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Innovative Adaptation of MPF Model to Recognition of Thermal Behaviour of Operated Industrial Low Emission Burner System

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The paper presents validation of innovative adaptation of modified plug flow (MPF) model to recognition of thermal behaviour of industrial system of low emission gas fuel burners operated in radiant chamber of vertical cylindrical fired heater placed in crude oil atmospheric distillation plant. The MPF model originally developed for calculation and identification of real distribution of heat flux along height (length) of combustion chamber burner testing facility of Institute of Process Engineering at Brno University of Technology is adapted and applied to situation of vertical cylindrical radiant chamber of fired heater in order to recognise a real thermal behaviour of actually operated low emission burner system and its influence on hardly operated fired heater characterized by high fouling rate of heated crude oil inside radiant tubes accompanied by significant deformations of radiant tubes. Results of adapted MPF model are confronted with results of fired heater heat flux operational measurements and with comparative results of CFD simulations and bears important observations concerning influence of thermal behaviour of installed burners system on fired heater operation.

1. Introduction to industrial problem

Fired heaters are the major energy consumption components of refinery processes. From this reason a high-performance fired heaters of radiation-convection type, containing radiant and convection section, are preferred especially for fundamental refinery applications. Radiant section (or radiant chamber) of such fired heater is dominant part of heater since the most of heat is transferred to heated fluid there. Fired heater´s design and operating is under continuous development, because their optimum design leads to higher efficiency, lower operating cost, lower energy consumption, and consequently lower amount of emissions being produced. However, energy saving design and operation of fired heater together with its operating reliability and required lifetime can be achieved only by proper application of integration techniques considering not only systematic approach for proper placement and conceptual design of such equipment but also its reliable detail design based on accurate thermal-hydraulic calculations (Lam et al., 2014).
Moreover, design of fired heaters for refinery processes has to be performed in accordance of relevant design standards. The American Petroleum Institute Standard 560 (API, 2007) is a dominant and worldwide recognized fired heater design standard. However, contrary to regular updates of this standard, the principle of calculation of important operating parameters of the fired heater radiant section remains the same, based on average heat flux to the radiant tubes.
Although the average radiant section heat-flux rate is an important indicator of overall heater performance, it is not a good indicator of localized heater performance, because real heat flux varies in radiant section significantly from average value. Generally, the level of agreement of applied design standard rules, especially of typical local distribution of heat flux along the radiant section height (considering radiant chamber with the most widespread vertical up fired burner system) and real thermal behaviour of installed burners in radiant chamber fundamentally influences operating behaviours of whole fired heater. If the level of agreement is not good enough, a serious operating troubles of fired heated occurs. Typically it is a separation of vapour and

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liquid phase of heated fluid and rapid deposition of coke inside tube coil resulting in overheating of tubes, rapid decline lifetime of exposed tubes (frequently accompanied by their visible deformations), fast increasing of fluid pressure drop, and necessity of the plant shut down and decoking of fired heater (Jegla, 2013).
For purpose of close keep in touch with reality, actually operated fired heater with mentioned operating problems is taken as example to demonstration of practical usefulness of below presented approach. Considered fired heater is a typical vertical cylindrical fired heater (see Figure 1), containing standard radiant and convective section, commonly and long-time operated in crude oil atmospheric distillation unit (from which complete geometry and plant operating data are available). Radiant section of the heater and its tube system has been designed in accordance with the relevant abovementioned API Standard. Tubular system of radiant section represents two-passed tube coil created totally by 60 tubes (placed in one row around circular lining wall) with the constant tube outer diameter (d_o) 194 mm and with tube spacing (s) 350 mm. Each tube is approx. 17 m length. Tubular system is placed on tube coil circle diameter (D_C) of approx. 6.7 m. So the shape of radiant section is characterized by ratio of tubular system height (or length L) to tube circle diameter which is L/D_C = 17/6.7 = 2.5 (see Figure 2). Radiant section is equipped by two levels of observation doors for viewing all radiant tubes and all burner flames for proper operation and light off. These observation doors are located at the level of 5.0 m and 10.0 m above bottom of radiant section (see Figure 1). Each level contains 12 observations doors placed uniformly circumferentially radiant section.
Abovementioned operating problems of fired heater started four year ago, after approximately one year of fired heater operation with new low emission burner system (which replaced originally installed classic gas-fueled vertically up fired six burner system due to the need of compliance with emission limits). New burner system contains a total of six staged-gas burners vertically oriented and mounted on bottom of radiant section (see Figure 2), equipped with guide-vane stabilizers (swirlers), each of nominal firing duty 4 MW. So the (unchanged) nominal firing capacity (heat released) of fired heater is 24 MW. Unchanged fired heater flue gas waste heat air preheat system produce combustion air preheated to 170 °C and supply preheated combustion air to new burners by unchanged air duct distributing system. Results of standard rating thermal-hydraulic simulation of fired heater with low emission burner system for nominal operating conditions performed accompanying installation stage of low emission burner system informs that thermal efficiency of fired heater is 90 %, average heat flux of radiant tubes approaches 30 kW/m^2 and outlet flue gas temperature from radiant section (i.e. bridge wall temperature) is close to 700 °C.

