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Numerical Analysis of Heat Transfer in Radiant Section of Fired Heater with Realistic Imperfect Geometry of Tube Coil

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Complex numerical computations are performed for vertical cylindrical fired heater operated in crude oil atmospheric distillation unit to analyse the distribution of heat flux on the tubes of radiant section. The numerical model describes flow, gas combustion and radiative heat transfer inside the radiation section of the fired heater. Analysis of variations of heat flux on circumferential and longitudinal distribution on individual tube walls is executed comparing case of ideal (originally designed) tube coil geometry and tube coil containing typical real geometry imperfections (developed during years of operation). Results of heat transfer analysis confirm and quantify the significant effects of non-uniform heat flux distribution on individual radiant tubes negatively sharpened by geometry imperfections of tube coil. It is recognized, that fired heater design standards recommendations invoked in 1D design calculations of fired heaters are significantly underestimating real heat flux variability.

1. Introduction

Fired heaters for refinery processes are designed in accordance of relevant design standards. The American Petroleum Institute Standard 560 (API, 2007) is mostly used and thus can be considered as the dominant fired heater design reference worldwide (Jegla, 2008). Despite 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. While the average radiant section heat-flux rate is an 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 (Martin, 1998).

1.1 Motivation of study from fired heater design point of view

The significant variation of the real heat flux distribution around the length and circumference of fired heater tubes was studied in depth over the years by various authors resulting in estimation technique standardized in several updates of API Standard 530, with the latest version in (API, 2008). The calculation using the API Standard 530 (API, 2008) yields estimate of maximum tube temperature, which is a critical parameter for the safety and lifetime of the heater.
The maximum tube temperature is in design calculations estimated dominantly using the product of average radiant heat flux and several empirical correction factors, which can be insufficient for dependable decision support on the lifetime of tube systems under specific operating conditions. The purpose of the present work is thus to contribute to improving the accuracy of prediction of tube system lifetime through the analysis of real circumferential and longitudinal variation of heat flux inside standardly operated vertical cylindrical radiant section of fired heater designed by above mentioned API standards.

2. Description of analyzed fired heater

For numerical analysis purpose was taken typical vertical cylindrical fired heater (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.

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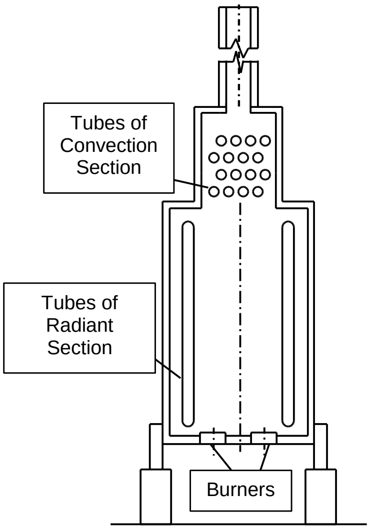

Figure 1: Sketch of vertical cylindrical fired heater arrangement

Figure 2: Important geometry imperfection in the bottom part of radiant coil

Radiant section of mentioned refinery fired heater and its tube system have been designed in accordance with the relevant abovementioned API Standards. Fired heater is of vertical cylindrical type (see typical scheme of such fired heater type in Figure 1) with nominal firing capacity of 24 MW and working in process of atmospheric distillation of crude oil. There are a total of six staged-gas burners vertically oriented and mounted on bottom of radiant section, equipped with guide-vane stabilizers (swirlers), each of nominal firing duty 4 MW.

Tubular system of radiant section is created by 60 tubes of outer nominal diameter 194 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 $L/D_C = 17/6.7 = 2.5$.

During years of fired heater operation the development of some imperfections of radiant tube coil geometry occurs. These imperfections are typical for most of long time operated fired heaters and consists of some kinds of deformations or deflection of some tubes from their original position. Figure 2 illustrates significant deformation which is far from designed conditions.

3. Modeling and measurement aspects of heat flux

Calculation prediction, modelling and measurement of heat flux variation in process and power combustion equipment are under continuing research and development activities academic and industrial research group. Brief discussion of the most important aspects from this areas is now performed in relation to our analysis.

