ON HEAT LOAD ESTIMATION IN FURNACES FOR WASTE AND BIOMASS COMBUSTION

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SUMMARY: Models for estimating the radiative heat load in furnaces for waste and biomass combustion are reviewed. For validation of refined models an experimental investigation is carried out in a small scale test facility. The facility is briefly described and the instrumentation for the various measurements is outlined. Preliminary experimental results are presented and measurement uncertainties are given. The next few steps in the research work are outlined.

1. INTRODUCTION

The heat load on the furnace or refractory walls in a combustion facility is governed by combined radiative and convective heat transfer processes but radiation is the dominating mode of heat transfer. A large portion of the recovered energy from waste and biomass fuels is released as combustible gases (e.g., CH_4, CO, H_2) in the furnace. In general thermal radiation may contribute to more than 90 % of the heat transfer in the furnace. To be able to model radiation is therefore essential if reasonably corrrect descriptions of the flow and temperature fields as well as calculation of the heat load on the walls are requested. Both particles and gases contribute to the thermal radiation. Depending on the type of fuel feeding and the grate system, the heat release from particles may vary betwween 5 – 70 % of the total heat release.

Design of furnaces is still usually based on experience and empirical data. However, modern methods based on computational fluid dynamics (CFD) are gradually being used more and more. The accuracy and reliability of such methods are to a large extent depending on the submodels for the combustion process, turbulence and the gas and particle radiation. The current project is focusing on models for prediction of the thermal radiation. By refined models it is believed one can contribute to a compact design of furnaces accordingly contribute to reduced. Then, in the long term, also guidelines for developemnt and optimization of furnaces in terms of reducing the investment and operating costs are foreseen.

A critical thing in model development is the validation versus experimental data. In this project a measurement program in a 400 kW grate fired test furnace has been set up between the cooperating partners. The overall target with the experiments is then to obtain data for gas and wall temperatures, wall heat fluxes, gas composition, particle distributions (in various forms) and amount etc.

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The objectives of this paper are to review radiative heat load computational models and present the experimental facility and the measurement techniques as well as some preliminary results.

2. REVIEW OF RADIATIVE HEAT LOAD MODELS

Engineering models for describing the heat flux to the walls of a furnace can be divided into three kinds, zero-dimensional, one-dimensional and multidimensional. A succinct introduction to the three models is given by (Viskanta and Mengüç, 1987). The zero-dimensional model is based on a steady state energy balance on the load over the furnace. If the convective heat flux is small the radiative heat flux can be calculated by knowing the energy change over the furnace, an average temperature of the furnace boundaries and the participating media, the exchange area and a radiative exchange factor. The radiative exchange factor, also known as Hottel's exchange factor, is a complex factor that are very much case dependent, depending on the sink to wall area ratio and the emissivity of the walls and the sink.

The predictive capability of the zero-dimensional model performs best in a combustion environment with a small drop of temperature throughout the furnace. In a one- dimensional model the temperature of the wall and participating media changes along the flow direction. An energy balance on a control volume can be set up to derive the heat flux to the walls. Unlike the zero-dimensional model an effective emissivity is introduce which includes both the gases and the furnace walls. Both the zero- and the one-dimensional models are dependent on a factor that includes the emissivity of both the walls and the participating media, particles and gases. More information about these emissivity based factors can be found in the book by (Hottel and Sarofim, 1970). When using multi-dimensional models the radiation modeling is most often connected with modeling of turbulent and reacting flows. The simplest approach in such an environment is to apply the optically thin limit, $\tau = \kappa L \ll 1$, i.e., there is no attenuation of radiation in the participating media, only emission, see (Goulard, 1960), (Barlow et al., 1999), (Collin and Boulet, 2013). With such an approach the radiation is introduced, into the existing solution framework, as a radiative source term which is proportional to the local temperature to the power of four and the absorption coefficient.

