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RESEARCH ARTICLE

Simulation of heat transfer in the convection section of fired process heaters

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Abstract

Heat transfer analysis of the radiation section in a fired process heater was carried out in order to determine the flue gas and process fluid temperatures in the zone separating the convection and the radiation sections. Such a determination is a pre-requisite for the heat transfer analysis of the convection section.

A Matlab computer programme for the heat transfer analysis of the convection section was written and the results presented graphically including process heat load, the amount of absorbed heat per layer in the convection section and the temperature profiles of combustion gases, tube wall and process fluid.

Keywords

Fired heater · flue gas temperature · convection section.

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1 Introduction

Fired heaters are a versatile class of equipment whereby fluids flowing in tubes mounted inside the furnace are heated by gases produced by the combustion of a liquid or gaseous fuel. These heaters are widely used in petroleum refining and other chemical process industries.

Fired heaters are built with two distinct heating sections: a radiant section in which process fluids are directly heated by radiation from the flame, and a convection section in which hot flue gases leaving the radiation section circulate at high speed through a tube bundle. Heat is recovered from the flue gases and transferred, chiefly by convection, to the process fluid, increasing thereby the overall thermal efficiency of the fired heater which is dependent to a large extent on the effectiveness of the recovery of heat from the flue gases [1]. Given that the thermal efficiency depends also on the size of the heat exchange surface area in the furnace, the efficiency may be further increased by the use of finned or studded tubes in the convection section in order to increase the heat transfer area.

Fired heaters are usually classified as cylindrical or box-type heaters depending on the geometrical configuration of the radiant section or combustion chamber. In the cylindrical-type furnace, the radiation section is in the shape of a cylinder with a vertical axis, and the burners are located on the floor at the base of the cylinder. The heat exchange area covers the vertical walls and therefore exhibits circular symmetry with respect to the heating assembly. In box-type heaters, the radiant section has generally a rectangular or square cross section where the tubes may be arranged horizontally or vertically and the burners are located on the floor or on the lower part of the longest side walls where there are no tubes.

2 Heat transfer mechanisms in fired heater:

Heat is transferred in a fired heater by both convection and radiation in both sections of the furnace, where radiation is the dominant type of heat transfer in the radiant section and convection predominates in the convection section as the average temperature in this section is much lower. In both sections, the heat-absorbing surface is the outside wall of the tubes mounted inside the heater.

The total heat transfer to the process fluid can be estimated by the following equation:

$$Q_{\text{total}} = U_{\text{c}} \cdot A \cdot \text{ LMTD} \tag{1}$$

The radiant heat transfer follows the relationship:

$$Q_{\text{r}} = \sigma \cdot \left(\alpha \cdot A_{\text{cp}}\right) \cdot F \cdot \left(T_g^4 - T_w^4\right), \tag{2}$$

and convective heat transfer follows the relationship:

$$Q_{\text{conv}} = h_{\text{conv}} \cdot A_{\text{t}} \cdot \left(T_g - T_w\right) \tag{3}$$

3 Thermal evaluation of the convection section

The convection section must make up the difference between the heat duty of the furnace and the part absorbed in the radiant section. By means of using finned tubes in the convection section it is often possible to attain heat flux in the convection section that is comparable to that in the radiation section.

The bases for the calculation of heat transfer in the convection section were laid for the first time by Monrad [2]. Subsequently Schweppe and Torrijos [3] developed a method based on the work done by Lobo and Evans [4] on the radiation section. Other work done on the heat transfer in the convection section includes work by Briggs and Young [5] and the work of Garner [6] on the efficiency of finned tubes.

In general, heat transfer in the convection section is composed of the following:

1 Direct convection from the combustion gases.
Eq. (4), developed by Monrad [7, 8] may be used to estimate a film coefficient based on pure convection for flue gas flowing normal to a bank of bare tubes:

$$h_{\text{c}} = 0.018 \cdot Cp_{\text{flue gas}} \cdot \frac{G_{\max}^{2/3} \cdot T_{\text{avg}}^{0.3}}{D_o^{1/3}} \tag{4}$$

where $Cp_{fluegas}$ is the average specific heat of flue gas, and can be determined using equation (5) [10]:

$$Cp_{\text{flue gas}} = 1.0775 + 1.1347 \cdot 10^{-4} \cdot T \tag{5}$$

Eq. (4) does not take into account radiation from the hot gases flowing across the tubes, or re-radiation from the walls of the convection section.

