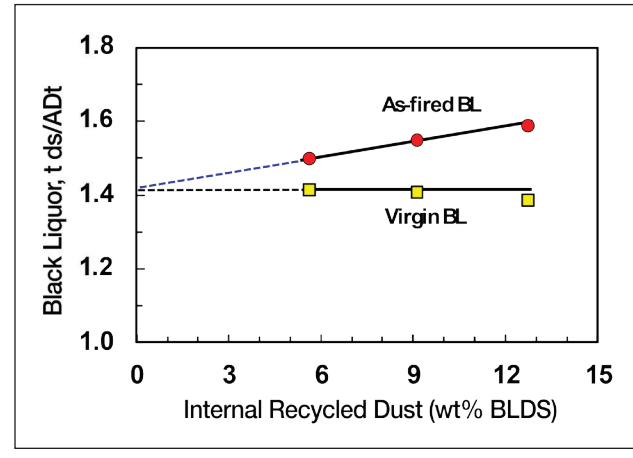
Figure 6 schematically shows the sampling locations. The



6. Sampling locations.



7. Average specific as-fired black liquor dry solids produced at each mill.



8. Average specific black liquor dry solids versus recovery boiler internal recycled dust load at mills 1, 2, and 3.

virgin black liquor samples were collected at the weak black liquor tank outlet, the as-fired black liquor samples were from the concentrated black liquor tank, and the dust samples were collected from the conveyor below the electrostatic precipitator. The samples were collected when the mills were at their normal pulp production rates and the boiler operations were stable. As in the reproducibility tests, the samples were dried at 105°C for 12 h before their TOC contents were determined. The amount of IRD in each case was calculated using Eq. (8).

No organic carbon was detected in any of the dust samples. This, along with the relatively pure white appearance of the samples, suggests that the recovery boilers at these mills were running well with little or no unburned char entrained in the flue gas. **Table II** summarizes the results of TOC analysis and the calculated internal recycled dust load for these mills. The dust load varied widely from mill to mill, averaging 12.7 wt% of as-fired BLDS for mill 1, 9.1 wt% for mill 2, and 5.6 wt% for mill 3. Within each mill, the amount also varied significantly from day to day, particularly at mill 2 where the value decreased from 15.2 wt% to 4.0 wt% BLDS in one day (July 13) and then increased back to 8 wt% the next day (July 14). Although it would have been beneficial to know what caused the high variation in IRD load at these mills, no attempt was made to investigate it because it was not the main focus of this study.

The results clearly show that the recovery boiler at mill 1 operated with the highest IRD load, followed by the recovery boiler at mill 2, with the lowest IRD load at mill 3. Mill operating data also showed that during the corresponding sampling period, mill 1 produced more specific as-fired black liquor solids (tons of solids/ton of air-dry pulp) than mills 2 and 3 (**Fig. 7**).

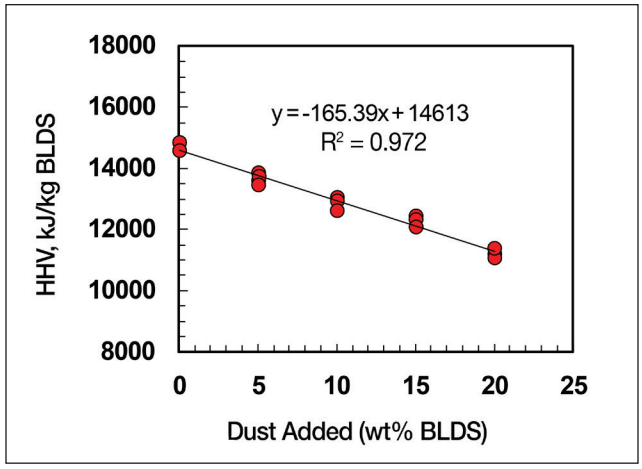
Figure 8 plots the average specific black liquor solids against the IRD load. There is a good correlation between the