The optical thin model has been modeled in a 50 MW grate fired furnace by (Klason et al., 2008) with other more elaborate models. The optically thin model, or as they called it; emission only, gave large over prediction of the radiative emission, hence the heat flux to the walls. For a more detailed and realistic description of the radiative transfer a solution of the radiative transfer equation (RTE) is needed. Models for the radiation properties of the participating media are also needed. The commonly known solution to the RTE, often found in commercial software, are the spherical harmonics method, P1-approximation, the discrete transfer radiation model, DTRM, the discrete ordinates method, DOM, and the finite volume method for radiation, FVM. A description of the models can be found in the book by (Modest 2003) together with a description of the RTE and the radiation property models. The DTRM is not described in the book by Modest, so the reader is referred to the work by (Lockwood and Shah, 1981) who developed this model.

The radiation property models are needed for both the radiating gases and the particles in the free board of the furnace. The absorption coefficient is one of the radiation properties that exists for both gases and particles. The scattering coefficient and the scattering phase function are two other radiation properties that are only relevant for the particles, when thermal radiation is considered. The simplest setup for the radiation properties is when no particles are present and then only the gas absorption coefficient need to be considered. The simplest representative model for the gas absorption coefficient is the black body weighted absorption coefficient, dependent only on temperature. One of these weighted absorption coefficients is the Planck mean coefficient. The Planck mean coefficient should be used with great care as it only works in some special cases and is most efficient for considering emission, see (Siegel and Howell, 1972). The Planck mean coefficient is not commonly used for representing the gas absorption coefficient in combustion environments where as for the particle absorption coefficient it more often used. The more elaborate gas radiative property models suitable for engineering calculations are often referred to as correlation models or global models. These models are correlated against detailed spectral models and offer a significant reduction of computational time at the cost of accuracy in the prediction of the radiative heat transfer estimations. The most commonly used correlation model is the weighted sum of gray gas model (WSGG), see (Hottel and Sarofim, 1967).

Some other correlation models are the spectral line weighted sum of gray gas model (SLW) developed by (Denison and Webb, 1993), full spectrum correlated-k (FSCK) by (Modest and Zhang, 2002) and the absorption distribution function (ADF) model by (Pierrot et al., 1999). Some of these models have been evaluated against spectral models in a high temperature environment with H_2O and CO_2 present in the work by (Pierrot et al., 1999). When we refer to particles in the overhead of the furnace we mean soot, fly ash, char and unburned fuel. Soot particles can because of their small size be approximated as non-scattering particles within the thermal radiation spectra. Because of this only the absorption coefficient needs to be considered. For soot the absorption coefficient can be described with the Planck mean or Roseland coefficient, see (Modest, 2003). A more elaborate model is the WSGG model that includes extra gray gases, see (Truelove, 1975), (Felske and Charalampopoulos, 1982). The improvement of using a WSGG approach for the soot is not obvious when comparing it to the Planck mean coefficient, see (Hofgren and Sundén, 2012).

Fly ash, char and unburned fuel give rise to both scattering and absorption/emission within the thermal radiation spectra. The properties of these particles can be described ones the spectrally dependent complex index of refraction and the particle mass size distribution are given. A good introduction to particle radiative properties in combustion environments is given by (Viskanta and Mengüç, 1987). They describe how to arrive to the spectrally dependent radiative properties of the particles. The spectrally dependent properties are connected with long computational times and such they are not suitable for engineering calculations of radiative heat transfer.

As mentioned earlier the Planck mean coefficients or other black body weighted functions are often used for the radiative properties of particles. This is the only available non spectral representation of particle radiative properties at the moment. The effect of using the Planck mean coefficients for particles in combustion like environments by benchmarking against the most elaborate spectral models that exist have most recently been shown by (Hofgren and Sundén, 2014). The conclusion was that large errors can be encountered with the use of Planck mean coefficients for particle properties. A WSGG like approach was also evaluated as an alternative to the Planck mean coefficients. The results of the WSGG like approach were both better and worse than the Planck mean approach. Other engineering models are needed for the particle radiative properties.

