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Experimental and Numerical Investigation of Wall Heat Fluxes in a Gas Fired Furnace: Practicable Models for Swirling Non-Premixed Combustion

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Natural gas combustion and combustion of other light hydrocarbon gases is still one of the primary means of gaining heat. This applies especially for process and energy industries, where gas combustion is used as heat source for various processes. It is therefore of crucial importance, that the combustion chamber is designed properly in order to optimize the heat transfer process. Recently, CFD (Computational Fluid Dynamics) tools have proved themselves as a great potential aid for designers and engineers. These tools allow predicting of various phenomena of practical interest.
The main focus of this study is to validate a numerical model for swirling combustion in terms of wall heat fluxes using reliable measured data. The first part of this study deals with the experimental measurement of wall heat fluxes. Two burner duties are taken into account: 745 kW and 1120 kW. The second part consists in a numerical analysis of the problem. The simulations are performed using unsteady RANS with four different turbulence models coupled with chemistry and radiation models. Boundary conditions are set identically to the experiment.
Two simulations are performed (one for each burner duty) and fine-tuned. The measured and simulated wall heat flux profiles are finally compared and shortcomings if the numerical model are reported and discussed.

1. Introduction

The study of flame structure is the subject of long-lasting interest within the combustion modelling community. Detailed in-flame measurements of temperature, velocity and species concentrations have served as validation of many of the existing combustion models. Unlike the in-flame properties, wall heat fluxes have been used for model validation only rarely. Heat flux measurements reported in the literature are either spot measurements or global heat transfer rates. Spot measurements however mostly provide just the thermal irradiation flux, not the actual radiative or total heat transfer rate as demonstrated in some studies of industrial furnaces and boilers (Hayes et al., 2001; Ströhle, 2004). Likewise, global heat transfer rates calculated from the total hot water (steam) production are insufficient for the validation of detailed predictions.
In contrast to that, the interest of engineering community focuses primarily on local heat fluxes and pollutant emissions. Emissions are studied namely to ensure compliance with legislative regulations, while heat fluxes are required to check proper furnace design and to ensure safe operation and durability. It is thus apparent that the correct prediction of local heat fluxes on heat transfer surfaces is

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one of the most important aspects of practical combustion simulations that should receive adequate attention.

Swirl-stabilised non-premixed flames are frequently used in industrial burners, but at the same time they present a huge challenge, since numerical prediction of swirling flows is very difficult. Only with the advances in large eddy simulations (LES), successful predictions of in-flame properties were reported (Fureby et al., 2007; James et al., 2007; Sadiki et al., 2006). However, the LES approach is still too computationally expensive for the simulation of large-scale fired heaters due to their huge dimensions (in the order of 10 m) and the need to resolve fine features like gas nozzles with diameters on the order of 1 mm. The only viable alternative for practical predictions in the present as well as for a number of years to come thus consists of models based on first or second-order turbulence closures.

2. Experimental Measurement

2.1 Experimental Facility

The wall heat fluxes measurements were performed in the experimental facility located at Brno University of Technology. The chamber has a form of a water-cooled horizontal combustion chamber with 1 m internal diameter and 4 m length (see Figure 1). The shell of the chamber is divided into seven sections; each of which has a separate water inlet and outlet and is equipped with a water flow meter and temperature sensors, allowing for accurate heat transfer rate measurement. The experimental facility is described in (Kermes and Bělohradský, 2008; Kermes et al., 2007) and details about the measurement precision can be found in (Vondál et al., 2010). A low-NOx staged-gas burner with axial swirl generator was employed and fired by natural gas. Flame ignition and stabilization is performed by a small (25 kW) premixed natural-draft pilot burner. Its thermal duty was included in the total thermal duty.

This facility has been used for several measurements. Although with different scope (Bělohradský et al., 2008; Kermes and Bělohradský, 2008; Kermes et al., 2008).