3.1 Aspects of basic calculation prediction of heat flux variation

Design of fired heaters is generally performed for allowable average radiant heat flux, as one of the most closely watched design factors of fired heaters. Determining of average radiant heat flux (q_r) requires as first step to determine the radiant heat duty (Q_r). Its calculation generally depends on many factors, including the furnace geometry, combustion conditions and heated fluid temperature. For radiant section heat duty calculation are frequently used well-established, 1D generalized techniques, such as Lobo-Evans, Wimpress etc., as reviewed for example in (Couper et al., 2005). However, 1D techniques heavily rely on general and ideal assumptions regarding the shape of distribution of heat flux along length and circumference of tubes in coil. For instance, an influence of distance between wall surface of radiant section and placed tube centre is usually considered using so called view factor. In case of typical vertical cylindrical fired heater with radiant tube coil designed as one single tube row against the lining wall, when the distance between wall surface and tubes centreline is less than spacing of tubes, the view factor can be read from Figure 3a), according to ratio of tube spacing (s) and tube outer diameter (D). In this figure we also can see how much of the total value of view radiation factor of tubes (solid line) should come from direct radiation of flue gas (dashed line) and reradiation from lining wall (dotted line). When the radiant heat duty (Q_r) is determined, the average radiant heat flux (q_r) is obtained by dividing Q_r by the total radiant heat transfer area (A_r).

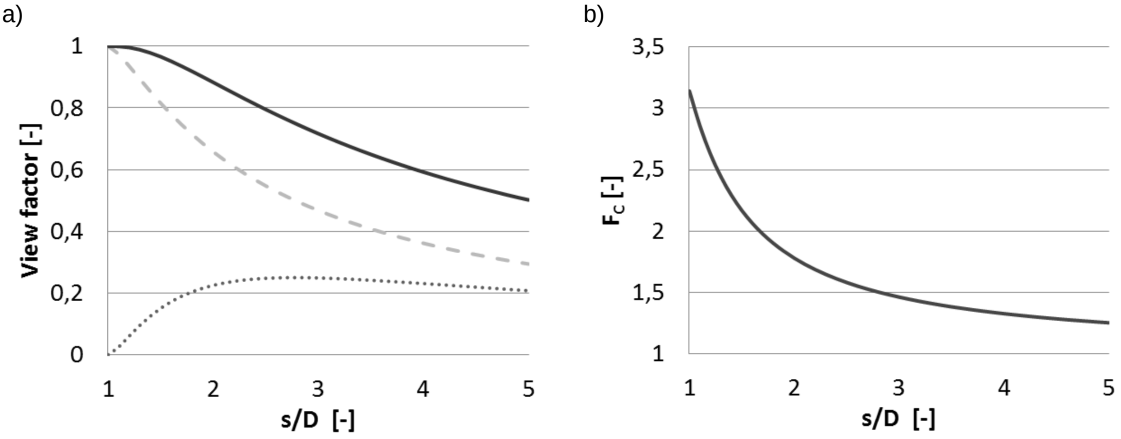

Figure 3: a) View factor for single tube row against the lining wall (solid line – total radiation, dashed line – direct radiation, dotted line – reradiation from wall), b) Tube-circumference heat flux variation factor F_C for single tube row against the lining wall (based on data from API, 2008)

The obtained average radiant heat flux (q_r) is then used for prediction of so-called local-maximum radiant heat flux q_m. According to API Standard 530 (API, 2008), the local-maximum radiant heat flux q_m can be calculated from average radiant heat flux q_r as follows:

$$q_m = F_C \cdot F_L \cdot F_T \cdot \left(q_r - q_{rc}\right) + q_{rc} \qquad (1)$$

where F_C is a tube-circumference heat flux variation factor, F_L is a tube-longitudinal heat flux variation factor, F_T is a tube-surface temperature heat flux variation factor and q_{rc} is the convective component of the average radiant section heat flux q_r.

Because the entire tube circumference is considered also in calculating q_r (as described in text above Figure 3) tube-circumference heat flux variation factor F_C tends to be in such 1D calculation somewhat higher. Factor F_C varies with tube spacing, as demonstrates Figure 3b).

