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Thermal Regime of the Radiation Chamber of the Butane-Propane Pyrolysis Furnace

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Abstract. Within the framework of the differential method of thermal calculation of furnaces, the thermal regime in the radiation chamber of a tubular furnace for pyrolysis of the propane-butane fraction was determined using propane as a raw material. The fuel used was natural gas, mainly methane. The interrelated processes of combustion of fuel gas, heat and mass transfer in the combustion chamber are analyzed by numerically solving finite-difference analogs of the integro-differential equation for energy transfer by radiation and differential equations in partial derivatives of conservation of energy, momentum, combustion and turbulence models. As a result of the calculations, the fields of temperature and velocity of combustion products in the radiation chamber, the temperature of the inner surface of the lining, and heat fluxes to the tubular screen were established. Specific consumption of equivalent fuel per ton of propane and heat losses have been determined. Optimal operating modes of the furnace have been established, recommendations have been made for reliable and economical operation of the furnace.

INTRDUCTION

Text. Ethylene, used as a raw material for the production of polymers and rubbers, is obtained in the process of pyrolysis of hydrocarbons in tube furnaces [1]. In this work, the thermal regime in the radiation chamber of a universal tube furnace for pyrolysis of gaseous ethane-recycle or butane-propane SRT-II, intended for the production of ethylene, is analyzed. Thermal cracking of propane in tubular reactors occurs due to the absorption of the heat of combustion products of fuel gas and is accompanied by the formation of ethylene, methane, hydrogen and other products.

Primary reactions of propane pyrolysis:

$C_3H_8 \rightarrow CH_3 + C_2H_5$; $C_2H_5 \rightarrow C_2H_4 + H$; $CH_3 + C_3H_8 \rightarrow CH_4 + C_3H_7$ chain initiation.

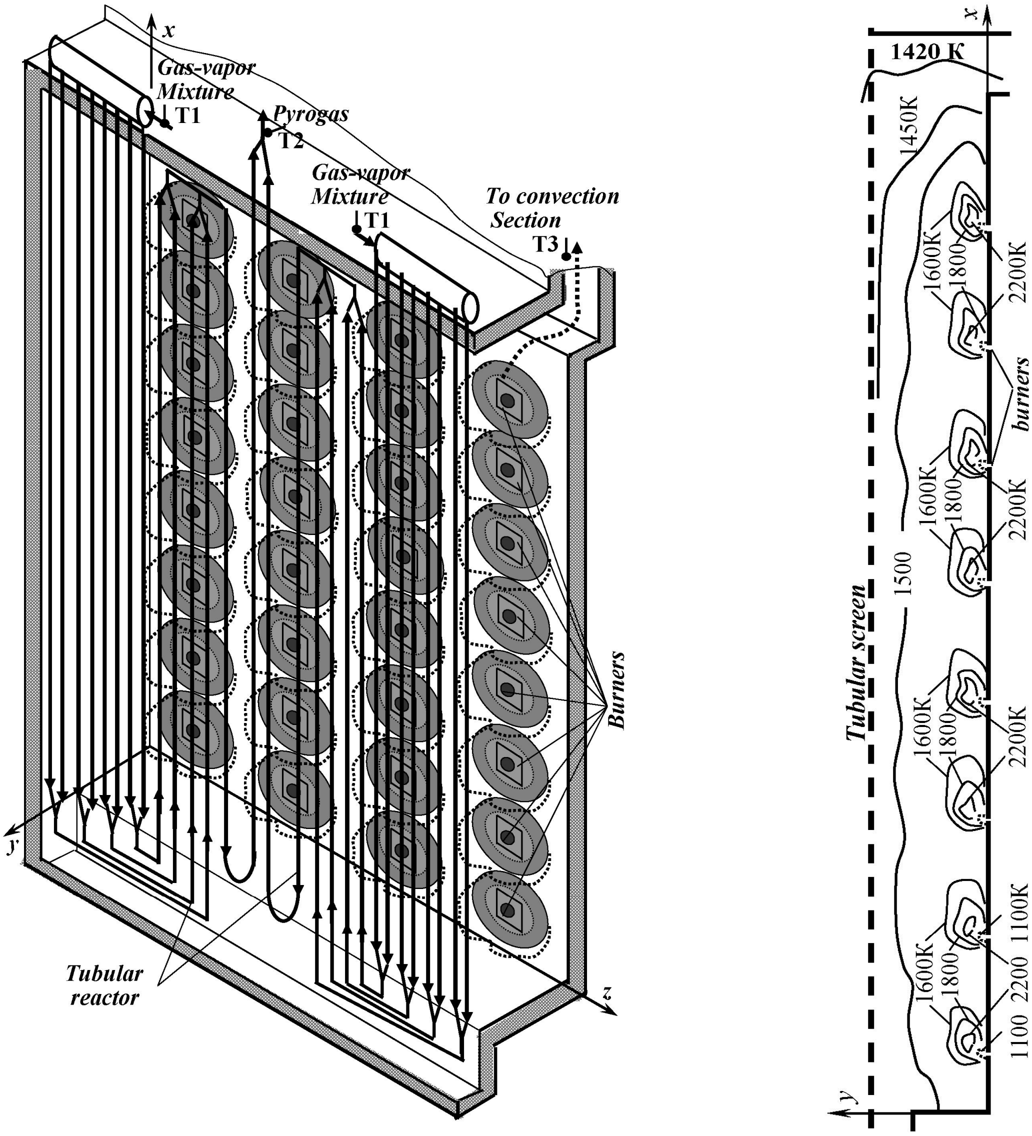
$C_3H_7 \rightarrow C_2H_4 + CH_3$; $2\ C_3H_8 \rightarrow C_2H_4 + C_2H_6 + CH_4$ chain development.