2. EXPERIMENTAL

2.1 The 400 kW grate fired boiler

The test boiler is a scaled down version of a grate fired boiler. The boiler is a 5 bar hot water boiler equipped with a vibrating grate and double screw feeders. The grate measures (L x W) 1.2 x 0.8 m and is designed as a panel wall. The furnace is insulated in the lower part of the furnace (from the grate and approximately 0.5 m upwards) while the rest is just walls. 1st pass is empty and the 2nd and 3rd passes are integrated with the economizer. The unit is designed as an academic test facility and is equipped with several access points for testing purposes. Among other things, there are ports directly above the fuel bed, as well as ports in the water circuit, etc. Thus, it is possible to carry out measurements and take samples with a very wide range of interesting parameters.

The furnace has the dimensions: height 3700 mm, length 1414 mm and width 1039 mm. The length and width are given according to the position just on top of the grate. Figure 1 shows a cross section of the furnace looking from the side. Figure 1 also reveals the access ports, being 39 mm in diameter, used for studying the furnace, marked with the numbers 1-26. Primary air is supplied through the grate to the fuel and secondary air is supplied from both the front and back sides of the furnace. Supply of tertiary air is also available but was not supplied during the measurements. The three levels of secondary and tertiary air can be manually adjusted to obtain different configurations of flow in the combustion process. The nozzles can be both closed and angled, see Figure 2.

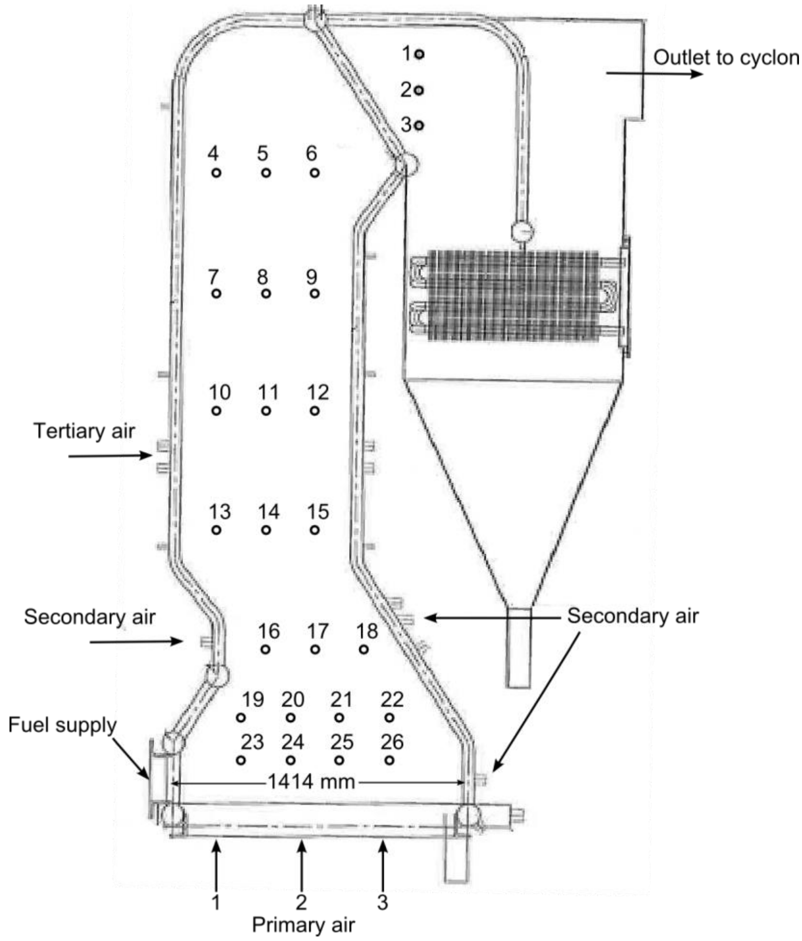

Figure 1. Furnace cross section at center position from the side of the furnace.

