DESIGN AND OPERATING ASPECTS INFLUENCING FOULING INSIDE RADIANT COILS OF FIRED HEATERS OPERATED IN CRUDE OIL DISTILLATION PLANTS

Z. Jegla, J. Kohoutek and P. Stehlik

Brno University of Technology, Institute of Process and Environmental Engineering,
Technicka 2, 616 69 Brno, Czech Republic, E-mail: jegla@fme.vutbr.cz

ABSTRACT

Crude oil heated in a fired heater flows inside tube coil consisting of two distinct sections: a convective section and a radiant section. While the flow of fluid in coil of convective section is one-phase liquid flow, the fluid flow inside radiant tube coil is accompanied by boiling and evaporation process, i.e. two-phase flow occurs there. Fouling process on the fluid side of radiant tube coils causes several problems which make outwardly as operating troubles of different kind according to operating conditions and type of application (distillation).

The most frequent problem associated with fouling is rapid deposition of coke in tube coil resulting in fast increasing of fluid pressure drop and necessity of the plant shut down and decoking of fired heater. Another problem is undesirable cracking of fluid especially in fired heaters of vacuum distillation plants. Cracking process results in formation of light cracked products, which burden a vacuum system of distillation plant and influence quality of products and also in formation of carbonaceous and coke deposits which adversely influence plant operation. Both above mentioned and often interrelating problems are usually caused by too high or non-uniform heat flux of radiant coil or low fluid flow velocity or combination of both.

The contribution discusses the most important design and operating parameters influencing fouling process in radiant tube coils and through industrial examples documents disposable tools of designer and operator and also limitations of designer and operator which restrict possibilities of fouling process mitigation inside radiant tube coils.

INTRODUCTION

Fired heaters operated in crude oil distillation plants are large and complex items. Two main types of fired heaters are used.

Cabin (or box) heater type, as those shown in Fig. 1, is preferred for large heat duty applications (approximately 20 MW and more) and contains horizontally oriented tubes (or tube banks) in both radiant and convection parts of heater.

Vertical cylindrical heater type, as those shown in Fig. 2, is preferred for small and or medium heat duty applications (below 20 MW) and contains vertically oriented tubes in radiant chamber and horizontally oriented tubes (or tube banks) in convection parts of heater.

Following further description of individual parts of fired heater (of two above mentioned types) and operating parameters gives us an idea about situation and basic possibilities of designers (and operators) with relation to fouling process inside and outside tube coils.
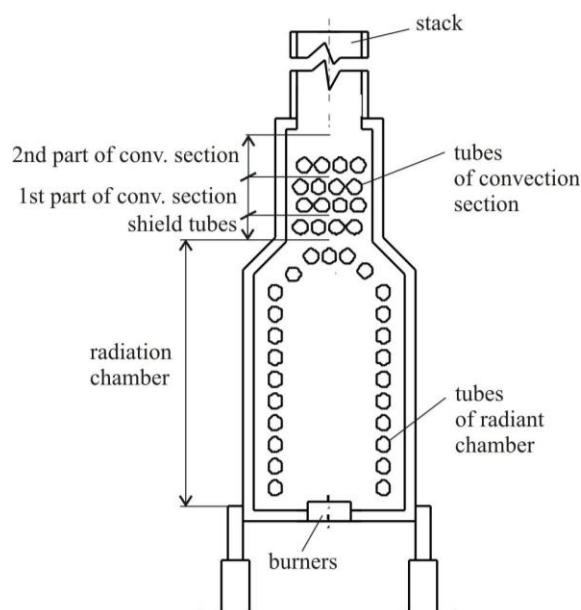

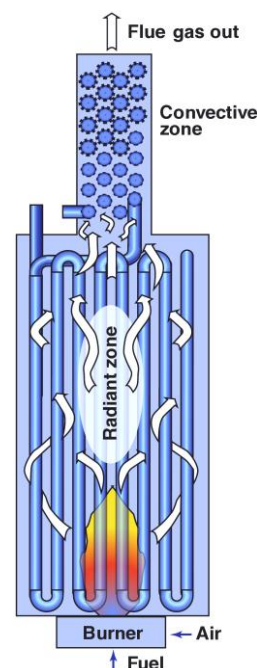Fig. 1 Cabin type of fired heater (according to Jegla, 2006).

Fig. 2 Vertical cylindrical heater (according to Pelini, 2008).

Fired heater parts and operating parameters

Arrangement and design of individual parts (tube coils and tube banks) of fired heaters (together with operating parameters of heated hydrocarbon fluids and combustion products) dominantly influences their tendency to fouling from inside and outside of the tubes. Following description presents typical situation in fired heaters operated on atmospheric and vacuum crude oil distillation plants.