2.2 Wall Heat Fluxes Measurements

Two different burner duties were tested: 745 kW (case 1) and 1120 kW (case 2). The local wall heat fluxes were measured based on the heat absorbed by the cooling water. Stabilization of the experiment was established with respect to local wall heat fluxes in all sections of the furnace, which were monitored continuously. After reaching a steady state, the measurement procedure began and data were collected for about 30 min. The operating conditions for both cases are presented in Table 1.

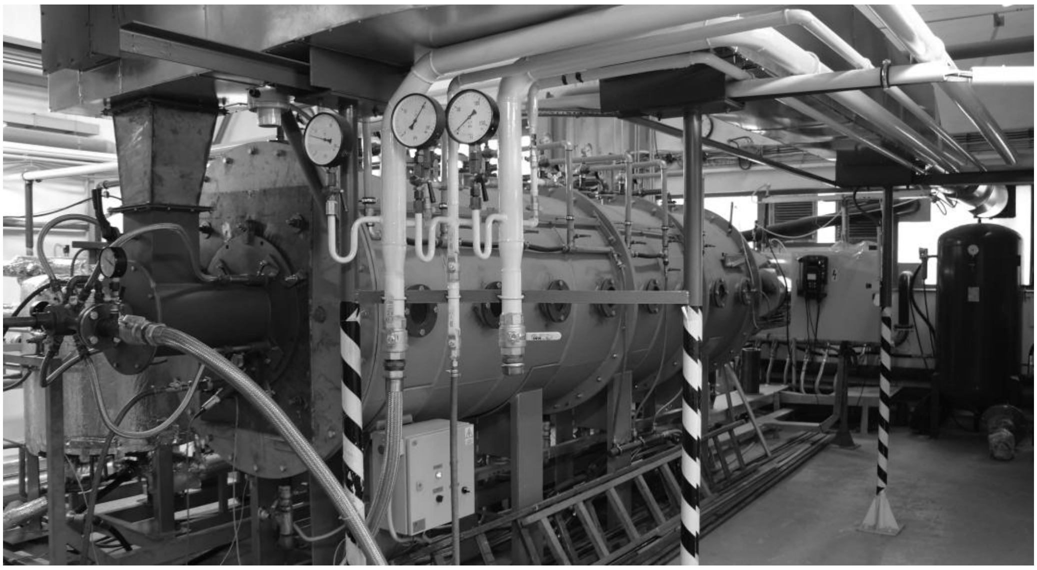

Figure 1: Testing facility

Table 1: Operating conditions

		Case 1	Case 2
Thermal duty	[kW]	746.9	1119.6
Natural gas flow rate	[kg/s]	0.0152	0.02278
Air flow rate	[kg/s]	0.29	0.436
Natural gas temperature	[°C]	16.31	16.83
Air temperature	[°C]	11.75	14.54

3. Modelling

For each of the two cases a combustion simulation was performed using commercial CFD package Ansys Fluent. The problem was carefully set up taking into account recent results of a related investigation (Vondál and Hájek, 2011). The main goal of these simulations was to predict heat fluxes absorbed by the cylindrical water-cooled combustion chamber walls for two different burner duties, namely 745 kW and 1120 kW.

3.1 Computational Grid and Setup

For the purposes of numerical analysis a mesh was constructed in the software Gambit. The total number of computational cells (97 % of which are hexahedral) was nearly 1,200,000, with approximately 200, 65 and 135 grid nodes in the axial, radial and tangential directions respectively. During the computations the mesh was adapted according to temperature and vorticity gradients, leading to a total of approximately 1,500,000 computational cells.

Four boundary conditions types were applied – mass flow inlets (for combustion air and methane), pressure outlet, prescribed temperature on the water-cooled walls of 80 °C (Vondál and Hájek, 2009) and adiabatic condition for the remaining walls. Boundary and operating conditions were set identical to the experiment.

3.2 Turbulence and Chemistry

The flow field was obtained by solving the unsteady Reynolds-averaged Navier-Stokes equations. Four different turbulence models were tested: k-ε realizable, k-ε RNG (based on renormalization group theory), k-ω SST (Shear-Stress Transport) and RSM (Reynolds Stress Model).

