In-furnace temperature and heat flux mapping in a kraft recovery boiler

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ABSTRACT: Gas temperatures, incident heat flux, and surface temperatures were measured in a large kraft recovery boiler. The measurements were a part of an extensive campaign planned and carried out to support validation of models based on computational fluid dynamics. The gas temperatures were measured with three different techniques: infrared (IR) pyrometer, suction pyrometer, and unshielded thermocouples. In addition to the temperature measurements, the radiative heat flux was measured in a number of locations in the boiler using a portable heat flux probe, and the surface temperatures inside the boiler were measured using a portable single-band IR camera.

Application: There is a great need for validation data with combustion models for kraft recovery boilers, especially for in-furnace measurements. In addition, this paper contains practical information on experience gained using different measurement techniques. This can be utilized by mills when doing their own in-furnace measurements.

There is a great need for validation data for combustion models of furnaces. For power boilers, a few measurement campaigns have been reported in the literature for oil-fired boilers [1], pulverized coal-fired boilers [2,3], and for fluidized bed boilers [4]. CFD modeling of black liquor recovery boilers are challenging in that many of the necessary submodels, such as fuel spraying models, droplet combustion models, and char reactions models, are unique to this process. This means that experience from other types of boilers can be utilized only partially. However, for black liquor recovery boilers, very little data on in-furnace measurements have been reported. Vakkilainen et al. measured gas and temperatures in three locations in a recovery boiler [5]. Validation data for CFD models are especially scarce. Saviharju et al. presented velocity and temperature measurements in the super heater region [6]. They used a specially developed probe to measure the velocities and a suction pyrometer to measure the temperatures. The most extensive study so far is most likely the DOE study [7] on validation of CFD-based recovery furnace models.

In this paper, some results from an extensive measurement campaign aimed at producing data for evaluation of CFD modeling are reported. In this campaign, temperature measurements, heat flux measurements, gas composition measurements, spray characterizations, char bed observations, and carryover measurements were performed. In addition, the black liquor composition and its combustion behavior were investigated. The gas composition measurements have been presented by Vainio et al. [8] and the char bed observations by Engblom et al. [9]. This paper focuses on temperature and heat flux measurements. It is interesting to note that Grace et al. [7] conclude that "the idea of validating a complete model against data from full furnace testing is to a very real extent a fallacy. It is very difficult, if not actually impossible, to make sufficient measurements to actually test model predictions." To a large extent, this seems to still be true, although this paper shows that the technical means to carry out an extensive campaign has improved during the last decade.

EXPERIMENTAL

Kraft recovery boiler measurement campaign

An extensive measurement campaign was carried out with a large kraft recovery boiler. The boiler had a liquor burning capacity of 4450 total dissolved solids (TDS)/day. During the campaign, the boiler load was 70% of the nominal capacity and the dry solids content of the black liquor was approximately 82%.

Three full days were used for measurements. During two of the days, the boiler was operated with a flat char bed. The bed shape was controlled by adjusting the black liquor spray temperature, the spraying angle, and the air distribution. The results presented in this paper are from measurements during this operational mode. Temperatures were measured with three different techniques, i.e. unshielded thermocouples, suction pyrometer, and infrared (IR) pyrometer. Heat flux measurements were carried out with a portable heat flux probe. The surface temperatures of the inner walls were measured using a portable single-band IR camera. The IR camera was also used to film the black liquor sprays and to observe the char bed. The IR video films from the two permanently installed IR cameras were also recorded for later analysis. Gas composition was measured using a probe at several locations in the furnace. Before the electrostatic precipitator (ESP) filter, a continuous gas measurement point was also installed.

In the campaign, probes were used to measure the amount of carryover particles. The composition of the carryover was studied using a scanning electron microscope/energy-dispersive X-ray spectroscopy (SEM/EDX). Black liquor and smelt samples were collected and their composition was analyzed. Finally, process data for the whole week was collected. The process data includes recordings of flow and temperature of black liquor, air, and steam; temperature readings from the boiler; and concentration measurements after the boiler bank and in the stack.