Radiation (combustion) chamber

In the radiation chamber takes place the combustion of fuel on burners, which leads to very high flue gas temperatures (reaching 900 to 1,500°C). Tubes usually located close to cabin walls are exposed to high heat fluxes and to radiation-convection mechanisms of heat transfer with dominant radiation component. These high flue gas temperatures (due to burn-off and direct effect of fouling components) do not allow applications of extended surfaces or any other techniques of heat transfer enhancement and compact solutions. The only feasible method is to use plane surfaces (i.e. plane tubes). It is possible to optimize their location with respect to economically effective utilization of released heat by tube system in radiation chamber (Jegla, 2008).

Crossover from radiation chamber to convection section– the shield section

Part of tube coil(s) which is located in flue gas stream between radiation chamber and convection section is called shield tubes (or shield section). This part of tube system is the most exposed part of the heater tube system since due to common action of radiation heat flux from radiation chamber as well as intensive convection flue gas heat flux coming from radiation chamber to convection section. Flue gas temperatures at the crossover between radiation and convection sections typically range from 900 down to 700°C, they are obviously lower than in radiation chamber. However, intensive heat transfer disables practical application of enhanced and compact solutions mostly due to heat transfer surface burn off. This section then also enables only plane surface solutions (i.e. plane tubes) (Jegla, 2006)

First part of heater convection section

First part of heater convection section is located in the area of convection section above the shield section in the area of flue gas temperatures reaching from 500 to 700°C. Lower values of flue gas temperature pertinent to decreasing influence of radiation component. This section enables enhanced (compact) solutions depending on fouling and burn off properties of flue gas. If there is no risk of fouling, application of fins is feasible and achieving of "compact" design can be possible. If there is any chance of fouling by flue gas, lower degree of heat transfer enhancement can be used, such as studded surfaces (studded tubes) (Jegla, 2006).

Second part of heater convection section

First part of heater convection section is followed by second part of heater convection section which is located in the area of flue gas temperatures reaching from 300 to 500°C. Actual value of lower boundary of the mentioned flue gas temperature region is influenced by temperature differences between heater inlet temperature of heated fluid (i.e. into second convection section) and heater outlet flue gas temperature – see diagram in Fig. 3. (Typical inlet temperature of fluid heated inside heater tubes, ($T_{f,inlet}$), ranges for example in case of heaters for atmospheric and vacuum distillation of crude oil typically from 250 to 350°C. Thus, outlet flue gas temperature from this section ($T_{fg,outlet}$) reaches from 300 to 350°C.)

It can be note that in this convection section (flue gas temperature range) it is usually possible to full utilization of potentials of compact and enhanced solutions respectively with respect of consider compact and enhanced solution (with respect to fouling properties of flue gas).
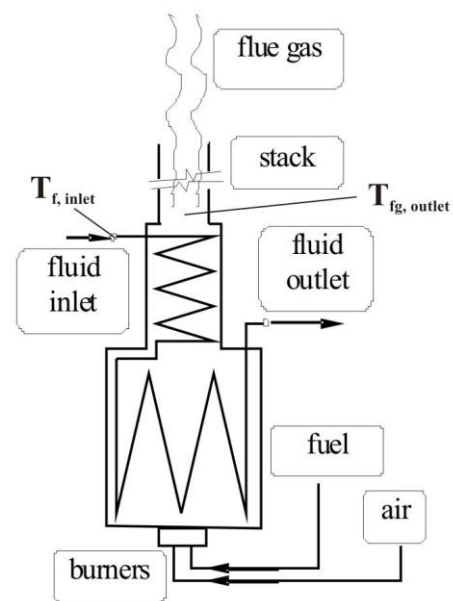

Fig. 3 Typical flow scheme of fluids in fired heater.

Depending on possibilities (with respect to fouling properties of flue gas), it is possible to obtain here even higher degrees of compactness since burn off is no longer a problem in this temperature range. Thus, higher density of fins or studs can be applied than in first part of furnace convection section. However, the selection of a concrete degree of compactness or enhanced solution should be supported by results of operating and technical and technical-economic balances (optimization) (Jegla, 2006).

Utilization of flue gas waste heat from heater

Flue gas usually comes out of furnace convection section with temperature reaching 300°C. Potential of flue gas temperature utilization (approximately 300-150°C) greatly depends on temperature of flue gas dew-point.

Effective utilization of this type of low potential waste heat requires compact or enhanced solution depending again especially on flue gas fouling properties. This type of heat is commonly used for preheating of combustion air for furnace burners, which allows to importantly reducing the amount of noble fuels (Jegla et al., 2005).

FOULING PROCESS INSIDE RADIANT COIL OF REFINERY HEATERS AND ASPECTS OF ITS MODELLING

Arrangement of flow of oil heated in fired heaters operated on atmospheric and vacuum distillation plants is schematically shown on Fig. 3. Oil firstly enters to second part of heater convection section and then flows inside convective tube bank systems in counter-current direction to flue gas.