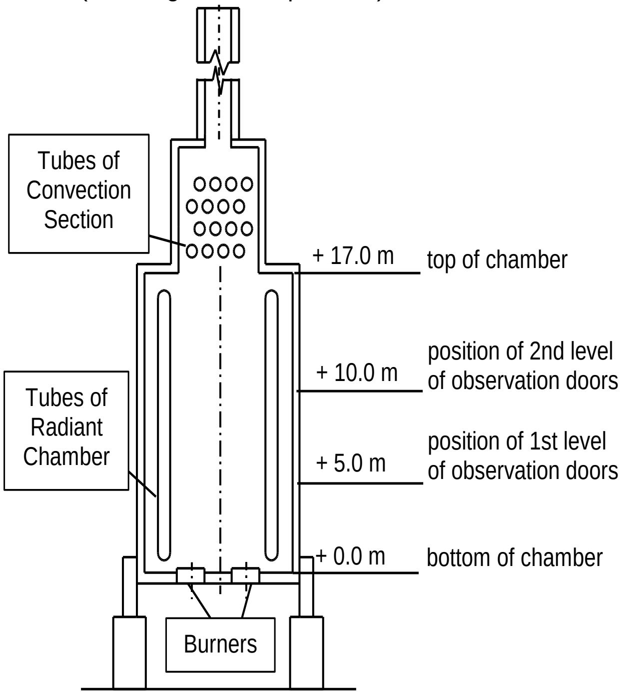

Figure 1: Sketch of fired heater situation with observation doors levels.

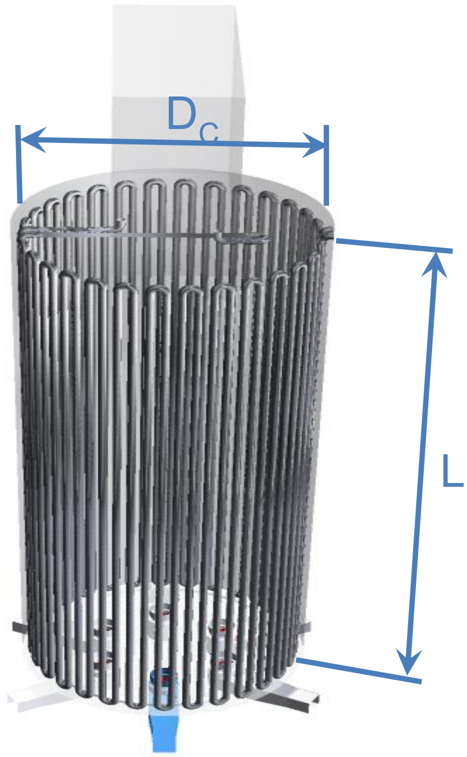

Figure 2: Visualisation of tubular and burner system in radiant chamber.

2. Operational measurement and numerical analysis of local heat flux inside radiant section

Since standard process measurement of fired heater at nominal operating conditions agrees very well with results of rating calculation and not indicate any potential problem (for example average measured value of bridge wall temperature is close to 700 °C) the only explanation of surprising operating troubles of fired heater (visible high deformations of several radiant tubes and unacceptable increasing of heated fluid pressure drop inside radiant tubes due to fluid coking process) is an unexpected heat flux distribution from flue gas to tubes inside radiant chamber.