Gas temperature measurements

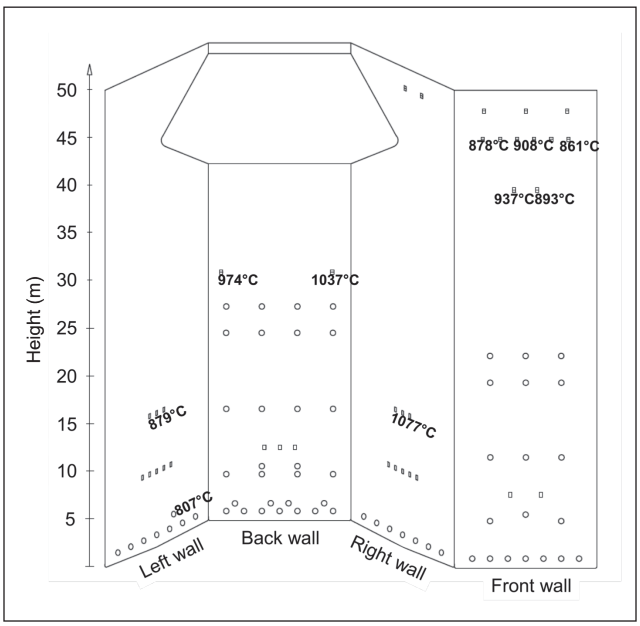
Gas temperature measurements seem to be trivial. However, in recovery boilers, gas temperature measurements are far from such. Three different measurement methods were tested, i.e., unshielded thermocouples, suction pyrometer, and IR pyrometer. Two different IR pyrometers were tested, one measuring soot particle temperature at 0.7-1.1 µm and one using CO_2 radiation within a narrow band close to 4.6 µm.

The unshielded thermocouple measurements were done using a 6-mm-diam K-type thermocouple. The tip of the thermocouple was unshielded, but a stainless steel pipe was used to prevent the thermocouple from bending. With the unshielded thermocouple, most measurements were taken 1.5 m from the inner wall.

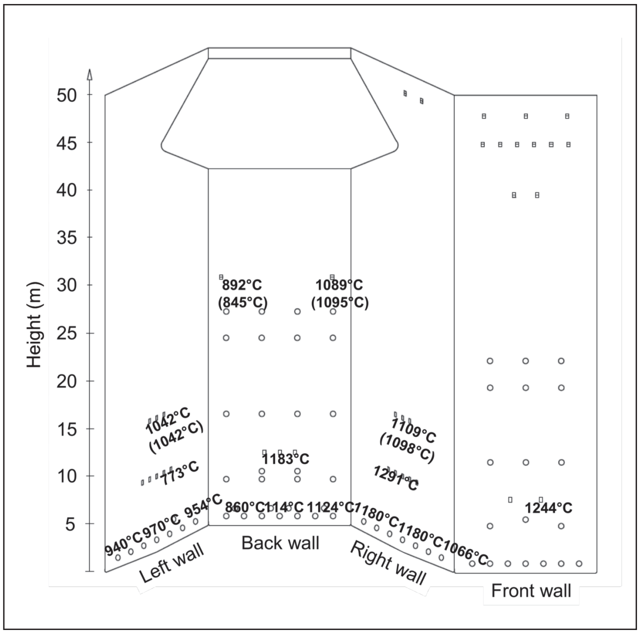
Figure 1 displays temperatures measured during one day with the unshielded thermocouple. In this figure, the average temperatures are shown. In some of the points, a substantial variation in the temperatures could be observed during the measurement period. For example, at a measurement point above the tertiary air level, the temperature varied between 901°C and 1040°C during a 3 min measurement period. On the other hand, at the same elevation, but in a different point, the temperature varied only with 6°C during a measurement period of more than 1 h.

Figure 2 shows temperatures measured with an IR radiation pyrometer (Metis MY46, Sensortherm). The temperatures in parentheses were measured during a different day of the campaign, but with boiler operated in the same mode. The pyrometer reading is based on CO_2 radiation within a narrow band close to 4.6 mm. The reading given by the IR pyrometer is not a point measurement, but a weighted line average. Based on the conditions in the furnace, it could be estimated that the IR pyrometer reading represents the gas temperature 2-3 m from the inner furnace wall. With the IR pyrometer, a temporal resolution of 250 ms could be achieved.

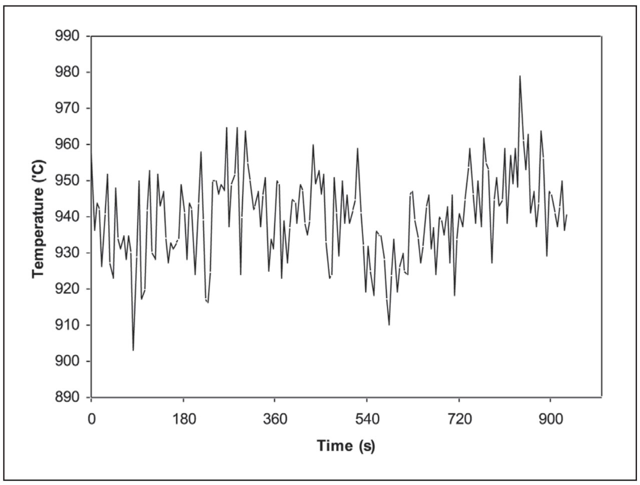
Figure 3 shows an example of the time history of the temperature in one measurement location. The figure shows very fast fluctuations in the temperature field. This data provides additional information on the conditions prevailing in