Mill 1			
Sampling Date	TOC in Black Liquor		IRD
	Virgin	As-Fired	
	g/kg BLDS	g/kg BLDS	wt% BLDS
Jul 26	311	275	11.5
Aug 01	309	266	13.8
Aug 23	322	282	12.2
Sep 12	310	265	14.5
Sep 14	309	274	11.2
Average	**312**	**273**	**12.7**

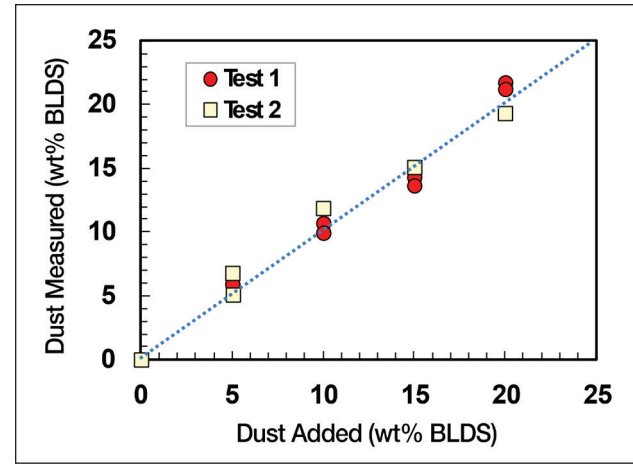
Mill 2			
Sampling Date	TOC in Black Liquor		IRD
	Virgin	As-Fired	
	g/kg BLDS	g/kg BLDS	wt% BLDS
Jul-11	323	292	9.8
Jul-12	340	289	15.2
Jul-13	326	313	4.0
Jul-14	326	299	8.4
Jul-15	338	311	8.0
Average	**331**	**300**	**9.1**

Mill 3			
Sampling Date	TOC in Black Liquor		IRD
	Virgin	As-Fired	
	g/kg BLDS	g/kg BLDS	wt% BLDS
Sep-28	335	310	7.3
Sep-29	328	314	4.3
Oct-26	336	320	4.7
Oct-27	344	329	4.3
Oct-28	341	316	7.1
Average	**337**	**318**	**5.6**

II. Total organic carbon content in black liquors and calculated internal recycled dust load.



9. Effect of dust addition on the higher heating value of a virgin black liquor sample from mill 4.



10. Comparison between the amount of dust measured by the proposed heating value method and the amount of dust initially added to virgin black liquor.

average specific as-fired black liquor solids at these mills and the average IRD load in their recovery boilers.

Figure 8 also shows the specific virgin black liquor solids produced at each mill, calculated based on the specific as-fired black liquor solids and the internal recycled dust load, using Eq. (1). Unlike the specific as-fired black liquor solids, the specific virgin black liquor solids were the same for all three mills: 1.41 tons of BLDS/a.d. ton of pulp. The results are understandable. Because these mills employed the same pulping technology, used the same type of wood species (eucalyptus), and used the same amount of chemicals (effective alkali-to-wood ratio) to produce bleached eucalyptus pulp, the specific virgin black liquor solids produced at each mill are expected to be similar.

Extrapolating the data toward 0 wt% IRD load shows that without the presence of internal recycled dust, the virgin and as-fired black liquor solids would have been identical. The results, again, support the validity of the TOC method.

ALTERNATIVE METHOD

Precipitator dust contains a negligible amount (< 0.1 wt%) of unburned carbon or char, even when it appears to be grayish and contaminated with char. Thus, when mixed with virgin black liquor in the mix tank and returned to the boiler with the as-fired black liquor, the dust only increases the liquor mass, not its heat content. The dilution and heat absorption effects of the dust mass will lower the heating value of the as-fired black liquor compared to that of the virgin black liquor. As in the case of TOC, this difference in liquor heating value can be used to estimate IRD load, using Eq. (9), a modified form of Eq. (6):

$$\text{IRD} = \frac{\text{HV}_{\text{Virgin}} - \text{HV}_{\text{As-fired}}}{\text{HV}_{\text{Virgin}} - \lambda_{\text{Dust}}} \times 100 \qquad (9)$$

where IRD is expressed as wt% in as-fired black liquor solids; $\text{HV}_{\text{Virgin}}$ and $\text{HV}_{\text{As-fired}}$ are the heating values of virgin liquor and as-fired black liquor, respectively; and λ_{Dust} is the heat absorbed by the dust in the bomb calorimeter during the heating value measurements.