During the pyrolysis process, a number of other reactions occur, leading to the formation of aromatic hydrocarbons. As a result of the condensation of aromatic hydrocarbons, coke is formed. To obtain the highest ethylene yield, it is necessary to carry out an organized supply of heat to tubular reactors and to stop the development of secondary reactions. For this, the pyrolysis gas at the coil outlet is sharply cooled to a temperature of 350 ... 470 °C in a quenching-evaporating apparatus (QEA).

The pyrolysis process is carried out at a temperature of 800 ... 855 °C in the presence of dilution steam. Dilution steam reduces the partial pressure of hydrocarbons, which increases the selectivity of the process in the direction of increasing the yield of ethylene and propylene, and also reduces the formation of coke in the tubular reactor and resins on the heat exchange surfaces of the QEA pipes. In the pyrolysis of propane, the yield of ethylene is less than in the pyrolysis of ethane and is 30.2% by weight, but propane gives a high yield of propylene (up to 15.2 %). The hydrogen yield is 1.3% by weight. The conversion of propane during its pyrolysis (the ratio of the amount of raw materials split during pyrolysis to the amount of raw materials supplied) reaches 85 ... 90 %.

METHOD

A diagram of the fourth part of the radiation chamber of a tubular furnace is shown in Fig. 1 a. Fig. 1b shows the coordinate system for two-dimensional mathematical modeling of physicochemical processes in the combustion chamber and the form of isotherms obtained as a result of the numerical solution of the system of initial equations.



(a) (b)

FIGURE 1. Figure 1. a) scheme of the one-fourth of the radiation chamber of the propane pyrolysis furnace: – thermocouple; b) coordinate system and type of isotherms in the radiation chamber.

The propane-butane fraction pyrolysis furnace consists of convection and radiation sections. In the radiation chamber there are four double-sided heating tubular coils. In the convection section, raw material, dilution steam, feed water are preheated, and high pressure steam is superheated. The dilution steam is mixed with the hydrocarbon feed and then sent to the upper mixed feed preheater section. A mixture of hydrocarbon feedstock and dilution steam is fed into the radiation chamber after the lower heating section through an external transition pipeline. Before being fed into the tubular reactor, the temperature of the raw material is measured by thermocouples T1, and the temperature of the cracking products T2 is measured at the outlet of the tubular reactor (Fig. 1 a). Thermocouples T3 are also installed to measure the temperature of flue gases coming from the radiation chamber to the convection section T3.