2 Radiation from the gases
As an approximation, the radiation coefficient of the hot gas may be obtained from the following equation [7–9]:

$$h_{\text{rg}} = 9.2 \cdot 10^{-2} \cdot T_{\text{avg}} - 34 \tag{6}$$

3 Radiation from refractory walls
Re-radiation from the walls of the convection section usually ranges from 6 to 15% of the sum heat transfer by pure convection and the hot–gas-radiation coefficient. A value of 10% represents a typical average. Based on this value, the total heat transfer coefficient for the bare tubes convection section can be computed as [11]:

$$h_o = (1.1) \cdot (h_c + h_{rg}) \tag{7}$$

4 Radiation escaping from the combustion chamber into the first several rows of tubes in the convection section close to the radiation section, commonly referred to as the shield section as they "shield" the remaining tubes from the direct radiation from the radiant section. The shield section normally consists of two to three rows of bare tubes, but the arrangement varies widely for the many different heater designs. These rows are directly exposed to the hot gases and flame in the radiant section, and in order to estimate the radiation escaping from the combustion chamber into the convection section, the same formula already used in the radiant section may also be used [12]:

$$Q_f = \sigma \cdot \left(\alpha \cdot Acp_{shld}\right) \cdot F \cdot \left(T_g^4 - T_w^4\right) \tag{8}$$

where:

$$Acp_{\text{shld}} = \text{N}_{(\text{tube})_{\text{shld}}} \cdot S_{\text{tube}} \cdot L_{\text{tube}} \tag{9}$$

and T_w is the mean tube wall temperature and can be estimated using Eq. (10) in terms of the inlet and outlet process fluid temperatures, t_1 and t_2, respectively [13]:

$$T_w = 100 + 0.5 \cdot (t_1 + t_2) + 273 \tag{10}$$

Since all heat directed towards the shield tubes leaves the radiant section and is absorbed by these tubes, the relative absorption effectiveness factor, α, for the shield tubes can be taken to equal one.

Total heat transfer in the convection section is then equal to the sum of escaping radiation across the shield section, if applicable, and the heat transferred by convection and radiation into the tubes,

$$Q_c = Q_f + U_c \cdot A_c \cdot \text{ LMTD} \tag{11}$$

Where:
Q_c = total heat transfer in the convection section.
Q_f = Escaping radiation.
A_c = Area of heat transfer.
LMTD = Log mean temperature difference $= \dfrac{(T_1 - t_1) - (T_2 - t_2)}{\ln\dfrac{(T_1 - t_1)}{(T_2 - t_2)}}$
U_c = coefficient of heat transfer by convection and radiation (overall heat exchange coefficient), which can be determined by Eq. (12) [14]:

$$\frac{1}{U_c} = \frac{1}{h_i} + f(e, \lambda) + \frac{1}{h_o} \cdot \frac{S_i}{S_o} \tag{12}$$

where:

$$f(e, \lambda) = \frac{R_i}{\lambda} \cdot \ln\left(\frac{R_o}{R_i}\right) \tag{13}$$