Figure 2. Secondary air nozzles on back wall (2nd level)

2.2 The measurement equipment

2.2.1 Radiometer

The radiative heat flux on the walls was measured with a Gunners meter which is a wide angle radiometer, see (Gunners, 1967). Gunners is the name of the inventor, i.e., Nils-Erik Gunners. Figure 3 (a) shows the Gunners meter. The total length of the Gunners meter is 30 cm from the left side, where the air purge is supplied also showing the outgoing wire, to the right side where the thermal radiation enters. The outer diameter is 30 mm. The thermal radiation enters the radiometer through a small hole, approximately 1 mm in diameter.

Inside the radiometer a gold plated semi-ellipsoidal cavity focuses the thermal radiation onto a thermopile. The signal out from the Gunners meter is a mV signal which is translated to a heat flux from a calibration curve. The calibration curve is created by using a black body oven. Each calibration curve is connected to a specific Gunners meter. Figure 3 (b) shows two Gunners meters while they are measuring on a furnace wall. The yellow hoses are for water cooling, the white hoses are for air purge. The purpose of the air purge is to avoid particles from blocking the small 1 mm hole.

Figure 3. Left figure (a) shows the Gunners radiometer. Right figure (b) shows two Gunners radiometers mounted on a furnace wall.

2.2.2 Suction pyrometer

The suction pyrometer is a more common measurement device than the radiometer. The purpose of the suction pyrometer is to measure the true gas temperature. The thermocouple is protected from thermal radiation losses inside the suction pyrometer nozzle, see Figure 4 (a). This protection from radiation losses is important to measure the true temperature. A second fact that is important is a high gas flow rate over the thermocouple.

The high gas flow velocity, 50-100 m/s, ensures that the convective heat flux dominates over all other heat flux losses that are present. The high gas flow rate is created by sucking the hot combustion gases over the thermocouple. The suction pyrometer is 33 mm in diameter and 2 meter long, the product name is SP1925 and constructed by the company METLAB Miljö AB, Sweden. It has a K-type thermocouple. Water cooling is also needed for this device. The device went through a calibration test at an approved calibration facility in Denmark prior to the measurements. Figure 4 (b) shows the suction pyrometer when it is used for the temperature measurements inside the flame zone close to the opposite wall and close to the grate.

Figure 4. Left figure (a) shows the nozzle of the suction pyrometer. Right figure (b) shows the suction pyrometer inside the furnace close to the grate.

2.2.3 FTIR unit and probe

The Fourier transform infrared (FTIR) absorption spectroscopy has been used for measuring the concentration of all relevant combustion gases. The principle of the FTIR unit is that the hot gases are transferred from the furnace into the measuring unit and spectral data is used to determine the concentrations.

The FTIR unit that has been used is a GASMET CEMS system with an additional O_2 analyzer. To take measurements inside the furnace a ceramic probe is used which is attached to a heated suction hose. The hose and FTIR unit is heated to 180°C to avoid condensation of corrosive gases and water. The FTIR unit is capable of measuring a large number of species. In this study the focus has been on the main radiating species, H_2O and CO_2, but also CO and O_2 for further combustion analysis.

2.3 Operating conditions and fuel analysis

The tests were carried out with a regular wood pellet fuel, see Figure 5. The fuel handling system is very flexible and can change between different fuels in batches. Nevertheless it was chosen to use regular pellets to obtain the most stable operation to obtain measurements under stable conditions. The fuel size and properties are presented in table 1 and 2, respectively.

Figure 5. Photograph of wood pellet fuel used in boiler during the measurements.

