Heat Flux Measurement Methods for Process Furnaces – a Case Study

Jiří Vondál*, Jiří Hájek

Institute of Process and Environmental Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2, Brno 616 69, Czech Republic
vondal@fme.vutbr.cz

The distribution of heat loads to heat exchanging surfaces in process furnaces (fired heaters, boilers) is an important factor influencing efficiency of the process as well as lifetime of the unit. This work compares two heat flux measurement methods in a controlled environment of large-scale laboratory combustion facility. The experiment makes use of a low-NOx burner firing natural gas at 745 kW thermal duty. Heat fluxes are measured firstly by a water-cooled Schmidt-Boelter sensor (Hukseflux SBG01), which represents the typical approach applied in industrial practice. Second method is based on segmental design of water-cooled walls of the combustion chamber. The latter method provides total heat flux measurement on the process medium side and has several advantages over the standard method. This paper provides a comparison of heat flux distributions measured by the two methods as well as a quantitative analysis of the strong and weak points of both methods. Researchers and practitioners alike should find this paper helpful in interpretation of measured heat flux data.

1. Introduction

The measurement of heat fluxes is one of the methods used to analyse the performance of various combustion systems. In industrial applications, heat fluxes are measured mostly either to monitor the growth of fouling on heat exchanging surfaces or to analyse the distribution of heat flux on combustion chamber walls, as reviewed by Paist et al. (2002) and utilized in boundary condition data by e.g. Maier et al. (2012). Besides that, researchers have applied heat flux measurements for a variety of purposes, prominent among which is the validation of computational fluid dynamics (CFD) combustor models, see e.g. Butler and Webb (1993) for a typical experimental study in a coal-fired utility-scale boiler, which also includes a review of previous measurements and Kuang et al. (2012) for a recent similar study. Utilization of heat flux measurement is also reported for an oxy-fuel regime by Ditaranto et al. (2011).

There are basically two main classes of heat flux measurements in combustion applications as pointed out by Paist et al. (2002); those that measure incident (radiative) heat flux and those that measure the absorbed heat flux. Arai et al. (1996) provides a different broad classification of heat flux measurements, namely indirect methods made by calculating heat transfer rates and direct measurements using nonperturbing heat flux density sensors.

It is important to stress, that most existing methods developed for the measurement of heat fluxes through furnace walls do not measure the real value of heat flux that would go through the wall without the heat flux sensor. In fact, the harsh environment in combustion chambers requires the sensors to be either sturdy for permanent installation or in the case of less robust sensors, to be used only for short periods of time. However, sensors typically represent a disturbance to the heat transfer surface. In permanent sensors, the disturbance mostly has the form of thickened wall or other add-on installation as e.g. in (Taler et al., 2009).

In the more delicate sensors the sensor typically has its own heat sink and the probe is made of different material than the furnace, thus its surface temperature and emissivity also differs, among other less important physical properties. Thus the measured heat flux density is different from the heat flux density absorbed by the process tubes. Typically the measured variable is incident radiation, in some probes

summed with convective heat transfer. The probes thus absorb and measure all the heat that is available in the measurement location. On the furnace's heat absorbing surfaces (cooled by process medium) the conditions are greatly different. Surface temperatures are typically higher and thus great part of the irradiation is radiated back to the combustion chamber.

In gas fired heaters that are common e.g. in oil refineries, the motivation for heat flux measurement is typically the analysis of heat flux uniformity, which is desirable due to various reasons including intensity of coking inside the tubes and lifetime of tubes. Operators use the measurement e.g. after burner retrofit to find whether the distribution of heat flux density has improved, i.e. whether it is more uniform. In this context, heat flux measurements are used together with CFD modelling for detailed analysis of combustor performance. The measurements are done by sensors inserted through small inspection holes in furnace walls. As pointed out above, there is an issue of fundamental difference between heat transfer to the process medium and these measured total heat flux data. It is of course possible to compare predicted irradiation from a CFD model with the measured irradiation, but these values are rather abstract for the operators as they are much higher than the heat flux going through tube walls to the process medium.

This work concentrates on the absorbed heat fluxes. Two direct measurement methods are applied to measure heat flux at the furnace wall. A water-cooled Schmidt-Boelter sensor is applied as a typical probe for the measurement of heat fluxes, representing sensors that are used in the industry. A novel method of heat flux measurement implemented on a large-scale laboratory combustion facility (up to 2 MW) is applied in parallel to the above method. It is shown that the novel approach enables quantitatively significantly more accurate measurements than the Schmidt-Boelter sensor. Properties of the two methods are discussed in detail and it is explained how the novel approach can be used to validate CFD model predictions. The case study of the two heat flux measurement methods provides heat flux profile along the flame of a low-NO_x staged-gas burner firing natural gas at 745 kW.