Oil preheated by this way than though the crossover tubes flow to the radiant chamber. Here the arrangement of the flow of crude oil is dictated by the technical possibilities and requirements not only from thermal-hydraulic point of view of heated crude oil but also by the distillation column and connection pipelines (so called transfer lines) requirements.

Thus in case of cabin type of heater the crude oil can flow from "top" to "bottom" of radiant chamber and/or from "bottom" to "top". Moreover the most of applications is processed for large capacities and thus the multi-pass arrangement of radiant (and convection) tube coils systems is necessary. This requirement importantly influences especially arrangement of radiant coil system. As illustration of this aspect, Fig. 4 and 5 show the typical multi-pass arrangements of tube system in refinery fired heater for six-pass and four-pass and cases.
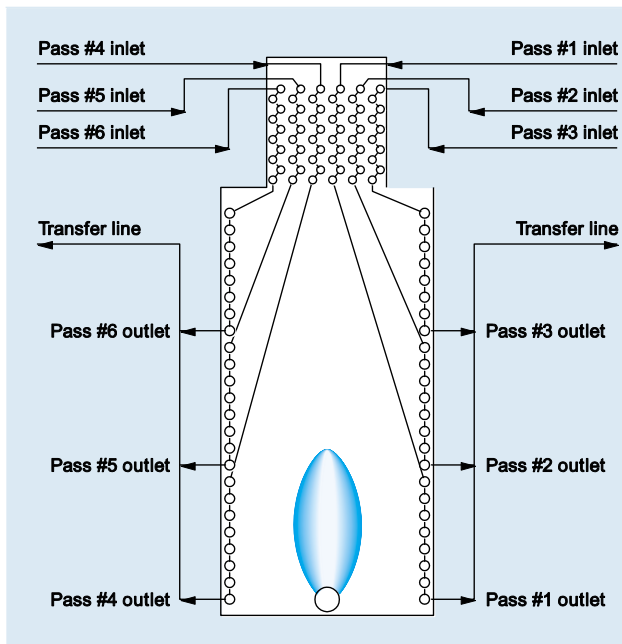

Fig. 4 Typical six-pass arrangement of (crude) fired heater (Martin, 1998).

Oil preheated in the convection section of heater is still in liquid-phase only. However, during flow in radiant section the oil starts boiling and vaporization, because the role of heater is to preheat and prepare (i.e. evaporate) oil to requirements of distillation column. The presence of two-phase fluid flow inside the radiant coil plays an important role in relation to modeling of fouling process of oil inside radiant coils of heater.
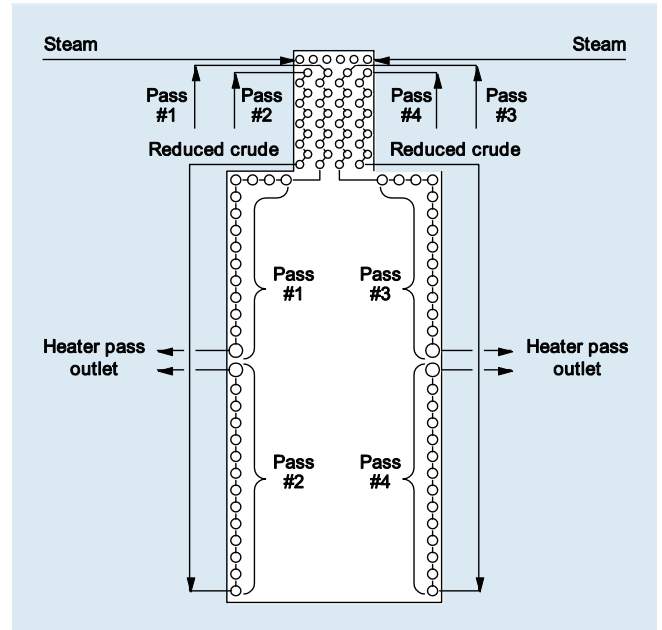

Fig. 5 Typical four-pass arrangement of (vacuum) fired heater (Martin, 1998).

Fouling inside radiant coils take effect in the form of rapid deposition of coke from the oil in tube coil. The presence of coke results in fast increasing of fluid pressure drop and necessity of the plant shut down and decoking of fired heater. Another result is the appearance of hot spots and overheating of tube resulting to tube failure. Fig. 6 demonstrates the effect of coke (fouling) layer on tube metal temperature in comparison with the case without presence of coke on example of radiant tube from crude vacuum heater.
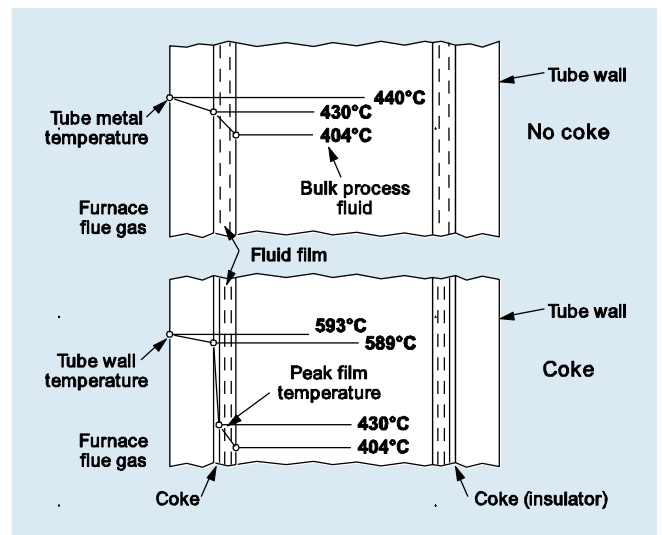