To account for turbulence chemistry interactions and combustion the Eddy-Dissipation model (Magnussen and Hjertager, 1977) has been employed. This model falls into the family of eddy breakup models and therefore combustion occurs as soon as fuel and oxidants are mixed. Due to the simplifying assumptions only a single-step reaction mechanism has been used.

3.3 Radiation

In combustion chambers, the main mechanism of heat transfer is radiation. However, by this time no generally accepted model has been developed. For this study the discrete ordinates model has been used due to its reasonable computational demand. A recent model for the absorption coefficients has been implemented (Yin et al., 2010), which is based on approach of the weighted sum of grey gases model.

4. Results and Discussion

This section provides a summary of computed results and comparison of the various turbulence models employed. Both comparisons of the predicted local wall heat fluxes with experimental measurement can be seen in Figure 2 and Figure 3. The error bars in the figures represent the standard deviation.

In case 1 it can be said that good agreement is achieved with all turbulence models (see Figure 2). After a closer look the RSM model provides the best agreement (only in the last section it is surpassed by the other models). However, it is important not to forget, that the RSM model is by far the most computationally expensive among the other models. The k-ε RNG and k-ω SST models give very similar results, while the k-ε realizable model, compared to the others, gives the poorest predictions. Overall, the section where the least agreement is achieved is the 7^{th} section.

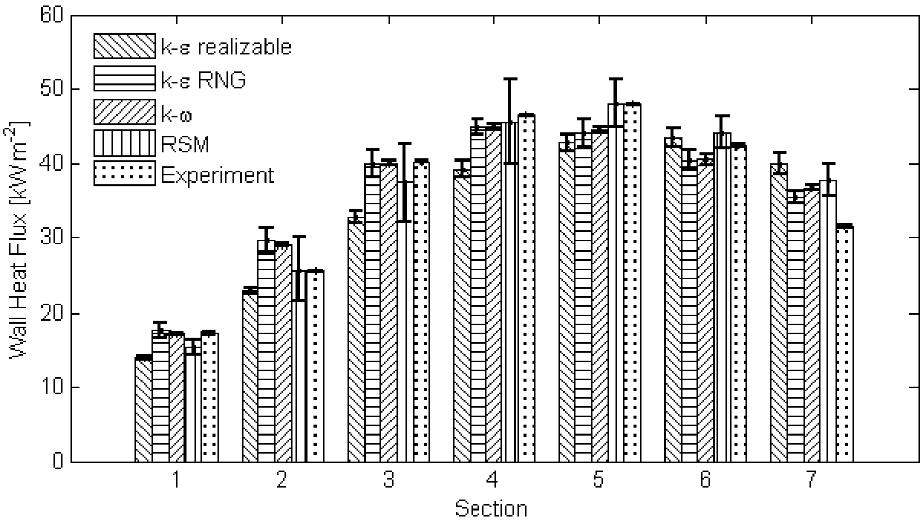

Figure 2: Comparison of predicted local wall heat fluxes between simulation and experiment – 745 kW

The comparison of case 2 is reported in Figure 3. When compared to the previous case, the prediction is not as successful. Again, all models have only small deviations. In the first four sections all models underpredict the wall heat fluxes, while in the last two sections they are overpredicted. Similar trends can be also found in the previous case, but they are not as distinct as in this case. It is also interesting to note, that most models predict an increase of wall heat flux between section 5 and 6, while the experimental data have the opposite trend. No model can be clearly said to give best agreement. The k-ε realizable and k-ω SST models give very similar results similarly and a similar resemblance can be found among the the k-ε RNG and RSM models. The 7^{th} section is, as in the previous case, where all models struggle to give acceptable predictions.