2. Experimental set-up

Combustion facility where the present experimental study was performed has been described in detail e.g. by Kermes and Bělohradský (2010) or recently by Bělohradský and Kermes (2012) and this work includes only the most important parameters. The facility is equipped by a cylindrical horizontal combustion chamber with 1 m internal diameter and 4 m long. The cylindrical walls are water-cooled, while the end walls are insulated on the inside by aluminosilicate fibrous mat 10 cm thick. The cylindrical walls are composed of seven annular segments with independent supply of cooling water. Inlet and outlet temperature of the cooling water is measured as well as flow rate through each of the segments. Other permanent instrumentation includes outlet flue gas composition, gas and combustion air flow rate measurement and several other parameters. Each of the segments has two opposing lateral inspection windows which can be used for insertion of measuring probes. The facility is equipped by a high-level control and data acquisition system, which collects all measured parameters to a PC.

Note that the design of the combustion chamber along with the instrumentation of the cooling circuit enables the measurement of absorbed heat in each of the segments. Similar design of a large-scale (MW range) laboratory furnace has been in use since 1980's by researchers in Imperial College, see e.g. Dimitriou et al. (2003). Their vertical combustion chamber is composed of 10 segments, 6 of which are water-cooled and 4 are refractory-lined. The water circuit however lacks the necessary instrumentation for heat flux measurement. Another similar large-scale combustion chamber with segmental design is operated at the Technical University of Lisbon, see e.g. Casaca and Costa (2011). In this facility, half of the walls are made of refractory material and only the outlet portion is water-cooled. Small-scale segmental combustion chamber has been used by Nemoda et al. (2005) to analyse in detail swirling flame (thermal output on the order of 10 kW). To the knowledge of the authors, neither any of combustion facilities described in the literature has the necessary instrumentation nor has been used to measure heat transfer to the walls. The present approach is therefore considered innovative.

2.1 Schmidt-Boelter heat flux sensor

The probe used in experiment is manufactured by Hukseflux (type SBG01). It is a water-cooled heat flux sensor of Schmidt-Boelter design (see Figure 1). It measures heat flux densities up to 200 kW/m^2. Its actual sensor is a thermopile measuring the differential temperature across a small plastic body inside the probe. The accuracy of measurement with SBG01 is ± 6 % (with calibration done at the manufacturer), on 95 % confidence level. Response time of the sensor is about 0.3 s, depending on the measured heat flux intensity. Emissivity of the sensor tip is greater than 0.95 and the receiver is coated by a special black paint with rough surface, having good directional response. It is a passive sensor, with analog voltage output. It measures the total heat flux absorbed by the probe, which is the sum of incident radiative heat flux and convective heat flux. Radiative heat flux however dominates in the present application.

Figure 1: Heat flux sensor for spot measurement

It is important to note also possible drawbacks of the method. The measurement has a point character so that e.g. any deviation of the measured flame from symmetry is reflected in the result. Also, the measurement is by its nature prone to several sources of additional error. Typically, the experimenter changes position of the probe to measure heat fluxes in individual windows, which entails opening the windows, sealing the probe in the opening, calibrating its position to be flush with inner wall and correctly orienting the probe to point towards the furnace axis. Any geometrical error and any imperfectness of sealing the window introduce additional error into the measured value, which is not covered by the calibration of the probe.

It is important to note that data measured by the Schmidt-Boelter sensor are not related with the amount of heat extracted by cooled furnace walls. The measured values cannot be integrated to provide an estimate of the total heat transfer rate in the furnace.

2.2 Novel segmental measurement method

The measurement of absorbed heat flux is in this case performed by making heat balance on the cooling medium (water) in each of the furnace segments. The measured variable is however different from sum of incident and convective heat flux. Significant amount of heat is emitted back to the combustion chamber, as the cooled walls are made of thick steel plate and thus temperature gradient inside the wall leads to substantially higher surface temperature on the flame side than in the case of the heat flux sensor. The method is in the following called segmental heat flux method, which expresses its integral nature and also stresses the importance of segmental design of the combustion chamber that makes this measurement possible. The data measured by this segmental method are suitable for validation of CFD models and the measured variable is practically more relevant than e.g. incident radiative heat flux.