Fig. 6 Effect of presence of coke layer on tube metal temperature of vacuum heater radiant tube in comparison with situation without presence of coke layer (according to Martin, 1998).

Another problem associated with fouling is undesirable cracking of oil especially in fired heaters of vacuum

distillation plants. Cracking and coking bring from operating point of view following typical problems.

Oil cracking in crude vacuum units typically causes:
- Production of non-condensable gases which can cause flooding of existing vacuum systems or an enormous investment cost of a new vacuum system;
- Deterioration of products quality (viscosity index and stability of products);
- Heavy cracking coke particles could be found in the bottom product with all the disagreeable consequences.

Oil coking means deposits in the tubes which lead to:
- Higher metal (surface) temperature of tubes, which can cause tube walls to fail prematurely;
- Higher pressure drop due to reduced (by deposit) tube cross flow area;
- Parts of coke could peel off and accumulate inside the column.

From above observations it is clear that the fouling inside the radiant coils is caused by chemical reaction of the oil with the hot tube surface. Current models for modeling of fouling caused by chemical reaction in oil refining processes (Wilson et al., 2002) are based on interaction of "deposition" and "removal" term and with increasing complexity continuing the development started by first research works (Nelson 1934; Kern and Seaton, 1959; Watkinson and Epstein, 1969;etc.).

However, models are focused on fouling of oil in the liquid phase only which is the most frequent case in heat exchanger oil preheat trains. Moreover, models are based on constant heat flux, constant mass flow rate and the bulk fluid temperature of oil. Thus, in case of radiant coils of fired heaters and two-phase flow of heated oil the application of these models is limited and indicative only. An important observation made by Atkins (1962) was that in the fired heater tubes fouling deposits appeared as two layers; an outer porous and a hard crust of deposit next to the tube wall.

In practice, the heater designers and operators work with strongly limited tools for design and operation of fired heaters from oil fouling point of view. The most important aspects will be now discussed.

DESIGN AND OPERATING ASPECTS OF HEATERS INFLUENCING FOULING INSIDE RADIANT COILS

Chemical reaction of oil fouling inside radiant coil is dependent mainly on the oil composition, temperature and residence time in the radiant coil. Other words, in term of thermal-hydraulic parameters, it can be state that oil composition influences the actual flow conditions (evaporation of oil, oil activation energy, etc.) at given operating parameters (i.e. pressure, temperature), oil film temperature is influenced by heat flux and oil film heat transfer coefficient and oil residence time is function of oil velocity (which is influenced by tube size and actual flow conditions). Main important identified parameters influencing the oil fouling process will be now further discussed.

Bulk vs. film temperature

Oil flowing inside radiant coil is heated by the tube metal temperature driven by the heat flux from hot flue gas outside the coil. Generally the heat input rate is controlled to achieve desired bulk oil temperature exiting heater. However, in being heated to the required outlet, the oil film in contact with the inner heating tube surface is always exposed to a higher temperature than the bulk oil. In the most applications it is the oil film temperature, not the bulk oil temperature, which limits the duty of the heater and usable life of the oil (Pelini, 2008).

The bulk oil temperature at the outlet of the heater is easily measured and it is usually the process variable used to control the heat input to heated oil. In contrast to bulk temperature, the oil film temperature is not usually measured directly, and it has to be calculated by the heater designer.

In the given local part of radiant coil the oil film temperature (T_f) can be calculated from oil bulk temperature (T_b) and film temperature rise (ΔT_f) as follows:

$$T_f = T_b + \Delta T_f = T_b + q_{ri}/h_i \tag{1}$$

where q_{ri} is a local heat flux to radiant coil (local radiant heat flux) and h_i is a film heat transfer coefficient.

Thus, this equation gives us clearly answer why the two different heaters (i.e. with different q_{ri} and/or h_i) operated with the same duty, oil flow rate and heater bulk oil outlet temperature may have significantly different film temperature profiles.