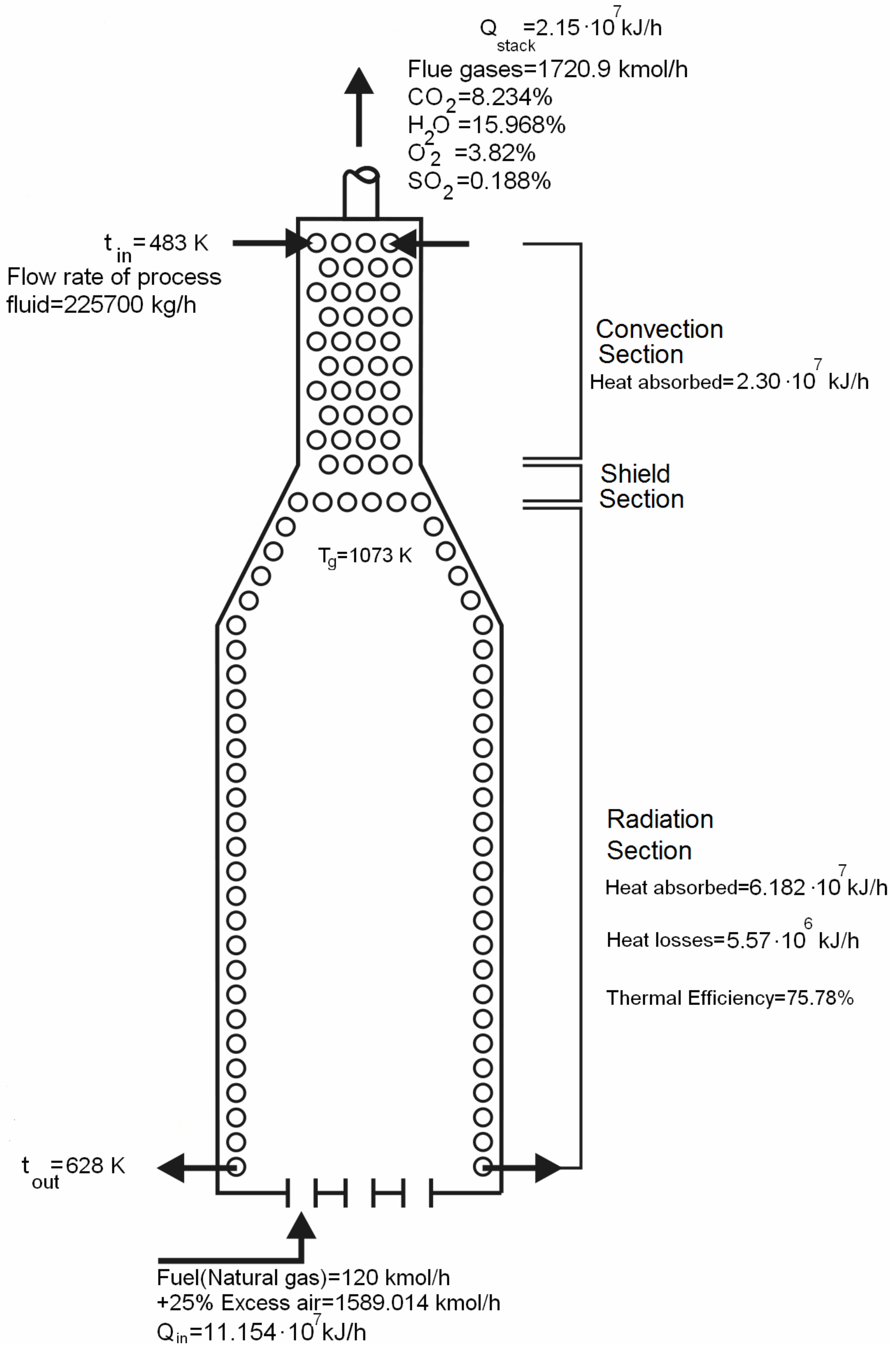

Fig. 1. Floesketch of fired process heater

and

$$\lambda = -0.157 \cdot 10^{-4} \cdot T_w^2 + 79.627 \cdot 10^{-3} \cdot T_w + 28.803 \quad (14)$$

Eq. (14) was obtained using the least square method for curve-fitting the thermal conductivity data of the tube material used (Table 1) [15, 16] in terms of tube temperatures.

For turbulent flow, 10000<Re<120000, and $L/D_o \geq 60$, the value of h_i is given by [14]:

$$h_i = 0.023 \cdot \frac{k}{D_i} \cdot Pr^{1/3} \cdot Re^{0.8} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (15)$$

where:

$$k = 0.49744 - 29.4604 \cdot 10^{-5} \cdot t \quad (16)$$

Eq. (16) was obtained using the least square method for curve-fitting the thermal conductivity data of process fluid from [7] in terms of process fluid temperature.

$$\ln(\mu) = -0.2207 \cdot \ln^2(t) + 0.5052 \cdot \ln(t) - 11.8201 \quad (17)$$

Eq. (17) was also obtained using the least square method for curve-fitting the viscosity values of process fluid data from [9] in terms of process fluid temperature.