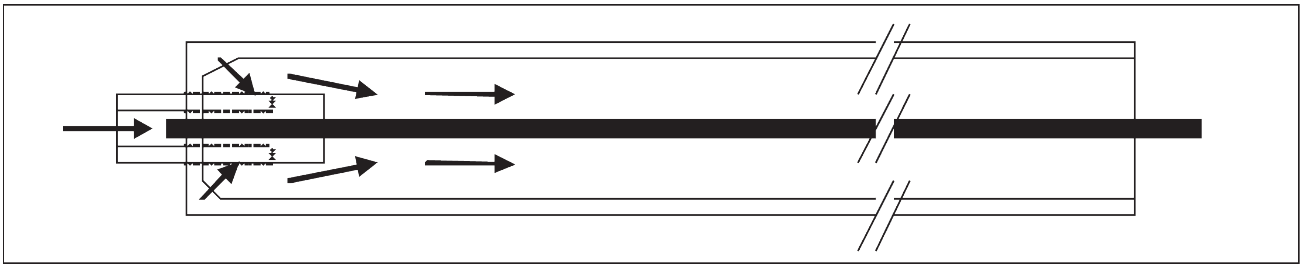
1. Gas temperatures measured with an unshielded K-type thermocouple.



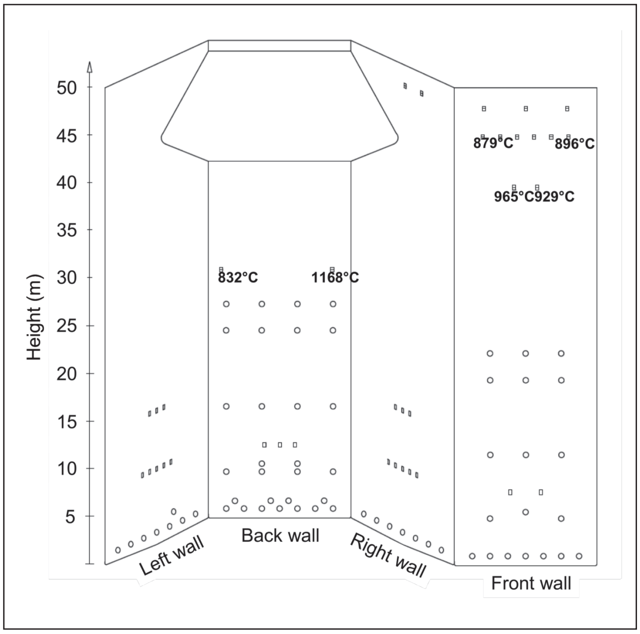
2. Gas temperatures measured with an IR radiation pyrometer recording CO_2 radiation within a narrow band close to 4.6 µm.



3. Time resolved gas temperature reading of the IR pyrometer measured approximately 1 m above the char bed.



4. A schematic picture of the suction pyrometer. Gas is drawn from the furnace through the ceramic tip. A thermocouple is used to measure the temperature of the gas sucked through this tip.



5. Temperature measured with a suction pyrometer.

the furnace compared to temperature data obtained with methods using thermocouples. During the campaign, the highest temperature recorded with the IR pyrometer was 1500°C, i.e., the upper limit of the operational range of the IR pyrometer used during the campaign. A second pyrometer, based on the soot particle temperatures at 0.7-1.1 µm, was also used. However, it was found that the one based on the CO_2 band was more suitable for recovery boiler measurements due to the disturbance from the high concentrations of sodium salts on the other IR pyrometer.