To verify this hypothesis (since the thermal behaviour of installed low emission burners was not available) it was decided to perform the independent two half days measurements of local heat flux inside radiant section (during carefully operated nominal conditions of fired heater by operator) and subsequently completed results of measurement by detail numerical computations of heat transfer inside radiant section of fired heater with using computational fluid dynamics (CFD) model employing commercial system ANSYS FLUENT.

Since the another important aim of refinery operator is to install this type of low emission burners to next refinery fired heaters in the near future, the final task of mentioned measurement and CFD works was to identify the real thermal behavior of this type of low emission burner in suitable and quantifiable form allowing its easy implementation to standard rating thermal fired heater calculations to identify potential real behavior of next fired heaters employing this type of burner in future.

Operational measurements – generally, measurement on fired heater during its operation usually allows identifying the real local heat flux only at certain locations of radiation section. So, it does not provide an overall picture of the distribution of heat flux along the section height (length). Moreover, such operating measurement requires special and expensive measuring equipment (most often thermography or heat flux meters) with trained operating staff (Jegla, 2013). In the presented fired heater case, observation doors of radiant section were used as suitable places and positions to measurement of true local heat flux. Commercial heat flux meter with trained staff was employed to perform a scheduled independent two half days measurements of local heat flux inside radiant section. Obtained results of measurement were statistically evaluated and profiles of local maxims, minims and average values of local heat fluxes located at the level of 5.0 m and 10.0 m above bottom of radiant section (each completing measurements results from 12 observation doors circumferentially radiant section) were obtained. Mean values of local heat flux provided by these operating measurements are presented for both measured radiant section levels in Figure 3.

Computational analysis of heat transfer – combustion conditions of burners, setting of CFD model and results of detail numerical computations of heat transfer inside radiant chamber of the fired heater were already published and discussed by Jegla et al. (2015b). Numerical results of vertical mean heat flux profile in radiant section of actually operated fired heater are presented in graphical form in Figure 4.