4 Simulation of heat transfer

Davalos, Fermandez and Vallejo proposed a method for the simulation of direct vertical cylindrical fired heaters [17]. This method may be used for predicting the overall behaviour of the

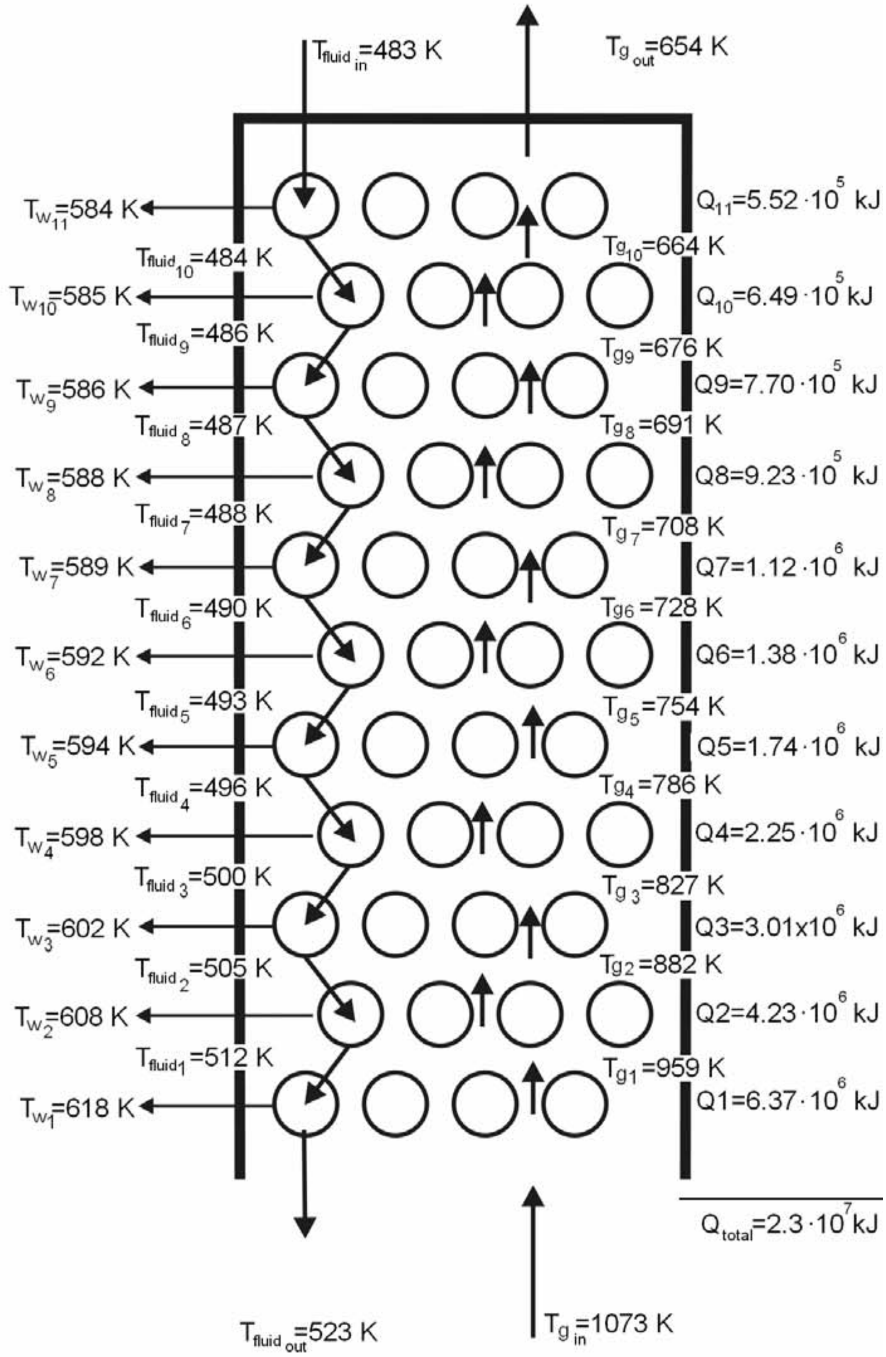

Fig. 2. Temperature rofiles for combustion gases, tubewall and fluid process and absorbed heat per layer in the convection section

convection section without giving information on the heat flux and temperature gradients. Such information may, however, be obtained by carrying out calculations for each segment of the tubes in the convection section. This implies the use of iterative methods. The temperatures of the flue gas and process fluid in the zone separating the convection and the radiation section may be also obtained by using this procedure for an analysis of the radiation section.