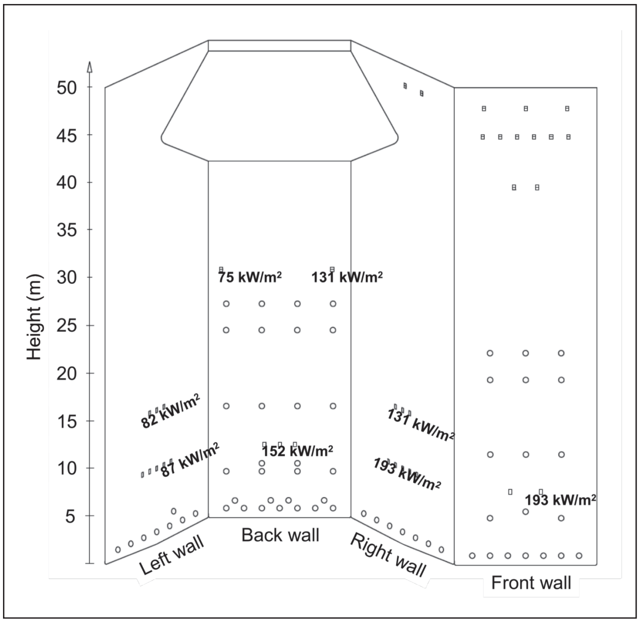
As a third measurement technique, a suction pyrometer was used. **Figure 4** displays a schematic picture of the suction pyrometer. In the suction pyrometer, the thermocouple is shielded from radiation using a ceramic shield. During the campaign, both N-type and K-type thermocouples were used. The suction pyrometer works as an ejector pump driven by the cooling air. A high air velocity through the ceramic pipe guarantees that convective heat transfer from the gas to the thermocouple is dominating. That way, the suction pyrometer measures the true gas temperature. A similar suction pyrometer has been used by Saviharju et al. [6] to measure temperatures above the bull nose and in the superheat region.

During the measurement campaign, a total of twenty-five suction pyrometer measurements were taken. Of these, only seven were successful. Although seven successful measurements were taken above the tertiary air level, the ceramic shield did not stay in place in eight other trials. In four cases, the thermocouple broke during the measurement. All trials lower down in the furnace were unsuccessful. In most cases, the reason for failure was that the ceramic shield did not stay in place. In two cases, the pyrometer was plugged by unburned black liquor. **Figure 5** shows the measured temperature with suction pyrometer. With this pyrometer, the measurement points were 2 m from the inner furnace wall.

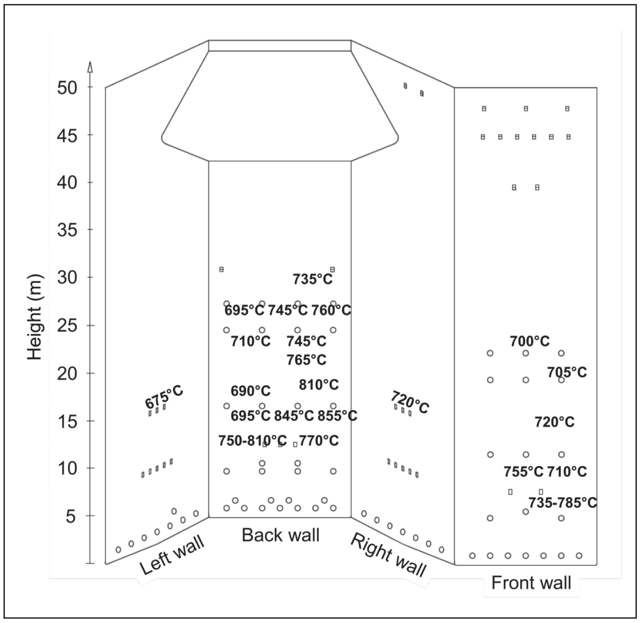
Comparing the obtained temperature readings with the different techniques revealed that the IR pyrometer readings and the suction pyrometer readings agreed well. The unshielded thermocouples and the suction pyrometer gave similar results in the bull nose area. Lower down in the furnace, the temperature readings obtained with the unshielded thermocouples seemed unreliable. In some points, the readings were lower than those obtained with the IR pyrometer, whereas in other points they were higher. The probable reason is the stronger influence of radiation in the lower part of the furnace. Nevertheless, comparing the temperature readings is not straightforward. For example, in the lower part of the boiler, the average temperature varied from 1175°C to 1314°C in three different measurements with the IR pyrometer from the same location.