There is also, in refinery practice, very frequent case when heater placed in refinery unit is operated alternately for heating two or more similar types of oils for the same duty (processing of several crude oils from different suppliers). Moreover, operation of one heater with alternately heated two similar types of oils for the same duty and bulk inlet/outlet temperatures can have (due to slightly different oil composition) significantly different bulk temperature profiles. For demonstration this fact the Fig. 7 and Fig. 8 show the oil bulk temperature profile of two alternately heated oils in the radiant coil in case of crude vacuum heater.
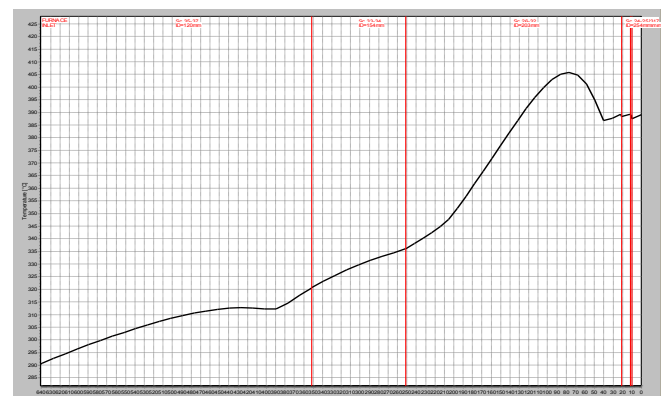

Fig. 7 Illustrative software screen: bulk temperature profile for "oil 1" heated in radiant coil of crude vacuum heater (x-axis: radiant coil length, y-axis: bulk temperature).

As can be seen from Figures 7 and 8, oil composition (properties) importantly influences oil bulk temperature profile.

Fig. 8 Illustrative software screen: bulk temperature profile for "oil 2" heated in radiant coil of crude vacuum heater (x-axis: radiant coil length, y-axis: bulk temperature).

Moreover, heat requirements for simultaneous heating and evaporation of some oils are (for given flow and tube size) too high in some local parts of radiant coil and the heat flux can not cover local heat requirement. Such situation results in appearance of temperature "peak" on bulk temperature profile in these local parts of radiant coils, as can be seen from example on Fig. 7.

Film heat transfer coefficient

Mentioned equation for oil film temperature contains the heat transfer coefficient (h_i). This thermal parameter generally depends on oil properties and oil flow regime and velocity. In case of heating of oil in one phase (i.e. liquid only or gas only) the determination of film heat transfer coefficient is relatively reliable. However, determination of film heat transfer coefficient for two-phase oil flow is complicated and unreliable. Therefore, some heater design standards (for example API Standard 530, 2003) recommend for determination of two-phase film heat transfer coefficient an approximate solution. However, these approximations are very rough (and suitable for tube material selection purposes only) and don't reflect real situation of flowing oil. In contrast of this, the theoretically derived correlations for accurate determination of two-phase oil film heat transfer coefficient are too complicated and, moreover, results are significantly differ author from author.

Table 1. Comparison of results of correlations for film heat transfer coefficient for nucleate boiling of light oil (adapted from Hewitt, et al., 1994).

Author(s) of Correlation	Film heat transfer coefficient [W/(m^2.K)]
Foster-Zuber	5,512
Rohsenow	1,182
Mostinskij	2,528
Bier et al.	5,134
Cooper	23,212

As example demonstrating typical situation in determination of two-phase film heat transfer coefficient the Table 1 (adapted from Hewitt et al, 1994) comparing film heat transfer coefficients for nucleate boiling of light oil calculated according to different authors, is presented.

Thus, the calculation of two-phase film heat transfer coefficient still depends of heater designer experience and actual correlation preference.

Two-phase oil flow regimes and velocity profile

Two-phase flow of heated oil inside heater radiant coil is accompanied by boiling and increasing of oil evaporation. Thus, the simultaneous and continuous changes of two-phase flow regime are a result of this heating process. The orientation of tube coil significantly influences the own nature and character of changes of these two-phase flow regimes. Moreover, individual two-phase flow regimes (for example bubble flow, slug/plug flow, churn flow, annular flow, mist flow etc.) are accompanied by significantly different values of film heat transfer coefficient. In case of vertically oriented radiant tubes (i.e. vertical cylindrical heater, Fig. 2) some undesirable two-phase flow regimes cannot arise (for example stratified flow). However, their appearance can flourish in case of two-phase flow inside horizontally oriented radiant tubes (i.e. cabin type heater, Fig. 1) improperly sized (or operated significantly out of heater design).

Appearance of such undesirable two phase flow regimes is the reason for local overheating of some parts of radiant tubes (due to low film heat transfer coefficient) due to absence of liquid film on some parts of inside surfaces of radiant tubes.

However, on the other side, proper design of radiant coil for achieving the "safe" two-phase oil flow regimes (such as annular two-phase flow) cannot be the reliable solution from fouling point of view, when the (liquid) film heat transfer coefficient (in relation to local heat flux) is not sufficiently high.