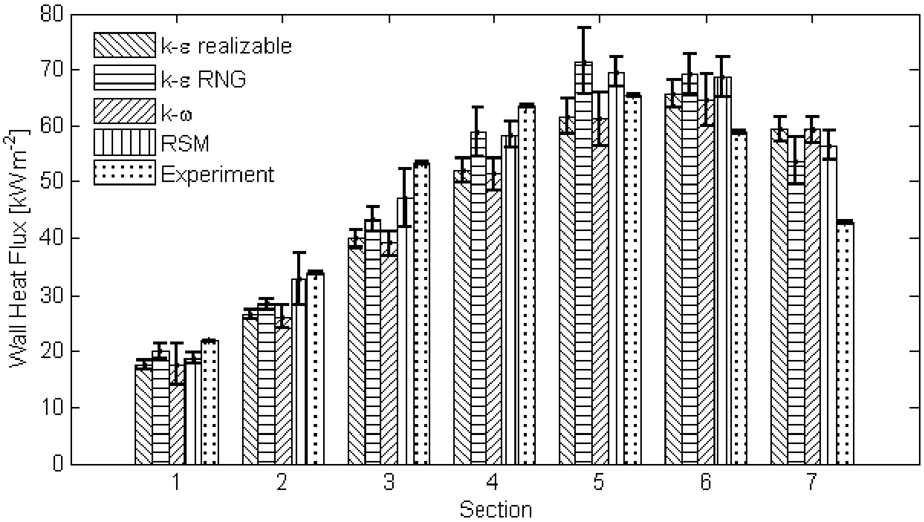

Figure 3: Comparison of predicted local wall heat fluxes between simulation and experiment – 1120 kW

Although the only difference between the two simulated cases was the burner duty, in the case 1 good agreement was achieved unlike in case 2. Even with the up-to-date radiation approach (Yin et al., 2010) the simulation results in case 2 cannot be considered good. From Figure 3 it can be seen that the predicted flame is longer, which means that the mixing of fuel and oxidizer is occurs at a smaller rate then in reality. This clearly shows the difficulty of modeling swirling flows. As the burner duty is increased, the gas velocities increase as well accentuating the role of swirling in the mixing process. The swirling phenomenon has not yet been fully understood and current turbulence models are not able to capture its complex flow structure properly (Mitrofanova, 2003).
In general it cannot be said the RSM model is superior compared to the two-equation models. Although it gives slightly better predictions of local heat fluxes the growth of computational effort is significant and is likely to disqualify this model when it comes to industrial applications.
An overview of total heat fluxes in the combustion chamber is reported in Table 2. In case 1 all models give reasonable agreement with only small differences among them. In case 2 k-ε realizable and k-ω SST give very accurate prediction of the total wall heat flux while k-ε RNG and RSM gives much worse predictions. It is worth noting that the RSM model gives in both cases the least accurate predictions.

Table 2: Total Wall Heat Fluxes

	Case 1 [kW]	Deviation [%]	Case 2 [kW]	Deviation [%]
k-ε realizable	426.8	2.59	595.3	0.19
k-ε RNG	445.3	1.63	619.9	4.33
k-ω SST	448.6	2.37	589.3	0.82
RSM	452.9	3.35	635.7	7
Experiment	438.2		594.1	

5. Conclusion and Future work

This study addresses the issue of turbulent swirling gas combustion. Two cases with different burner duties (745 kW and 1120 kW) were addressed both experimentally and numerically. Four commonly used turbulence models were compared in terms of local wall heat fluxes predictions and confronted with experimental measurements. The results indicate that in the case of higher duties (case 2) the used models struggle to capture the swirling effect, which results in slower mixing of fuel and oxidizer leading to longer flames and mismatch between predicted and measured wall heat fluxes. It can be argued, that there are turbulence models able to overcome these shortcomings, but unfortunately they are still too computationally expensive to be employed across the board. Furthermore it is shown that the advanced RSM model has difficulties predicting total wall heat fluxes as accurately as simpler two-equation models. More research is therefore needed to better understand the swirling process and to find efficient ways to improve current models or to develop new ones.

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