Radiative heat flux measurements

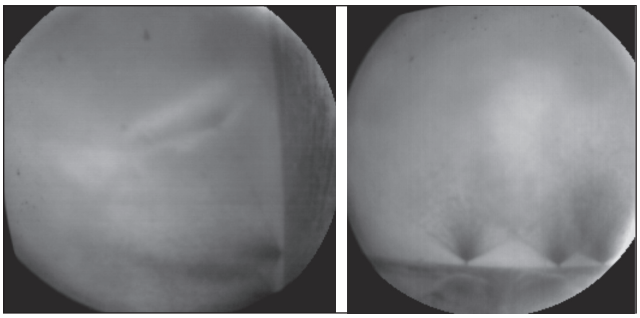
The radiative heat flux to the inner furnace wall was recorded in a number of positions. **Figure 6** shows the heat flux. The radiative heat flux probe consists of a copper cylinder, which is well-insulated, except for the base area where it is exposed to radiation. The temperature of the copper cylinder is measured by thermocouple. The rate of temperature increase is recorded and converted to radiative heat flux by calibration function. During the measurement, the probe was held such that the probe tip was at the same plane as the inner walls. The radiative heat flux varied between 60 kW/m^2 and 200 kW/m^2. It should be kept in mind that during the measurement campaign the boiler load was only 70%.



6. Radiative heat flux was recorded with a portable probe. The location of the probe tip was in-plane with the inner furnace wall.



8. Surface temperature of the inner wall measured with a portable IR video camera.



7. Raw images captured by the IR video camera. To the left, spray hitting the boiler wall forms an "on-wall char bed." The right image provides a top view of three liquor guns, including parts of the left boiler wall.

Wall temperature measurements

A portable IR video camera (IR-Furnace Camera PYROINC 320) was used to measure the wall temperature inside the boiler. The camera operates at the 3.9 µm band, where absorption by CO_2 and H_2O is almost negligible. With this IR camera, temperatures of 400°C–1500°C can be measured. **Figure 7** illustrates the raw images obtained with the IR camera.

Fifty frames per second were recorded with the camera. The wall temperature evaluations were carried out on a frame obtained from the average of 400–1000 single frames. When evaluating the wall temperatures, the effect of the furnace atmosphere must be taken into account. If the influence of furnace atmosphere is not too strong, it can be accounted for by determining radiation properties of atmosphere using images of cold air ports with known temperature and the measured gas temperatures. **Figure 8** shows the surface temperature of the inner walls measured with the IR camera.

The wall temperatures are typically between 680°C and 780°C, but some hotter regions with a heavy flux of impacting black liquor droplets could be identified. In these regions, the surface temperature reached 850°C. In Fig. 7, such a region can be identified. From the IR video sequence, it could be seen that there is a substantial flux of black liquor at the full opening angle of the spray. This black liquor hits the front wall where an "on wall char bed" is formed. In the middle of this char bed, where the majority of the black liquor droplets are landing, the temperature is lower than in the surrounding char bed. It is interesting to note that the typical wall temperatures are in close agreement with the T_{70} of the smelt as predicted by Backman et al. [10].

CONCLUSIONS

Gas temperatures, radiative heat flux, and wall surface temperatures were measured in a large recovery boiler. The IR radiation pyrometer, based on CO_2 radiation within a narrow band close to 4.6 µm, proved to be a versatile technique for measuring in the kraft recovery boiler. Since the technique is non-intrusive, the hostile environment inside the boiler is not a problem. The IR pyrometer is also able to detect fluctuation of the temperature where thermocouple-based techniques do not respond. The drawback of this technique is that no exact measurement point can be specified, since the IR pyrometer reading is the average of a line measurement.

The unshielded thermocouple is also rather easy to use, but in the furnace, where radiation is of great importance, this technique is not fully reliable. Also, in locations with a high flux of particles, the unshielded thermocouples are difficult to use. Above the bull nose, unshielded thermocouples are probably a good alternative.

The suction pyrometer could only be operated in the upper part of the furnace. Also here, a successful measurement generally required many trials. With the IR pyrometer, temperatures up to 1500°C were measured. Such high temperatures would require another type of thermocouple, compared to those used during the campaign. In addition, the fast fluctuations in the temperature, observed with the IR pyrometer, cannot be detected with thermocouples.

Heat flux measurements were carried out with a portable probe. The probe was easy to operate. The highest recorded heat flux was almost 200 kW/m^2.

Wall temperatures were measured using an IR video camera operating in the 3.9 µm band region. With the camera, it was possible to get a detailed view of the wall temperature distribution. In many cases, the reasons for uneven temperatures could also be identified. Yet, the high load of particles in the boiler limited the view. For example, it was not possible to get a detailed view of the char bed through the liquor gun openings. **TJ**

EDITOR'S NOTE

This paper was presented at the 2010 International Chemical RecoveryConference (ICRC) in Williamsburg, VA, where it received a Best Paper Award.

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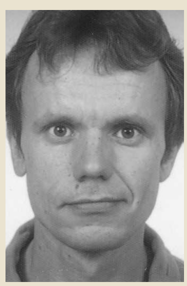

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