For example of this, Fig. 9 shows the heavy fouled (coked) radiant tube of crude vacuum heater caused by the annular two-phase flow regime characterized by not sufficiently high film heat transfer coefficient, and thus, by exceeding the limiting oil film temperature.

Fig. 9 Heavily fouled (coked) radiant tube of vacuum crude oil heater.

Moreover, velocity profile of two-phase (and or single phase) flow in radiant tubes is also significantly deformed by local flow resistances (i.e. bending) caused by presence of 90° or 180° elbows presented in radiant tube coils.

The Fig. 10 shows the formation of velocity profile and flow in a 90° curved tube. The maximum velocity (v_m) is (in comparison with average velocity, v_a) displaced to the outside due to wall friction influences and transverse eddies arise.
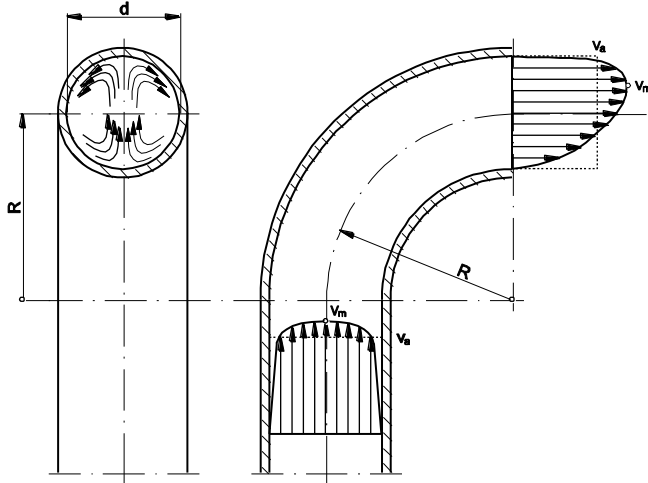

Fig. 10 Formation of velocity profile and flow in a 90° curved tube (according to Wagner, 1997).

Deformation of flow and velocity profile can in conjunction with local heat flux of the elbow lead to the fouling (coking) inside the elbow in the part with low oil velocity. Fig. 11 documents this fact on the concrete example of heavily coked a 90° curved tube from the radiant coil of crude vacuum heater.

Fig. 11 Heavily fouled (coked) 90° curved tube from the radiant coil of crude vacuum heater.

Average vs. maximum radiant heat flux and radiant heat flux imbalance in heater

Generally, the refinery fired heaters are designed for allowable average radiant heat flux (q_r). However, radiant section (radiant chamber) average heat flux is not a good indicator of fouling (coking) potential of most heaters. First step in the determination of average radiant heat flux is a determination of the radiant heat duty (Q_r).

In generals, the calculation of Q_r depends on many factors including the furnace geometry, combustion conditions and fluid temperature. Detailed procedures for radiant section calculation are beyond the scope of this paper, but there are well-established quasi-theoretical techniques for determining radiant chamber performance (for example Wimpress, 1978).

Once, the radiant heat duty (Q_r) is calculated, the average radiant heat flux (q_r) is the Q_r divided by the total radiant heat transfer area (A_r). The heater vendor reports the purchaser the average and local-maximum radiant heat flux. In simplified form it can be state, that local-maximum radiant heat flux q_m can be related to average radiant heat flux q_r as follows:

$$q_m = F_C \cdot F_L \cdot F_T \cdot q_r \qquad (2)$$

where F_C is a tube-circumference heat flux variation factor, F_L is a tube-longitudinal heat flux variation factor and F_T is a tube-surface temperature heat flux variation factor. In case of API heaters, the determination of local-maximum radiant heat flux q_m is more complicated task than is presented above and is described, for example in (Pelini, 2008).

The determination of individual correction factors F_C, F_L and F_T is a very difficult to quantify accurately, since there depends on the fuel characteristics, burner design, flame length, combustion conditions, arrangement and dimensions of radiant chamber and radiant coils, flue gas flow inside radiant chamber, etc.

For example, the API Standard 530 (2003) helps the furnace designers by the simplified recommendations in form of useful graphs for suitable and quick choice of values of above mentioned individual correction factors based on dominant influencing parameters.
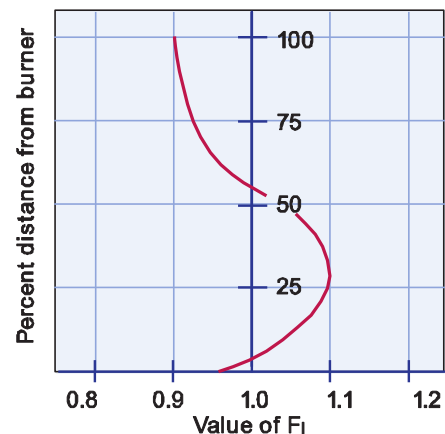

Fig. 12 Variation of F_L correction factor for typical heater application with classic burners (according to Pelini, 2008).