Table 1. Pellet size

Dimension	*Parameter*
Diameter (D)	6 mm
Length (L)	≤ 5 x D

Table 2. Fuel properties

Parameter	*Value*	*Measuring method*
Density	650-680 kg/m^3	SS 18 71 78
Mechanical durability	≥ 97.5%	CEN/TS 15210-1
Moisture	6-9%	SS 18 71 70
Ash	≤ 0.5%	SS 18 71 71
LHV	≥ 4.8 kWh/kg	SS-ISO 1928
Sulphur, S	< 0.01% *	SS 18 71 77
Carbon, C	50.4% *	LECO 600
Hydrogen, H	6.4% *	LECO 600
Nitrogen, N	< 0.1% *	LECO 600
Chlorine, Cl	0.03% *	SS 18 71 85
Oxygen, O	42.8% *	calculated

* Dry basis

During the three test sessions the boiler was running with an average thermal fuel input of 311 kW, 390 kW and 392 kW, respectively. The oxygen content in the flue gas at the outlet of the boiler was on average 7% wet basis.

Figure 6. Operation station for test boiler

2.4 Data acquisition

The data acquisition started from the center of the furnace. This reason was that we wanted to become accustomed with the measuring equipment before going towards the harsher conditions close to the grate. The response time for the suction pyrometer and Gunners radiometer is about 5 minutes. All measurements were carried out as thermal equilibrium had been reached.

For the suction pyrometer, 300 samples were generated with a frequency of 1 Hz, while for the heat flux measurements, 1200 samples were obtained with a frequency of 4 Hz. In other words, the data collecting time for both temperature and heat flux was 5 minutes. The FTIR unit took an average sample every minute. Measurements were taken for 4 minutes with the FTIR. An ensemble average was taken for the last three minutes as data revealed that the first minute was affected by gas remnants from preceding measurements.

2.5 Measurement uncertainty

For the suction pyrometer in which a K-type thermocouple is used for the temperature measurement, the accuracy of the thermocouple is 0.4% for the temperature above 500 °C. The A-type uncertainty for the temperature measurement is about 4%. Based on the normal distribution with 95% confidence, the uncertainty for the temperature measurement is 8%. For the radiometer which was calibrated against a black body oven, the accuracy is assumed to be 2%. The A-type uncertainty for the radiative heat flux measurement is about 7%. Based on the normal distribution with 95% confidence, the uncertainty for the radiative heat flux is 15%.

3. RESULTS

3.1 Repeatability

In this study, all the measurements were conducted at such a condition that the thermal load of approximately 400 kW has been reached in the test furnace. During the measurements, the operation parameters such as oxygen volume fraction, the fuel consumption, and the output power were real-time monitored. In addition, the measurement repeatability was also checked during the three-day operation. We selected the port 15 as a representative port in which the temperature was measured for three consecutive days with the suction pyrometer.

The results showed that the consistency was quite good and the fluctuations were limited, i.e., within 5 %.The temperature monitoring system of the furnace had a PT100 installed between ports 1-3 and 4-5. The average temperature for the three consecutive days were 521 °C, 551 °C and 563 °C, respectively. The lower average temperature during the first day was because the furnace had not reached thermal equilibrium until 30 minutes into the measurement campaign. Other than the small 30 minutes deviation the monitored temperature for the PT100 further supports the repeatability over the three days measuring campaign.

3.2 Measurement results

The most important factor for predicting the radiative heat flux to the walls is the temperature inside the furnace, as the heat flux is proportional to the temperature to the power of four. 19 out of the 26 ports were used for measuring the temperature, ports [1-4, 6-8] were left out. Not all ports were measured due to time constraints. Focus was therefore spent on the ports closest to the grate where the largest temperature gradients were expected. Figures 7 (a)-(c) present the temperatures at three different distances from the measuring ports, 28 cm, 56 cm and 84 cm, respectively. The temperature is rather uniform when comparing Figures 7 (a)-(c) for the same port at different positions. The uniform temperature distribution in Figures 7 (a)-(c) implies that if an extra horizontal position between the existing position was selected this would not give any extra information. As expected the largest temperature gradients and highest temperatures were found in the lower part of the furnace.

The primary air supply is divided into three sections, see Figure 1. During the measuring campaign problems arose with the air supply to the last section, i.e., section three. Higher air flow rate was therefore supplied in the first two sections giving rise to higher temperatures in this region and lower temperatures further down the grate.