Cooling circuit of the combustion facility includes an external air cooling tower and water storage tank, where the water goes from the cooling tower. Temperature of the water in the tank reaches equilibrium in about 45 minutes of sustained firing at constant thermal output. The stabilization period is about 5 times the circulation time of the whole volume of cooling water (about 3 m^3).
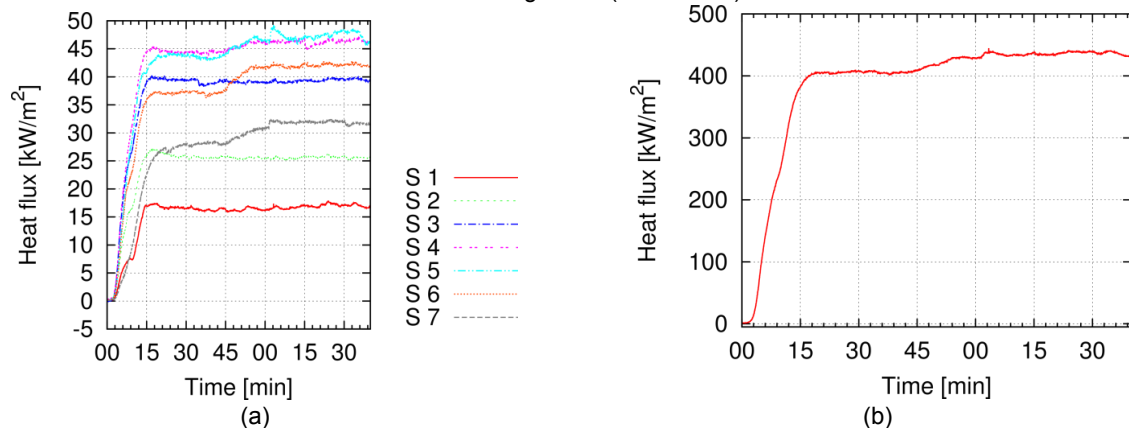

Figure 2: (a) Local wall heat flux; (b) Total wall heat flux

Compared to the heat flux sensor, response time of this method is much longer. Re-distribution of heat inside the furnace must reach equilibrium and all materials and media have to be heated up, which takes up to 50 minutes, as has been determined by the analysis of measured data in a series of experiments with different firing rates. An illustration of the stabilization of heat fluxes in the measurement is provided by Figure 2. Therefore, this method of heat flux measurement requires the furnace be operated at a steady state for at least 50 minutes, before reliable data can be collected.

Uncertainty of the measured heat fluxes may be determined by error propagation using known uncertainties in the measurement of temperatures and flow rates. The accuracy of the measured heat transfer rates may be determined using the calorimetric equation

$$Q = \dot{m}c_p \Delta T / A \qquad (1)$$

where Q is the heat transfer rate [kW/m^2], $\dot{m}$ is mass flow rate of the cooling water [kg/s], c_p is specific heat capacity [kJ/kg-K], ΔT is temperature difference [K] and A is the heat exchanging surface area of a section [m^2]. By applying the theory of error propagation (Braembussche, 2001) we can easily show that for the variance of calculated heat flux holds the following relation:

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{\sigma_{\dot{m}}}{\dot{m}}\right)^2 + \frac{\sigma_{T_{in}}^2 + \sigma_{T_{out}}^2}{\Delta T^2} \qquad (2)$$

In order to see what measures may be taken in the operation of the experimental facility to minimize measurement errors, we have to use standard deviations of the readings on mass flow meters and temperature sensors. These standard deviations are often proportional to the measured value, for example $\dot{m}_{true} = \dot{m}_{measured} \pm 0.005\dot{m}_{measured}$ and in some cases they are even constant in the working range, e.g. $T_{true} = T_{measured} \pm 0.3$ K (these are the values relevant for the present work). Thus the first term on the right side of equation (2) is typically independent of the operating conditions, but the denominator in the second term is inversely proportional to the cooling water mass flow rate. Consequently, error of the measured heat flux has been minimised by reducing flow rate of the cooling water down to a level which still ensures that boiling does not occur.

Repeatability of the measured data depends on good controllability of the experiment, which is very good thanks to the advanced control system. Repeatability has been verified by repeated measurements of the same flame, which have been performed after several months between the individual measurements to make sure that conditions in the test can indeed be repeated with precision. Data from two independent measurements of the same flame are presented in Figure 3. The largest uncertainty in setting up the measurement and also the largest obstacle in further improving repeatability is the air flow rate measurement. Currently it is determined indirectly from oxygen concentration in the flue gas, which leads to uncertainty of the air flow rate of 9.7 %. New direct method for the measurement of air flow rate with a potential to cut the uncertainty to a much lower level is already installed and will be used in future measurements, after tests and calibration.