Laboratory tests were performed to determine the validity of Eq. (9). A sample of virgin black liquor from a kraft mill (mill 4) was spiked with various amounts of precipitator dust from the same mill to produce black liquor/dust mixtures. These simulated as-fired black liquor samples were dried and analyzed for their higher heating values (HHV) using a Model 6300 bomb calorimeter (Parr Instrument Co.; Moline, IL, USA). As shown in **Fig. 9**, the HHV of the simulated as-fired black liquor decreased linearly with an increase in dust content ($R^2 = 0.972$). The linear relationship yields an HHV of -1926 kJ/kg BLDS for a hypothetical liquor/dust mixture at 100% dust (i.e., no liquor). This negative HHV value is essentially the λ_{Dust} itself (i.e., $\lambda_{\text{Dust}} = -165.39 \times 100 + 14{,}613 = -1926$ kJ/kg BLDS).

The tests were repeated on a different day. The obtained λ_{Dust} and HHV values were used to calculate the amount of IRD for two sets of tests using Eq. (9). The results are shown in **Fig. 10**. The measured dust amounts were in good agreement with the actual amounts added, confirming the validity of the method.

Results of numerous tests using different ESP dusts show that the term ($\text{HV}_{\text{Virgin}} - \lambda_{\text{Dust}}$) can be approximated as $\text{HV}_{\text{Virgin}}/0.9$. Eq. (9) thus becomes Eq. (10), which is simpler because it does not need to deal with ESP dust to obtain the internal recycled dust load:

$$\text{IRD} = \frac{0.9\left(\text{HV}_{\text{Virgin}} - \text{HV}_{\text{As-fired}}\right)}{\text{HV}_{\text{Virgin}}} \times 100 \qquad (10)$$

LIMITATIONS

The proposed TOC method and its alternative heating value method have their limitations. The methods can be used to determine IRD load only at a specific time, not on a continu-

ous basis. They work only for mills where the flows around the black liquor mix tank can be clearly identified as shown in Fig. 3.

For mills with two or more recovery boilers with one common black liquor mix tank, where a portion of the dust stream is purged from the system or is treated via an ash treatment system and where makeup salt cake is also added to the mix tank, the material balance becomes more complicated. The equations developed in this work may not be applicable without taking all important side streams into account.

As with other methods, the accuracy of the proposed methods depends strongly on the liquor sampling timing and location, and how well the precipitator dust has been mixed with black liquor in the mix tank. The TOC method is expected to be more accurate than the heating value method due to the simplicity of Eq. (8) compared to Eq. (9), which requires an additional term λ_{Dust}, or to Eq. (10), which requires an empirical correction factor of 0.9. Also, λ_{Dust} is related to the heat capacity of the dust and thus may change slightly with dust composition, and the liquor heating value may change with the state of oxidation of the liquor. Oxidized black liquor, for example, has a heating value 3%–5% lower than that of the liquor before it is oxidized.

The choice of method is more likely dictated by the availability of a TOC analyzer and/or a bomb calorimeter at individual mills. While TOC analyzers are more expensive to equip than bomb calorimeters, they are more available in many mills as they are also used for monitoring TOCs in various wastewater treatment streams and mill effluents [10] and for determining pulp yields [11].

CONCLUSIONS

A novel method has been developed that can be used to rapidly and accurately determine the amount of IRD in recovery boilers. The method is based on the change in either TOC content or the heating value of the black liquor after it has been well mixed with precipitator dust.