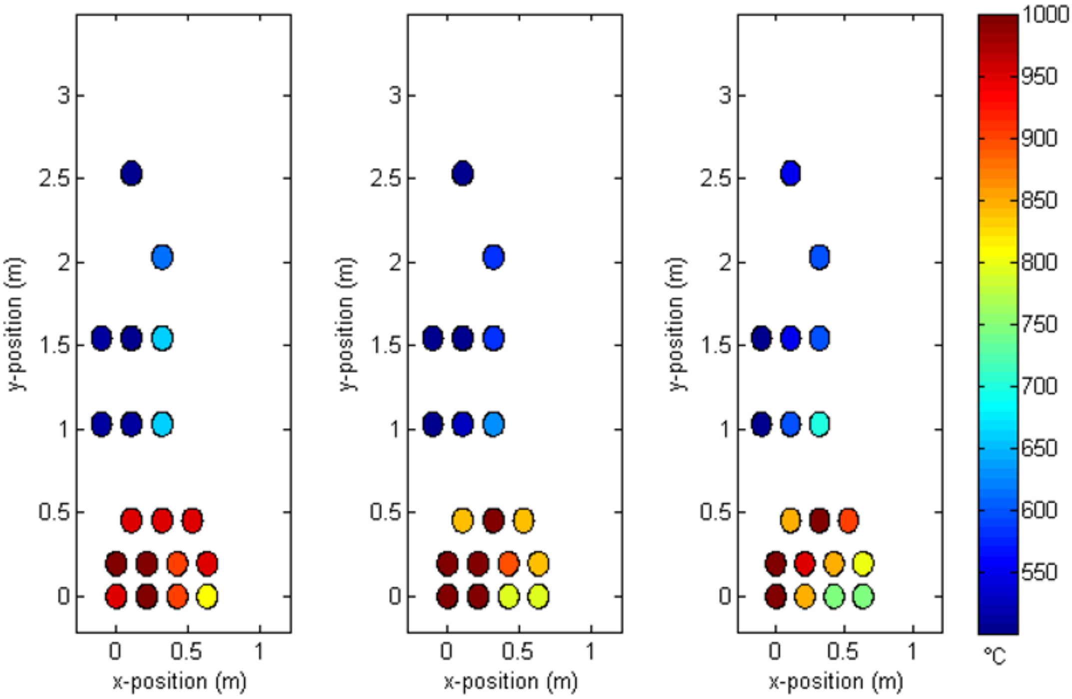

Figure 7. Local temperature distributions for positions 28 cm from the ports, left figure (a), furnace center positions 56 cm from ports, center figure (b), and 84 cm from ports, right figure (c)

The types of gases and their concentrations have a direct effect on the amount of thermal radiation transferred from the hot combustion gases to the walls. Water and carbon dioxide are the most important gases when thermal radiation is concerned. Other gases like CO and CH_4 emit thermal radiation but due to the fact that their concentrations, relative to H_2O and CO_2 concentrations, are smal and that they have important rotation-vibration bands close to H_2O and CO_2 band, their contribution becomes minor. Table 3 presents the gas concentration for 8 positions in the furnace, measured with the FTIR unit and probe. Several more positions were measured but for unknown reasons these gave erroneous results. Port 11, Table 3, deviates from the other results. The reason for this is that this point were measured during the 30 minutes period when the furnace had not reached thermal equilibrium, see section 3.1.

The radiative heat flux was measured at 20 out of the 26 ports. Ports 1, 3, 4, 6, 7 and 19 were not measured. As for the gas concentration and temperature measurements the radiative heat flux measurements were focused on the ports close to the grate where the highest fluxes were expected. Figure 8 (a) presents the radiative heat flux for the 20 measured ports. The radiative heat flux was at its highest, as expected, in the regions with high temperature. Figure 8 (b) presents a comparison with the black body temperatures corresponding to the measured heat flux.