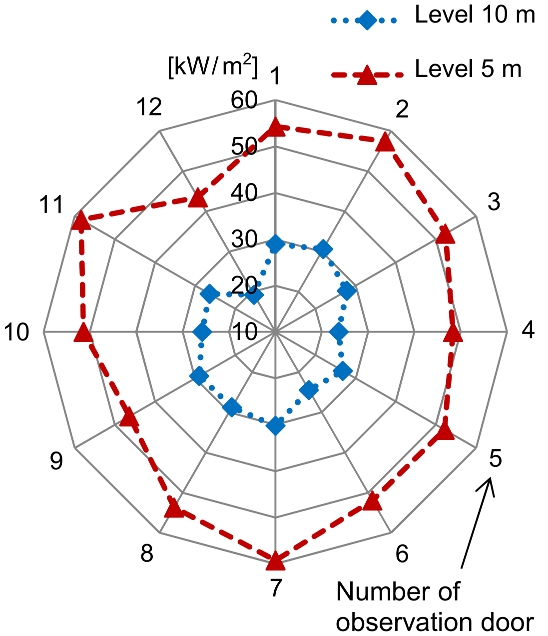

Figure 3: Measured local mean heat flux profiles

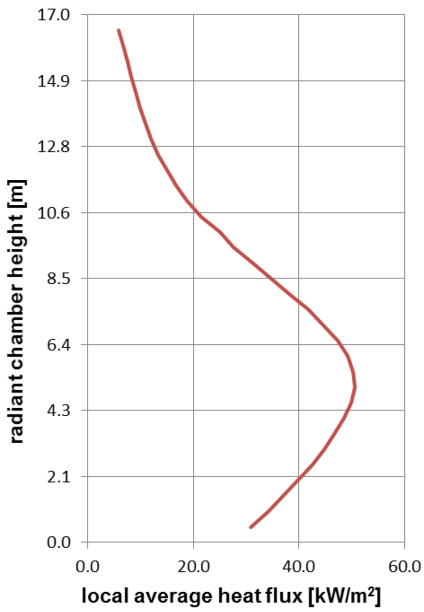

Figure 4: CFD results of mean heat flux profile

3. Modified plug flow model and its adaptation to fired heater radiant chamber

Modified plug flow (MPF) model was developed for identification of burner real thermal behaviour and to avoid thermal design problems related to current design methods based on the use of average heat flux, which does not provide sufficient information needed for exact design of inbuilt tubular heat transfer systems, especially when two-phase (i.e. vapour-liquid) flow of heated medium inside tubes occurs. The MPF model was first formulated by Jegla (2013) for a given specific burners´ testing combustion chamber of the Institute of Process Engineering (IPE) of the Faculty of Mechanical Engineering (FME), Brno University of Technology (BUT). Good predicative ability of MPF model was confirmed by Jegla et al. (2015a) by comparative calculations of 22 different combustion cases of testing burners with various combustion conditions. Results of this validation clearly shown, that the MPF model is capable to provide the real heat flux distribution profile along the combustion chamber height (length) and to identify the corresponding profile of fuel burnt profile unambiguously representing thermal behaviour of a given burner at specific combustion conditions.
The general principle of the MPF model is schematically presented in Figure 5, on the example of horizontally oriented cylindrical radiant chamber of length *L* divided into *n* number of small length segments. Local heat flux from the hot gases to the heat sink of *i-th* segment (q_i, [W/m^2]) is calculated from the heat (Q_i, [W]) absorbed by the segment heat transfer area (A_i, [m^2]) as a function of the local volumetric heat release rate (i.e. fuel burnt vol. fraction) which sum for whole chamber has to be equal to one. Worth noting that adaptation of MPF model to fired heater radiant chamber (its general calculation flowchart is in Figure 6) is iterative method employing so called modified mean gas temperature (T_{gM}) in the first segment (for details see Jegla, 2013) evaluated from mean gas temperature (T_g) in the first segment and the correction factor (C_{Tg}) calculated as ratio of heat absorbed by heat transfer area in the first segment (Q_{1w}) and the total heat absorbed by heat transfer area of all segments of radiant chamber (Q_{Tw}).