However, variation of values of individual correction factors is considerable and heater designer in the design (and or rating) heater solution stage is not able to accurate quantify these factors for actual solved heater application. It

can be clearly illustrated on example of variation of tube-longitudinal heat flux factor F_L, through Figs. 12 and 13 demonstrate in simplified manner its depending on burner type and combustion conditions.
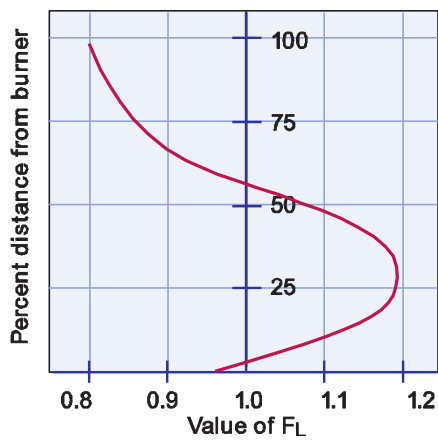

Fig. 13 Variation of F_L correction factor for heater using high intensity burners with short flames (according to Pelini, 2008).

As can be seen from Figs. 12 and 13, the typical local-longitudinal maximum radiant heat flux is obviously in first one third of radiant chamber height (from chamber bottom). However, from own experience, the importantly different cases of heaters are known, where the local-maximum radiant heat flux was identified at top of radiant chamber as a result of combination of combustion process fluctuation on number of burners and changed flue gas flow through radiant chamber influenced by transverse eddies arise.

Computational prediction of such real situations in radiant heat flux distribution is very limited, expensive and requiring highly experienced engineer specialised on numerical heater modelling. Moreover, such computational prediction can be performed in some specific cases only, using Computational Fluid Dynamic (CFD) calculations, when burners detail design and operation (necessary for CFD simulations) are known and achievable.
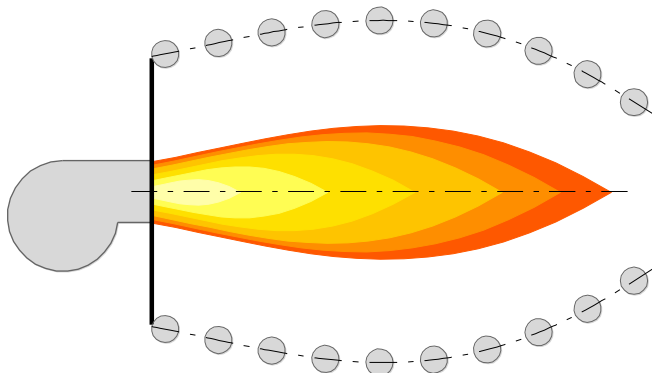

Fig. 14 Equalization of heat flux along the flame zone by adapting heating surface to flame shape (from Wagner, 1997 - adapted for refinery heaters).

From above discussion it is clear, that theoretically derived solutions of equalizing of radiant heat flux in whole

radiant chamber heat transfer system (see Figs. 14 and 15) are not practically applicable in crude refinery heaters due to thermal-hydrodynamic requirements of oil flowing inside tubes and current combustion, design, operating and realisation technical limitations.
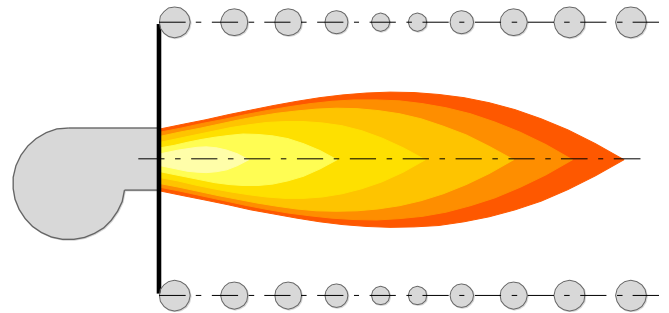

Fig. 15 Equalization of heat flux along the flame zone of cylindrical shape by changing the tube cross-section (from Wagner, 1997 - adapted for refinery heaters).

Due to above mentioned aspects; the real operating of refinery fired heaters is accompanied by more or less significant heat flux imbalances. However, radiant heat flux imbalances can cause high fouling (coke) formation rates and high tube metal temperatures.
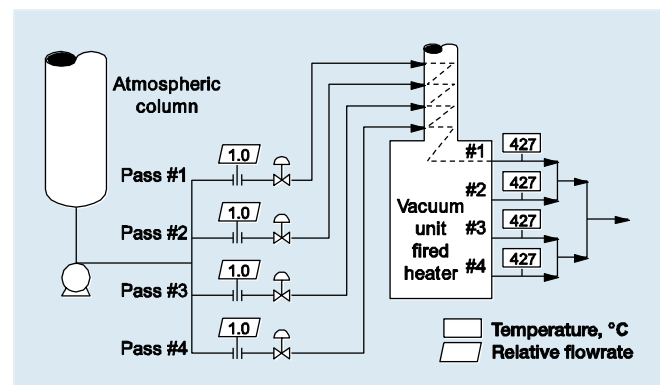