Table 3. Gas concentrations for 8 positions 56 cm from the ports.

Port	*H_2O vol.%*	*CO_2 vol.%*	*CO ppm*	*O_2 vol.%*
5	11.50	12.10	267.00	6.20
10	12.00	12.30	172.00	6.50
11	7.95	7.08	114.00	12.60
14	11.40	12.30	161.00	6.88
15	12.10	12.20	148.00	6.88
18	11.4	10.70	429.00	6.67
22	11.31	8.43	1550.00	5.09
26	10.27	8.48	659.00	8.39

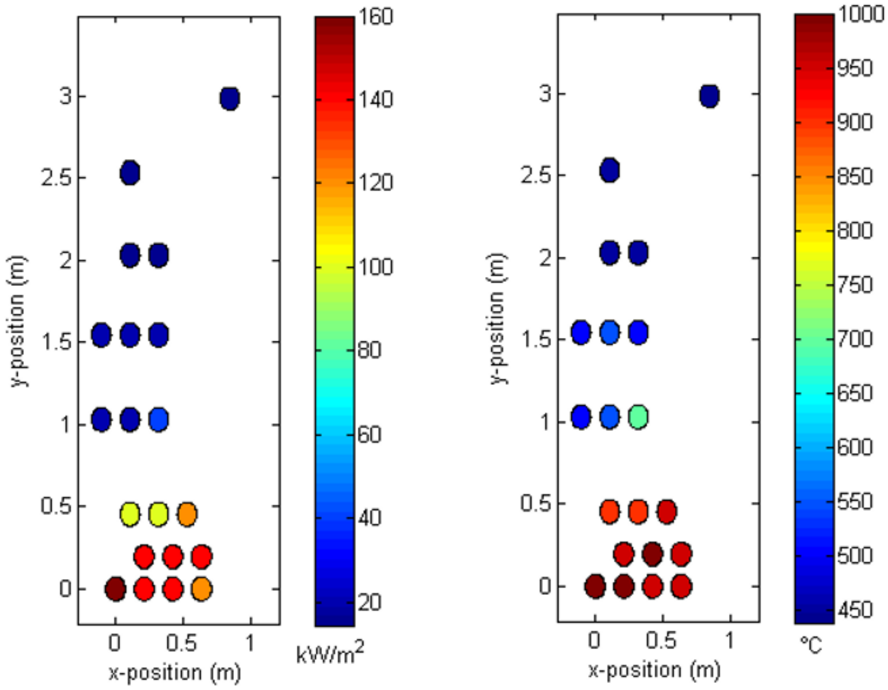

Figure 8. Radiative heat flux for the measured ports, left figure (a), and the corresponding black body temperature, right figure (b).

4. DISCUSSION AND CONCLUSION

The measurements taken on the small test scale furnace is an important step in developing and validating existing radiative heat transfer and property models. The temperature and gas concentration distributions are two important factors when determining the radiative heat flux by the models. Validation of these models can be made against the measured radiative heat fluxes. Two other important factors that have an effect on the radiative heat flux are the temperature of the furnace walls and the particles in the furnace.

Temperature measurements with an IR-camera were conducted on the exterior of the furnace. These temperature images will be used when evaluating the furnace wall inside temperature distribution. This is a very crude method and an approach with thermocouples mounted inside the furnace will be considered in future measurements. Particles were collected from the cyclone to give some indication of the participating particles. The problem by measurements of particles far downstream is that it is not a representative indication of the particle load in the furnace especially in the highly radiating zones close to the grate.

When comparing the corresponding black body temperatures, Figure 8 (b), with measured temperatures, Figure 7, it is found that these temperatures are very close to each other. The radiative gases cannot solely contribute to this close to black body radiation due to the short radiative distances that exist in the small test furnace. This indicates that the presence of particles must increase the radiative heat flux to the walls. Further investigations concerning the particles inside the furnace are needed to enable an evaluation of the predictive capabilities of the presented radiative heat transfer and property models.

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