Prediction of local-maximum radiant heat flux q_m from Eq(1) may be sufficient for the purpose of calculation of maximum radiant section tube skin temperature and tube material selection. However, for dimensioning of tubular system of radiant section (sizing of tube coil) and prediction of its thermal properties this is rather insufficient, because real heat flux distribution in radiant section strongly influences character of two-phase flow regimes of heated fluid in radiant tubes. Insufficient prediction of real distribution of heat flux in radiation section is frequently the source of important fired heater operating troubles, as described for example in (Jegla et al., 2011).

These problems stem from the known fact that accurate determination of individual correction factors F_C, F_L and F_T for Eq (1) is very difficult, since they depend on the fuel characteristics, combustion conditions, burner design, shape of flames and their interactions, arrangement and dimensions of radiant section and radiant coils, flue gas flow inside radiant section, etc.

The very promising 1D method for more accurate prediction not only local-maximum heat flux but also for variety prediction of local heat flux along height (length) of cylindrical radiant section seems to be method based on modified plug-flow model calculation technique utilizing for calculation actuall burner thermal behaviour obtained from experimental test of given burner on testing facility. Initial development stage of this predictive model (which is now under detail verification research) was presented by Jegla (2013).

3.2 Actual situation in fired heater numerical modelling methods and industrial experiments

Rigorous fired heater simulations reported in the literature have mostly concentrated on box or cabin types for various refinery processes. For example Oprins and Heynderickx (2003) studied radiation section of a thermal cracking furnace, while Lan et al. (2007) performed a coupled simulation of ethylene furnace and Hu et al. (2012) performed a coupled simulation of a naphtha cracking furnace equipped with long-flame radiation burners. Of these, only Lan et al. (2007) paid some attention to circumferential distribution of tube skin temperature and heat flux. In their case however, the tubes had flames on both sides.

Experimental works concerned with the measurement of heat flux in tubular furnaces and boilers have been mostly related with measurements and methods of measurement for the total heat flux along the

whole circumference of a tube. Even such measurements are however scarce, and robust methods for such measurements are not widely used as, among other, discussed e.g. in Taler et al. (2009), where new method to measure the local heat flux to membrane water-walls in steam boilers is proposed, however not applicable to the case of free standing tubes immersed completely in the radiating medium.
Measurements of tube skin temperature are obviously very demanding, too. Durable thermocouples do not offer sufficient spatial detail as well as accuracy. Optical methods are limited by direct visibility of the tube surface, making the measurement of circumferential profile of tube skin temperature very difficult. Even though interesting possibilities of 3D measurements in furnaces appeared recently (Cheng et al., 2014).
It therefore seems that rigorous numerical modelling is currently the best available technique to analyze in detail heat flux and tube skin temperature distribution on tubes in fired heaters, as, for example, recommended also Martin (1998).

3.3 Characteristics of applied numerical model

Computational procedure adopted for our analysis has been tuned for heat flux prediction in fired heaters as documented in (Vondál, 2012). It is based on application of best available techniques that are computationally manageable for the purpose of engineering computations.
Numerical model includes the reactive flow in the flames of the radiant section. Global single-step chemical mechanism is used to approximate the combustion reactions. Turbulence-chemistry interaction is included using eddy-dissipation model. Radiation is modelled by the discrete-ordinates method and absorption coefficient is determined by an updated weighted-sum-of-grey-gases model. Flow in the unit is unstable, caused mainly by precessing vortices of the flames and internal recirculation; thus simulation is performed in unsteady mode. Commercial system ANSYS FLUENT is employed for computations.
Boundary condition on the tube walls assumes a constant inner skin temperature, chosen in order to enhance direct comparability of data collected on individual tubes. Conduction in the tube walls is enabled in the radial direction as well as axially and tangentially (shell conduction). Shell conduction is enabled also in the wall of the furnace, and wall properties correspond to refractory bricks.
Radiant section's geometry and tube system geometric model of the studied fired heater closely resembles real situation of operated fired heater and has been designed with deliberate modifications of the nominal geometry that are observed in fired heater after a significant part of their lifetime. Thus the simulation not only enables to analyse the variability of heat flux distribution, study reasons that cause it, but also to analyse the effect tube coil deformations have on heat flux distribution.