2.3 Measured process

The object of measurements is a 745 kW non-premixed, swirl-stabilized flame of natural gas with air at ambient temperature, with excess air ratio 1.1. The flow displays large turbulent instability which is reflected in simulations by non-convergence in steady-state formulation of the governing equations as show by Sadiki et al. (2006). The large-scale instability has the form of precessing vortex, which is a common feature of many swirl-stabilized flames as discussed in depth e.g. by Syred (2006). The burner is a low-NO$_x$ design with staged gas, with four secondary gas nozzles and a guide vane swirl generator in the air stream.

3. Results and discussion

The purpose of the present measurements is to showcase a the segmental heat flux measurement method in comparison with point total heat flux measurement by Schmidt-Boelter probe.

3.1 Measured data

The data collected as inputs of equation (1), which yields the values of the absorbed heat flux include namely average temperatures of cooling water, which is the same at the inlet of all segments (after the initial stabilization period as explained above) and different at the outlet of each segment due to different absorbed heat flux. Further, flow rates in each segment are kept constant throughout the experiment. The flow rates have been set low in order to increase the temperature difference and minimize uncertainty in the measured heat flux, but sufficient to prevent boiling of the cooling water and thus local overheating of combustion chamber walls. The measured values for one of the repeated measurements are displayed in Table 1.

Table 1: Measured data

	Wall heat flux [kW/m²]	Maximum error estimate [%]	Water flow rate [kg/s]	Maximum error estimate [%]	Outlet temperature [°C]	Maximum error estimate [%]
Section 1	17.25	8.4	0.9033	0.5	25.2	1.19
Section 2	25.57	4.8	0.9314	0.5	29.8	1.01
Section 3	40.17	2.9	0.8937	0.5	36.1	0.83
Section 4	46.41	2.8	1.0022	0.5	37.0	0.81
Section 5	47.87	2.6	0.9438	0.5	38.7	0.78
Section 6	42.33	2.8	0.9234	0.5	36.7	0.82
Section 7	31.4	2	0.9592	0.5	44.2	0.68

Figure 3 shows both measured data sets obtained by the segmental method and thus documents the good repeatability. Along with the mean values are displayed also error bars indicating maximum error estimates based on error propagation analysis and uncertainty of the individual instruments (thermocouples and flow meters).
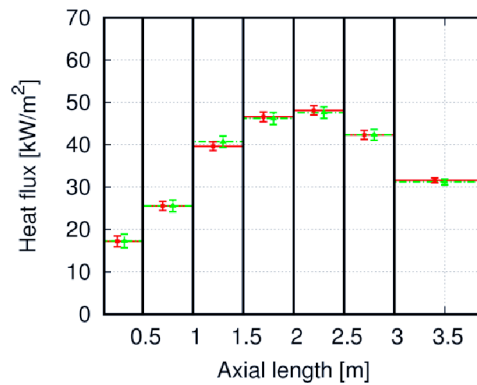

Figure 3: Repeatability of local wall heat flux measurement
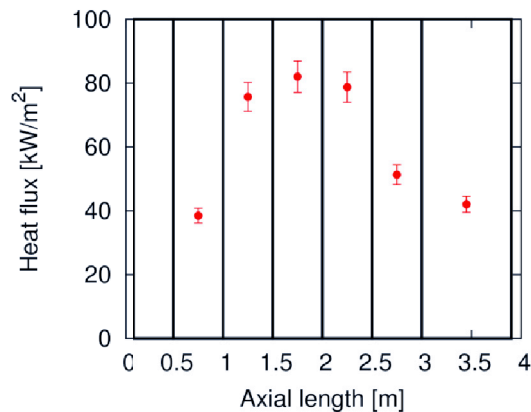

Figure 4: Spot heat flux measurement

Figure 4 displays data obtained by the Schmidt-Boelter heat flux sensor. It is immediately apparent that the result differs significantly from the segmental flux measurement. The measured variables are fundamentally different in the two methods as explained above, so the difference is natural. Not only are the heat fluxes measured by Schmidt-Boelter sensor about twice larger, but also shape of the profile is different. The peak value is shifted closer to the burner and the relative difference of peak and low values is greater.

4. Conclusions

The purpose of the present work was to measure wall heat fluxes in a water-cooled furnace by a standard probe (Schmidt-Boelter sensor) and to provide a comparison with and detailed specifications of a novel segmental method. It is shown that the segmental method has low uncertainty compared to the Schmidt-Boelter sensor and that the measured data are suitable for the validation of CFD model predictions. The main drawback of the segmental method is that its response time is much longer than of point sensors (including the Schmidt-Boelter probe) as it is directly coupled with the combustion system including cooling circuit. Its main advantage besides accuracy is that it provides values that directly correspond with heat fluxes occurring in real fired heaters. Thus the segmental heat flux measurement method is attractive to use in validation of CFD codes for the prediction of fired heaters and other combustion units with significant wall heat transfer.

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