There are two primary sources of heat input to the radiant section, the combustion heat of fuel, Q_{rls}, and the sensible heat of the combustion air, Q_{air}, the fuel atomization fluid (for liquid fuel when applicable) and the fuel, Q_{fuel}. The heat is taken out of the radiant section by the two heat transfer methods viz., heat absorbed by the tubes in the radiant Q_R and the shield Q_{shld} sections, heat loss through the casing, Q_{losses}, and sensible heat of the exiting flue gas, $Q_{\ flue\ gases}$. The temperature of the flue gas can then be calculated by setting up a heat balance equation for the case where fuel gas is used as follows [18]:

$$Q_{in} = \_out \tag{18}$$

where:

$$Q_{in} = Q_{rls} + Q_{air} + Q_{fuel} \tag{19}$$

$$Q_{rls} = m_{fuel} \times \text{NCV} \tag{20}$$

$$Q_{\text{air}} = m_{\text{air}} \cdot Cp_{\text{air}} \cdot (t_{\text{air}} - t_{\text{datum}}) \tag{21}$$

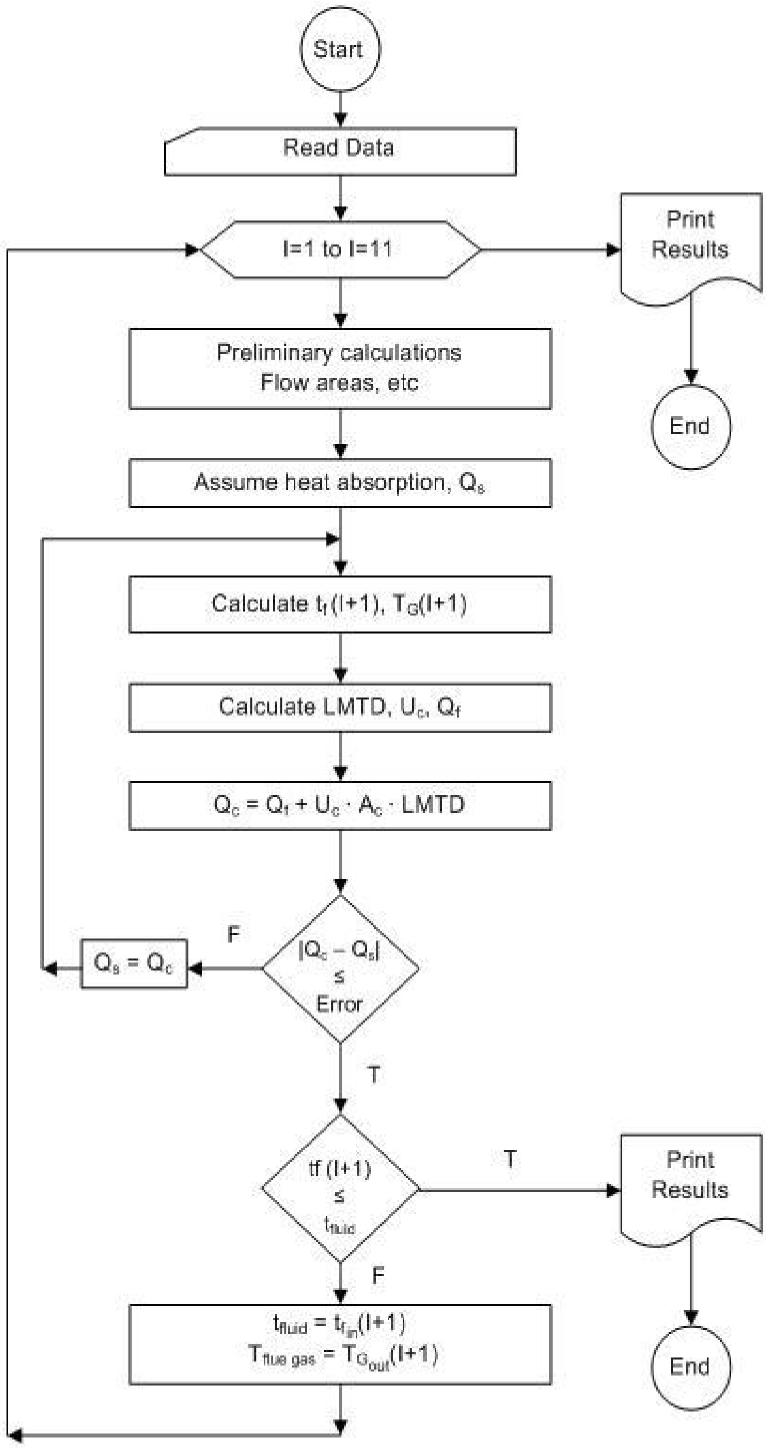

Fig. 3. Flowchart for the simulation of the convection section

$$Q_{\text{fuel}} = m_{\text{fuel}} \cdot Cp_{\text{fuel}} \cdot (t_{\text{fuel}} - t_{\text{datum}}) \tag{22}$$