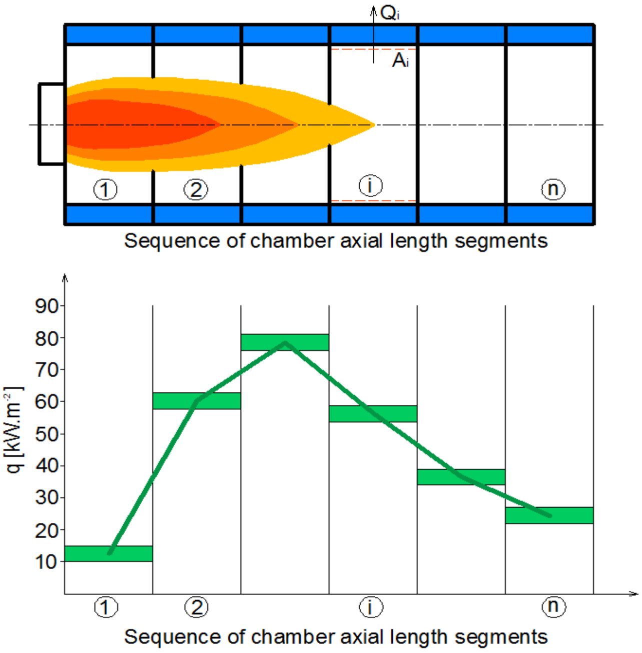

Figure 5: Sketch of general principle of MPF model

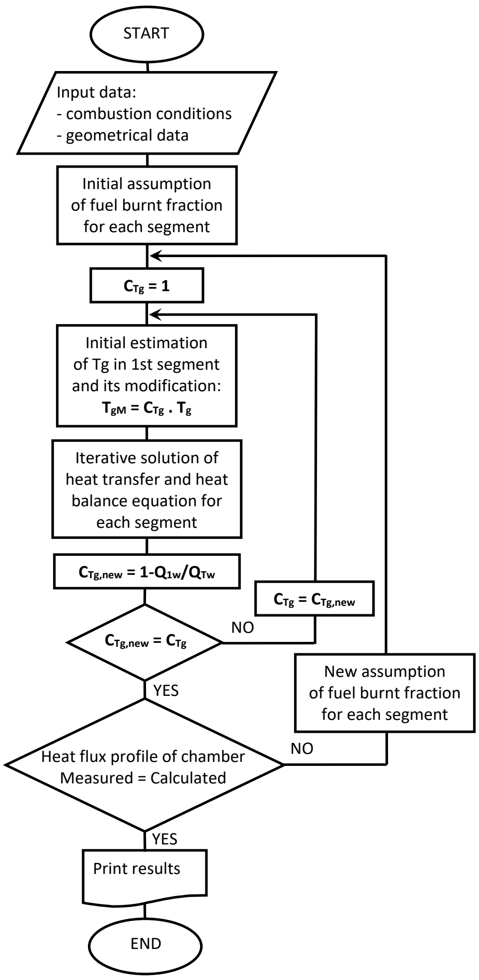

Figure 6: Flowchart of adapted MEF model

4. Application of MPF model to fired heater radiant chamber with low emission burners

It is obvious from Figure 6 that the MPF model predicts actual thermal behaviour of burner system (represented by fuel burnout profile) by best matching entered measured values of local heat fluxes of individual calculation segments with calculated ones. The accuracy of the predictions of MPF model so is influenced by two factors (i) availability of reliable measured data of local heat fluxes along radiant chamber and (ii) using an optimal number of computational segments.

In the case of adaptation MPF model for radiation chamber of fired heater the requirement of availability of reliable measured data of local heat fluxes along radiant chamber is overcame by using results of operational measurements from two level positions of observation doors (Figure 3) together with CFD results (Figure 4) for covering all radiant chamber height by known average heat flux variation of operating burner system. And determination of optimum number of computational segments for MPF model follows.

4.1 Sensitivity analysis for determination of optimum number of computational segments

A sensitivity analysis of influence of number of computational segments on resulting value of heat flux in individual segments was performed with supporting of reliable measured heat flux values obtained during abovementioned validation of MPF model on burners´ testing combustion chamber of the IPE. We considered part of testing chamber length where flue gas temperature decreases from 1,200 K (inlet temperature) to 800 K (outlet temperature) with known properties of flue gas and surface temperature of water-cooled wall of testing chamber. The number of virtual computational segments replacing this real length segment was subsequently changed (from 1 to 10) by changing of flue gas temperature range in calculation segment (for example for one computational segment replacing real length segment the temperature range is 400 K, for two computational segments replacing real length segment the temperature range is 200 K, etc.). Then from the local heat flux results of these virtual segments it was calculated average mean heat flux value of whole real water-cooled segment. Results of this sensitivity analysis are presented in Table 1.

Table 1: Main results of sensitivity analysis for determination of optimum number of computational segments

Number of computational segments [-]	1	2	4	8	10
Flue gas temperature range of each computational segment [K]	400	200	100	50	40
Average heat flux of real segment [kW/m^2]	13.99	14.87	15.05	15.11	15.11

It is obvious from Table 1 that exist certain optimum number of computational segments of MPF model allowing to obtain required accuracy of the average heat flux of given real length segment of chamber without necessity of further increasing of computational segments number. It can be seen from Table 1 that this optimum number of computational segments is characterized by achieving a flue gas temperature range in each computational segment below 100 K. Transferring this knowledge to the length dimensional form it is found that for so far MPF model experienced testing cylindrical chambers with height (length) to diameter ratio (L/D) in range from 2 to 4 the optimum length of each computational segment should be less than 15 % of chamber height (i.e. $L_{comp.\ segment} < 0.15L$). Adapting this knowledge to geometry of the solved radiant chamber of fired heater ($L/D_C = 2.5$; L=17 m) it is found that in this case the optimum length of each computational segment should be less than 2.55 m. From confrontation of this result with above presented results of operational measurements (Figure 3) and CFD simulation (Figure 4) for purpose of best mutual comparison of all values it was decided to apply 8 computational segments of MPF model each with length of 2.125 m.