Tests performed using the TOC method on recovery boilers at three different kraft pulp mills show that IRD varied widely, from 4.0 wt% to 15.2 wt% of the total as-fired BLDS fired in the boiler. While the specific virgin black liquor solids produced at these three mills was about the same, 1.41 tons/a.d. ton of pulp, the specific as-fired black liquor solids burned in recovery boilers were different—1.50, 1.55, and 1.59 tons dry solids/a.d. ton of pulp, respectively. The difference was directly related to the amount of IRD in the boilers.

Tests performed using the heating value method in the laboratory show that the method is also valid, but is not as accurate as the TOC method.

Now that the TOC method has been in place, our plan is to use it to investigate how IRD load may be affected by black liquor properties and by boiler operating conditions, and in turn, how it may affect the boiler thermal efficiency. **TJ**

ACKNOWLEDGEMENTS

The authors acknowledge numerous recovery boiler operators and laboratory technicians at three Fibria mills for their assistance in sample collection and analysis, as well as the partial support received from the Energy and Chemical Recovery Research Consortium at the University of Toronto.

ABOUT THE AUTHORS

We chose this topic to study because it can potentially be useful for recovery boiler operation and control. To our knowledge, no previous research has been done on this topic.

Because of the lack of information regarding the amount of internal recycled dust (IRD) in recovery boilers, it was difficult for us to know if the results we obtained were accurate. We addressed this problem by carrying out a series of calibrating curves for each individual boiler. Even a complex problem can be solved with a basic mass balance and a simple tool available at the mill. The most surprising finding was that while all three mills in this study employed the same pulping process, the amount of IRD in their recovery boilers was significantly different.

Mills now have a new method for determining IRD load in their recovery boilers; knowing this can help improve recovery boiler firing capacity and thermal efficiency. The next step is to use the method to investigate how the IRD load may be affected by black liquor properties and other boiler operating parameters.

Guimarães

Tran

Cardoso

Guimarães is process and biorefinery specialist at the Fibria Technology Center, Aracruz, Brazil. Tran is a professor in the Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, ON, Canada. Cardoso is an associate professor in the Department of Chemical Engineering, School of Engineering, Federal University of Minas Gerais, Belo Horizonte, Brazil. Email Tran at honghi.tran@utoronto.ca.

LITERATURE CITED

1. Tran, H.N., *Tappi J.* 69(11): 102(1986).
2. Wessel, R.A. and Verrill, C.L., *Eng. Conf., [Proc.]*, TAPPI PRESS, Atlanta, GA, USA, 1996, p. 775.
3. Janka, K., Wallén, J., and Backman, R., *Pulp Pap. Can.* 105(1): T15(2004).
4. Tavares, A. and Tran, H.N., *TAPPI J.* 80(12): 117(1997).
5. Tavares, A., Tran, H.N., and Reid, T., *TAPPI J.* 81(9): 134(1998).
6. Tamminen, T., Enroth, J., Landkammer, J., et al., *Int. Chem. Recovery Conf.*, TAPPI PRESS, Atlanta, 1998, p. 1047.
7. Tamminen, T., Kiuru, J., Kiuru, R., et al., *TAPPI J.* 1(5): 27(2002).
8. Frederick, W.J., in *Kraft Recovery Boilers* (T.N. Adams, Ed.), TAPPI PRESS, Atlanta, 1997, Chap. 3.
9. Tran, H.N. and Earl, P.F., "Chloride and potassium removal processes for kraft pulp mills: a technical review," *Int. Chem. Recovery Conf.*, TAPPI PRESS, Atlanta, 2004.
10. Ristolainen, M. and Alén, R., *TAPPI J.* 81(9): 195(1998).
11. Iwase, Y., Taneda, Y., and Inoue, T., *Int. Pan Pacific Conf. Proc.*, TAPPI PRESS, Atlanta, 1994, p. 15.