4. Results

Tubular system of analysed radiant section represents two-passed tube coil created totally by 60 tubes (placed in one row around circular lining wall) with the constant outer diameter (D) 194 mm and with tube spacing (s) 350 mm. Nominal distance of tube centre from lining surface is (e) 232 mm. The ratio s/D is then 1.8 and $e < s$. The height of radiant section is approx. 17 meters. In order to simulate poor fixation of individual tubes of the tube coil, some of the tubes are moved from the nominal position closer or farther from the wall and/or to neighbouring tubes.
Results from 1D global heat transfer analysis using the abovementioned method of view factors give the following main data about tube-circumferential heat flux variation. The flame-side maximum local heat flux is predicted at 172 % of average heat flux, wall-side minimum local heat flux is predicted at 58 % of average heat flux.
The variability of circumference local heat flux predicted by CFD simulation is however much higher than in the 1D design calculation. Flame-side peak heat flux is 332 % of average heat flux, while wall-side minimum is 16 % of average heat flux. This means that variability of the heat flux predicted by CFD simulation is about two times bigger than that predicted by a standard 1D model.
Resulting heat flux profile around the circumference of individual tubes presented below are taken from a level 5 m above the floor of radiant section, which is the height with peak heat flux as documented by Figure 4b. Figure 4a displays a polar plot of typical heat flux profile around tube in nominal location (also neighbours in nominal positions). Circumferential tube heat flux profiles predicted by the CFD simulation varies significantly among individual tubes even at the same height, as flow in the furnace is complex, recirculating and non-symmetrical.
When we predict local-maximum heat flux (q_m) for analysed radiant section using 1D model by Eq(1) with values of heat flux variation factors $F_C = 1.9$, $F_L = 1.1$ and $F_T = 1.0$, as recommended API (2008) we get a value $q_m = 55.64$ kW/m^2.
However, from Fig. 4b it can be seen that CFD analysis gives a value of maximum peak of heat flux profile in radiant section (i.e. max. value of solid line profile in Figure 4b) higher by more than 40 % (and absolute

local maximum heat flux, i.e. the place on “top” of the error bar profile in place of maximum in Figure 4b gives value higher by 70 %!).

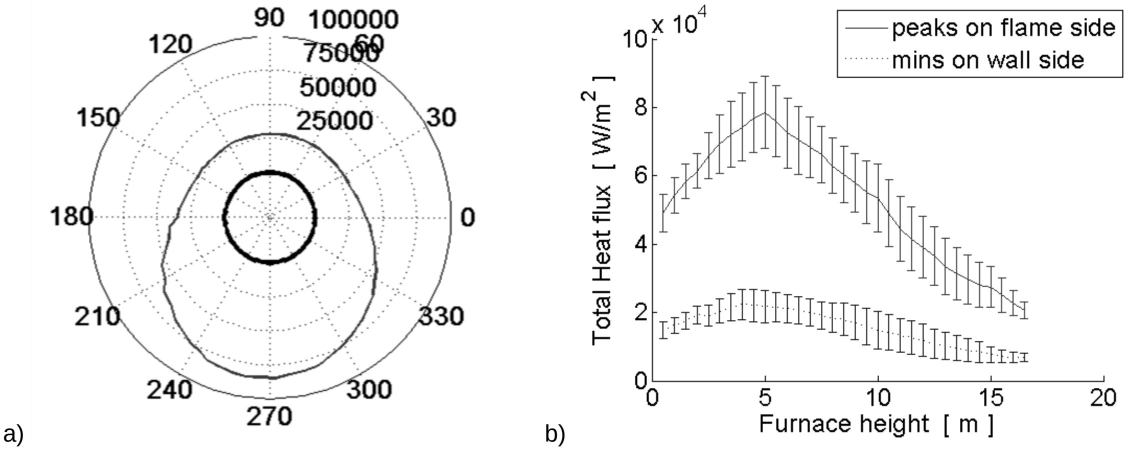

Figure 4 a) Tube circumferential total absorbed heat flux variation (values in W/m^2) on level 5 m from floor of radiant section (tube in nominal position), b) vertical (i.e. longitudinal) variation of total heat flux with error bars displaying standard deviation in half-metre horizontal sections