$$Q_{out} = Q_R + Q_{shld} + Q_{losses} + Q_{fluegases} \tag{23}$$

Where

$$Q_R = Q_r + Q_{conv}. \tag{24}$$

Where: Q_r is radiant heat transfer

$$Q_r = \sigma \cdot (\alpha \cdot A_{cp}) \cdot F \cdot \left(T_g^4 - T_w^4\right) \tag{25}$$

Q_{conv} is the convective heat transfer in radiant section

$$Q_{conv} = h_{\text{conv}} \cdot A_{\text{t}} \cdot (T_g - T_w) \tag{26}$$

$$Q_{\text{shld}} = \sigma \cdot (\alpha \cdot A_{cp})_{\text{shld}} \cdot F \cdot \left(T_g^4 - T_w^4\right) \tag{27}$$

$$Q_{\text{losses}} = (2-5)\,\% \cdot m_{\text{fuel}} \cdot NCV \tag{28}$$

$$Q_{\text{flue gases}} = m_{\text{flue gases}} \cdot Cp_{\text{flue gases}} \cdot (T_g - T_{\text{datum}}) \tag{29}$$

Then, by means of appropriate heat balance:

$$
\begin{aligned}
&m_{\text{fuel}} \cdot \text{NCV} + m_{\text{air}} \cdot Cp_{\text{air}} \cdot (t_{\text{air}} - t_{\text{datum}}) + \\
&m_{\text{fuel}} \cdot Cp_{\text{fuel}} \cdot (t_{\text{fuel}} - t_{\text{datum}}) \; = \\
&\;\; \sigma \cdot \left(\alpha \cdot A_{cp}\right) \cdot F \cdot \left(T_g^4 - T_w^4\right) + h_{\text{conv}} \cdot A_t \cdot (T_g - T_w) \\
&\;\; + \sigma \cdot \left(\alpha \cdot A_{cp}\right)_{\text{shld}} \cdot F \cdot \left(T_g^4 - T_w^4\right) + (2-3)\,\% \cdot m_{\text{fuel}} \cdot \text{NCV} \\
&\;\; + m_{\text{flue gas}} \cdot Cp_{\text{flue gas}} \cdot \left(T_g - T_{\text{datum}}\right)
\end{aligned}
\tag{30}
$$

The Newton-Raphson method [19] was used to solve the heat balance equation and determine the effective gas temperature, for which two Matlab programmes were written. The intermediate flue gas and process fluid temperatures can then be calculated using the following algorithm:

1 Assume heat absorption by the first layer of tubes.

2 From the assumed heat absorption it is possible to calculate the temperatures of the flue gas and process fluid by means of an appropriate heat balance.

3 Calculate the log mean temperature difference.

4 Calculate the heat transfer coefficient for convection and radiation from the flue gas.

5 Determine the contributions of escaping radiation if the tubes in the convection section are close to the combustion chamber.

6 Compare the calculated heat absorption with the assumed value, and if the difference between the two values is less than the allowed error, proceed to the following layer of tubes. The total heat absorption in the convection section is determined by the summation of the amounts of heat absorbed in all layers.

Based on the above analysis, a Matlab computer programme was written for the convection section of a box-type fired heater used for heating crude oil in an atmospheric topping unit at Homs Oil Refinery (see Fig. 3 for flowchart). Table 1 shows the geometrical characteristics for the heater, and Table 2 shows its Process data sheet and the characteristics of the fuel (gas oil), flue gas, process fluid and air.

By applying the analysis of the convection section for each layer of tubes separately, it was possible to ascertain the effects of using studded tubes.

The results obtained by this analysis are given in Table 3. The heat absorbed in the radiant section is 60% and the remainder is recovered from the hot flue gas in the convection section. By using finned or studded tubes in the convection section, the heat exchange surface area was increased to make possible the attainment of a heat flux in the convection section that is comparable to that in the radiation section, improving significantly by this means the overall thermal efficiency of the heater.