4.2 Main results of MPF model and its confrontation with other available data

The main results of MPF model adapted with above found optimum number of 8 computational segments to radiant chamber of fired heater are presented in Figure 7. In this figure are for comparison purpose presented also mean average values of operational heat flux measurements for two levels of observation doors. With using of Figure 3 a mean average heat flux 52.42 kW/m^2 is evaluated from average measured values at level of 5.0 m above bottom of radiant section and a mean average heat flux 26.81 kW/m^2 is evaluated from average measured values at level of 10.0 m above bottom of radiant section. Moreover, Figure 7 contains for mutual comparison purpose also mean average heat flux profile from CFD simulation presenting data from Figure 4 in directly comparative recalculated representation of average heat flux of 8 length segments.

Then, from Figure 7 allowing direct comparison of results of adapted MPF models with local average heat fluxes in two discrete levels of radiant chamber length and with comparable results of CFD computations it is clearly evident very good agreement between results of these all three sources (i.e. measurement, CFD, MPF model). It can be concluded that results in Figure 7 confirm that presented adaptation of MPF model to real radiant chamber of fired heater is capable with sufficient accuracy gives a true picture of operated low emission burner system in simple quantifiable form suitable for next practical utilization by thermal engineers.

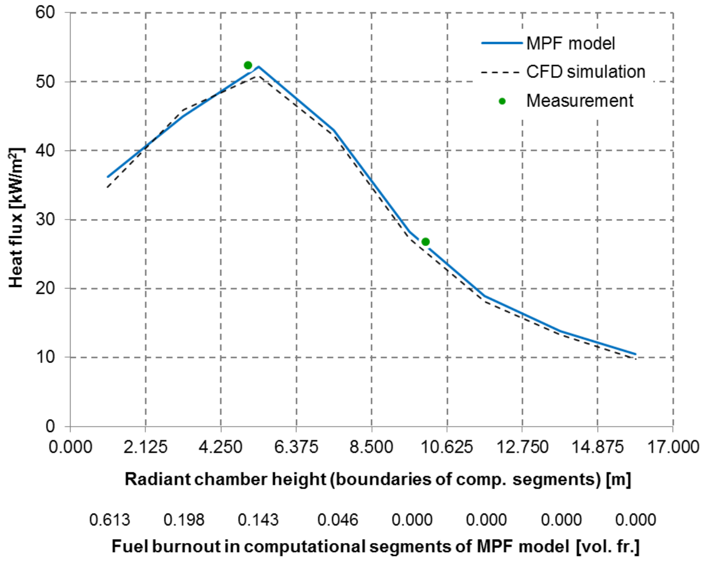

Figure 7: Comparison of results of adapted MPF model with measured valued and results of CFD simulation

5. Conclusions

Innovative adaptation of MPF model (originally developed for identification of thermal behaviour of burners tested in university burner testing facility) is presented together with its successfully validation through successful recognition of real thermal behaviour of industrial system of low emission gas fuel burner system operated in vertical cylindrical fired heater of crude oil atmospheric distillation plant. Highly appreciated is a very good agreement of MPF model results with results of demanding local heat flux measurement of operated fired heater and with results of time consuming CFD modelling. The important contribution of the work consists in the confirmation that the adapted MPF model is able to rapidly identify the real thermal behavior of this industrial type of low emission burner in suitable and quantifiable form allowing its easy implementation to standard rating thermal fired heater calculations to identify potential real behavior of next fired heaters employing this type of burner in future. Namely, identification of flame length and fuel burnout profile provided by MPF model in relation to identified real variation of average heat flux profile along height of radian chamber are the valuable information for process plant and fired heater engineers which cannot be provided by CFD simulations. For analyzed burner system of fired heater results of MPF model shown (see Figure 7) that fuel is completely burnt in first fourth calculation segments, namely 61.3 % of fuel in the first segment, 19.8 % in the second segment, 14.3 % in the third segment and 4.6 % in the fourth segment. Among other, it for example indicates that flames reach length of 6.5 m. More importantly, these values confirms and quantifies an original hypothesis that the source of fired heater operating problems is an unexpected heat flux distribution from flue gas to tubes inside radiant chamber specific for this type of operated burners.

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