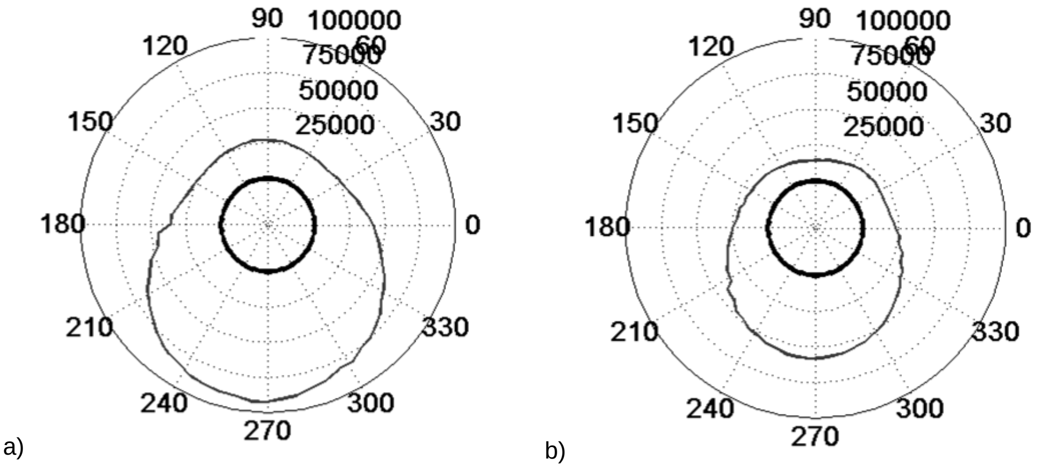

Figure 5 Tube circumferential total absorbed heat flux variation (values in W/m^2) on level 5 m from floor of radiant section, a) tube closer to flame than nominal, b) tube closer to wall

Historically, a maximum L/D_C ratio of 2.7 was considered good design practice to minimize heat flux variation in radiant section, as reported by Martin (1998). For such good shapes of radiant section, the values of tube-longitudinal heat flux variation factor F_L are recommended by (API, 2008) in range from 1.0 to 1.5. However, many operated fired heaters is designed above 3.0 L/D_C ratio of radiant section (typically cabin types of fired heaters). Such designs are classified as long, tall or narrow and have large heat flux variation (Martin, 1998). For such shape of radiant sections API (2008) recommends to use values of F_L factor above 1.5.

Radiant section shape (i.e. ratio of L/D_C) influences not only heat flux variation, but also overall fired heater economy (investment and operating costs) as reported by (Jegla, 2006) who identifies for given economic situation radiant section of vertical cylindrical fired heater with optimum ratio of L/D_C = 2.4.

Additionally to previous information, the above presented results of our numeric analysis for radiant section with L/D_C ratio 2.5 show (especially Figure 4b) that utilisation of staged (i.e. low-NO_x) burners can dramatically influence the heat flux variation even of such good shape radiant section. The maximum local heat flux variation obtained by CFD simulation (i.e. max. value of solid line profile in Figure 4b) show that for appropriate prediction of value of maximum local heat flux by 1D method through Eq(1) recommended by (API, 2008) it is necessary to use value of F_L factor higher than 1.5 (strictly speaking from range 1.5 to

1.6). Such value, however, is recommended by API (2008) to use in case of long, tall or narrow radiant sections only (as discussed above).

Two examples of typical geometry imperfections, i.e. tubes that are slightly shifted by D/2 towards the flame and to the wall, respectively, are presented in Figure 5. The influences of these geometry imperfections on circumference heat flux profile are clearly obvious from comparison with situation of the same tube without any geometry imperfection presented in Figure 4a. More detailed discussion of wall-tube distance influence on circumference heat flux profile is performed by Hájek et al. (2014).

5. Conclusions

Typical vertical cylindrical fired heater with staged gas burners operated in crude oil atmospheric distillation unit is simulated numerically to analyse the distribution of heat flux on the tubes of radiant section. Results are compared with classic standardized fired heater design calculations and significantly greater variability is revealed. Attention is also focused on the qualitative and quantitative impact of some typical real geometric imperfections often present in real tube coils. Results provide information allowing the critical assessment of the classical fired heater design methods and some of the assumptions and design standards recommendations involved in those design methods. Classic design calculation method has been shown to be optimistic regarding heat flux uniformity on the radiant section tube coil.

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