Fig. 16 Ideal crude vacuum heater performance characterized by equal pass flow rates and equal outlet oil bulk temperatures (according to Martin, 1998).
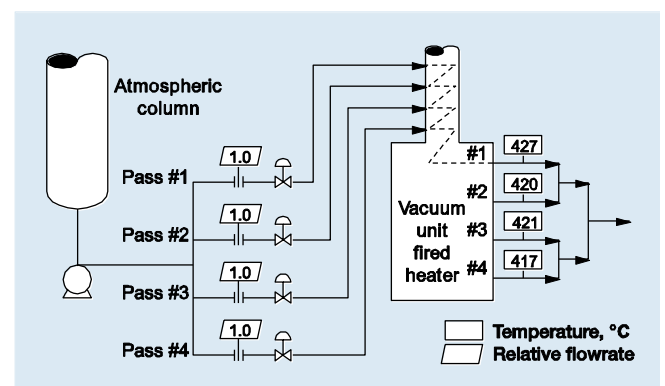

Fig. 17 Typical situation of vacuum crude heater with heat flux imbalances - equal pass flow rates produce different outlet oil bulk temperatures (according to Martin, 1998).

These imbalances reduce unit capacity, lower distillate yields or require unscheduled and premature heater shutdowns to remove the coke, all of which affect refinery profitability, as discussed in detail by Martin (1998).

Operation of multi-pass arrangements of high capacity heaters influenced by important a heat flux imbalance (see Figs. 4 and 5) is very difficult. Operators of such heaters can practically to solve the situation only by heater pass balancing in relation to measured heated oil heater outlet (bulk) temperatures. Situation is demonstrated through Figs. 16, 17 and 18 on example of crude vacuum heater operation. Fig. 16 presents ideal situation of heater operation. Due to presence of heat flux imbalances to individual passes the usually real situation in heater operation is presented in Fig. 17. For equalizing of oil bulk temperatures at heater outlet operators have to make pass balancing. Successful pas balancing is demonstrated in Fig. 18. However, in some cases, the pass balancing within allowable control range of individual pass flow is not successful, as demonstrated in Fig. 19. Such situations usually lead to heater revamp requirement.
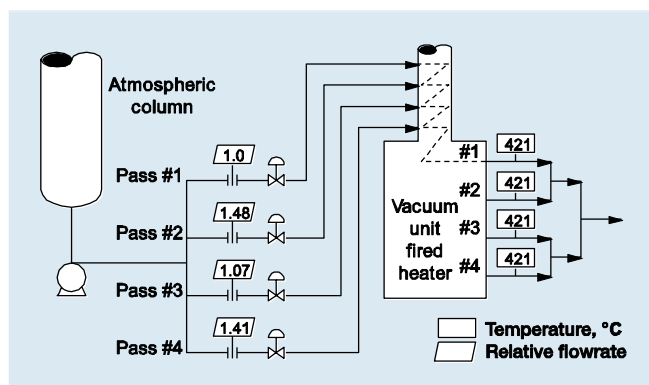

Fig. 18 Successful vacuum crude heater pass balancing – the flows through each heater pass are balanced to produce the same oil bulk outlet temperatures (according to Martin, 1998).
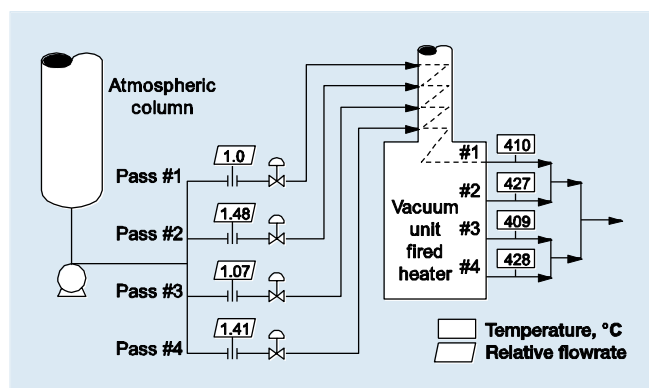

Fig. 19 Unsuccessful vacuum crude heater pass balancing – the flows through each heater pass are unsuccessfully balanced to produce the same oil bulk outlet temperatures (according to Martin, 1998).

CONCLUSION

Paper discusses the most important design and operating parameters influencing fouling process in radiant tube coils of fired heaters operated in crude oil distillation plants. Through industrial examples paper documents disposable tools of heater designers and operators and also limitations of designers and operators which restrict possibilities of fouling process mitigation inside radiant tube coils.

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