Fig. 1 shows a flow sketch for the furnace in which are indicated the combustion products, mass balance and overall energy balance and heat losses. Fig. 2 shows the temperature profiles for the process fluid, flue gas and tube wall and the amount of heat absorbed per layer in the convection section.

Tab. 1. Geometrical characteristics of box-type fired heater.

External Dimension of heater (m)	20.000×4.800×19.650
Total Number of tubes	100
Weight of heater (kg)	307000
Weight of refractories (kg)	298000
Geometrical characteristics of radiant section	
Number of passes	2
Number of tubes	60
Overall tube length (m)	20.824
Effective tube length (m)	20.024
Tube spacing, centre-to-centre (mm)	394
centre-to-furnace wall (mm)	220
Outside diameter of tube (mm)	219
Wall thickness of tube (mm)	8
Tube materials	Stainless steel 18 Cr-8 Ni, Type AISI 304
Geometrical Characteristics of Convection Section	
Total number of tubes	40
Number of passes	2
Number of shield tubes	8
Overall tube length (m)	20.824
Effective tube length (m)	20.024
Tube spacing, centre-to-centre (mm)	250
Outside diameter of tube (mm)	168
Wall thickness of tube of tube (mm)	8
Tube materials	Stainless steel 18 Cr-8 Ni, Type AISI 304

5 Conclusion:

Heat transfer analysis of the convection section of fired heaters necessitates knowledge of the effective gas and process fluid temperatures in the zone separating the convection and radiation section. For this purpose, heat transfer analysis of both convection and radiation sections of a box-type fired heater in a crude oil atmospheric topping unit was carried out.

A Matlab computer programme for the heat transfer analysis of the convection section was written and the results presented graphically including process heat load, the amount of absorbed heat per layer in the convection section and the temperature profiles of combustion gases, tube wall and process fluid.

The analysis carried out in this work demonstrated effectively the significant contribution of the convection section to the overall thermal efficiency of the heater.

Tab. 2. Process data sheet for box-type fired heater.

Item No.	21 H-1
Purpose/Service	Crude Heater
Design thermal load (Duty) (kJ/h)	$8.482 \cdot 10^7$
Unit process conditions	
Equipment type (Petroleum Refinery Homs)	Cabin 43-5-16/21 N
Process fluid	Heavy Syrian Crude oil
Fluid flow rate (kg/h)	225700
Specific gravity at 15°C	0.9148
UOP K	12.1
Molecular weight	105.183
Inlet conditions	
Temperature (°C)	210
Pressure (bar)	Max 19.5
Liquid density kg/m^3	914.8
Liquid viscosity cst at 70 °C	30
Percentage of weight of vapour	0.0
Outlet conditions	
Temperature (°C)	250 from convection, 355 from radiant section
Pressure (Mpa)	0.91
Percentage of weight of vapour	0.0
Design conditions	
Minimum calculated efficiency %	75.78
Radiation losses %	5.0
Flue gas velocity though convection (kg/m^2.s)	2.677
Fuel characteristics	
Type of fuel	Natural gas
Nett calorific value (kJ/kmol)	927844.41
Molar heat (kJ/kmol.K)	39.26
Temperature (?C)	25
Flow of fuel (kmol/h)	120
Molecular weight (kg/kmol)	19.99
Composition (% mol)	CH_4(80.43), C_2H_6(9.02), C_3H_8(4.54), iso-C_4H_{10} (0.20), n-C_4H_{10}(0.32), iso-C_5H_{12}(0.04), n-C_5H_{12}(0.02), CO_2(3.52), H_2S (0.09), N_2 (1.735)
Air characteristics	
Molar heat (kJ/kmol.K)	$33.915 + 1.214 \cdot 10^{-3} \cdot T$
Flow of air (kmol/h)	1589.014
Air temperature (?C)	25
Percentage of excess air	25%
Flue gas characteristics	
Molar heat (kJ/kmol.K)	$29.98 + 3.157 \cdot 10^{-3} \cdot T$
Specific heat (kJ/kg.K)	$1.0775 + 1.1347 \cdot 10^{-4} \cdot T$
Flow of flue gas (kmol/h)	1720.9
Molecular weight (kg/kmol)	27.82336
Composition (% mol)	CO_2(8.234), H_2O (15.968), O_2 (3.82), N_2(71.79), SO_2 (0.188)

Nomenclature:

A	Heat exchange surface area (m^2).
A_c	Area of tubes bank in convection section (m^2).
A_{cp}	Cold plane area of tubes bank in radiation section (m^2).
$A_{cp\ shld}$	Cold plane area of shield tubes bank (m^2).
A_t	Area of tubes bank in Radiation section (m^2).
$C_{P\ air}$	Molar heat of combustion air (kJ/kmol.K).
C_P	Specific heat (kJ/kg.K).
$C_{P\ flue\ gas}$	Average specific heat of flue gases flowing to a bank of bare tubes (kJ/kg.deg).
D_i, D_o	Inside and outside diameter of tube (mm).
F	Exchange factor
G_{max}	Mass velocity of flue gas at minimum cross section (kg/h.m^2)
L_{tube}	Effective tube length (m)
LMTD	Log mean temperature difference (°C)
NCV	Net calorific value of fuel (kJ/kg).
$N_{tube(shld)}$	Number of shield tubes.
Pr	Prandtl number at the temperature of the process fluid ($\mathrm{Pr} = \frac{C_p}{\mu \cdot k}$)

Tab. 3. Results of the Box-Type Heater heat transfer Simulation

Outlet temperature of radiation gases (°C)	800
Outlet temperature of convection gases(°C)	400
Process fluid at radiation inlet (°C)	250
Heat liberated by combustion (kJ/h)	$1.1193 \cdot 10^8$
Calculated heat absorption (kJ/h)	$8.821 \cdot 10^7$
Heat absorbed in radiation section (kJ/h)	$6.182 \cdot 10^7$
Heat absorbed in convection section (kJ/h)	$2.30 \cdot 10^7$
Flow of fuel (kmol/h)	120
Transfer area required (m^2)	464.77
Number of required shield tubes	8

Q_C Total heat transfer (kJ/h).
Q_f Escaping radiation (kJ/h).
Q_R Total heat transferred to radiant tubes (heat absorbed by radiant tubes) (kJ/h).
$Q_{conv.}$ Convective heat transfer in the radiant section (kJ/h).
Q_{air} Sensible heat of combustion air (kJ/h).
Q_{fuel} Sensible heat of fuel (kJ/h).
$Q_{flue\ gas}$ Heat in gas leaving radiant section (kJ/h).
Q_{losses} Assumed radiation heat loss (kJ/h)
Q_r Radiant heat transfer (kJ/h).
Q_{rls} Heat released by burners (kJ/h).
Q_{shld} Radiant heat to shield tubes (kJ/h).
Re Reynolds number at temperature of process fluid ($Re = \frac{D_i \cdot w \cdot \rho}{\mu}$).
R_i, R_o Inside and outside radius of tube (mm).
S_i, S_o Inside and outside heat surface area of tube (m^2).
S_{tube} Tube spacing (m).
T_1, T_2 Inlet and outlet effective gas temperatures, respectively (°C)
T_{agv} Average flue gases temperature (K).
$T_{fluid\ in}$ Inlet process fluid temperature to convection section (K)
$T_{fluidout}$ Outlet process fluid temperature from convection section (K)
$T_{g\ in}$ Inlet Effective gas temperature to convection section (K)
$T_{g\ out}$ Outlet Effective gas temperature from convection section (K)
T_g Effective gas temperature in firebox (K).
T_w Average tube-wall temperature (K).
U_c Over all heat exchange coefficient (kJ/h.m^2.deg).
e Tube thickness (e = R_o-R_i) (mm).
h_c Pure convection film coefficient (kJ/m^2K.h).
h_i Convection coefficient between process fluid and the inside wall of the tubes (kJ/m^2K.h).
h_{rg} Gas radiation coefficient (kJ/m^2K.h).
h_o Total convection heat transfer coefficient (kJ/m^2K.h).
k Thermal conductivity of process fluid (kJ/h.m.K)
m Flow rate (kg/h).
n_R Number of tubes in radiation section
t_1, t_2 Inlet and outlet process fluid temperatures, respectively (°C) ,
w Velocity of the process fluid (m/s).

Greek symbols:

α Relative effectiveness factor of the tubes bank.
λ Thermal conductivity of tube wall (kJ/m.K.h).
μ Viscosity of the process fluid at the average temperature (Pa.s).
μ_w Viscosity of the process fluid at the tube-wall temperature (Pa.s).
ρ Density of process fluid (kg/m^3).
σ Stefan-Boltzman constant=$2.041 \cdot 10^{-7}$kJ/h.m^2.K^4.

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