Propane or butane pyrolysis occurs in four SRT II tubular coils, each with 8 passes. The inlet and next passage of each coil consists of two parallel pipes. The remaining six passages consist of one pipe. The descending sections of the coils have a larger diameter than the ascending ones. The outlet pipes of the two screens are connected in pairs to one inlet line of the quench-evaporator.

The source of energy for carrying out endothermic reactions is natural gas, which is combusted after mixing with air in wall-mounted LPMW-5 burners. 64 burners are installed on each side lined wall of the radiation chamber in 8 rows, each tier contains 8 burners. Fuel gas is supplied to the burners via 8 vertical risers. The burners are rated at 186 kW and form small ring flares around the burner tip. It is assumed that the use of a large number of small burners will provide a uniform temperature field in the radiation chamber. The thrust required to maintain a reduced pressure in the radiation chamber is created by a smoke exhauster.

Combustion air is supplied from the environment through primary air dampers, which allow its flow rate to be regulated. The heat load of the burners is regulated depending on the heating value of the fuel gas by changing the supply pressure to the burners. Nominal overpressure of gas in front of the burners is 0.08 ... 0.2 MPa. In the calculations, the methane consumption for combustion was 0.765 kg / s. Excess air ratio $\alpha = 1{,}1$.

The width of the inner part of the radiation chamber is 2.04 m, the irradiated height of the tubular screen is 11 m. The thickness of the lined walls is 0.33 m.

Taking into account the symmetry of the radiation chamber relative to the tubular screen, the problem of complex heat and mass transfer is solved for half of the combustion chamber. Radiation, forced convection, turbulent thermal conductivity and heat release due to fuel combustion contribute to the heat exchange in the combustion chamber:

$$\frac{D}{Dt}\left(U + \frac{\rho \overline{\mathbf{u}}^2}{2}\right) = \mathrm{div}\mathbf{q}_R + \mathrm{div}\mathbf{q}_c + \mathrm{div}\mathbf{q}_{tc} + \mathrm{div}\mathbf{q}_{ch}. \tag{1}$$

where U – internal energy of combustion products; $\overline{\mathbf{u}}$ – vector of time-averaged velocity; ρ – average density of gases; $\mathrm{div}\mathbf{q}_R$, $\mathrm{div}\mathbf{q}_c$, $\mathrm{div}\mathbf{q}_{tc}$, $\mathrm{div}\mathbf{q}_{ch}$ – divergence of vectors of density of radiation, convective fluxes and reaction of fuel combustion.

The main importance in calculating the complex heat transfer in radiation chambers is the divergence of the radiant flux, which is included in the right side of the energy equation (1) and the volumetric density of heat release in the combustion regions of the gas-air mixture. However, the formation of the temperature field also depends on two other terms on the right-hand side of Eq. (1), i.e. on the features of the velocity field. The velocity field is obtained by solving the equation of motion, which in vector form has the form

$$\rho\,(\overline{\mathbf{u}} \cdot \nabla)\,\overline{\mathbf{u}} = -\nabla p - \left[\nabla \cdot \overline{\boldsymbol{\tau}}^{(l)}\right] - \left[\nabla \cdot \overline{\boldsymbol{\tau}}^{(T)}\right] + \bar{f}, \tag{2}$$

where $\overline{\boldsymbol{\tau}}^{(l)}$ – viscous stress tensor; $\overline{\boldsymbol{\tau}}^{(T)}$ – Reynolds stress tensor; $\bar{f}$ – mass forces.

Equation (2) is supplemented by the continuity equation:

$$\mathrm{div}\,(\rho\,\overline{\mathbf{u}}) = 0. \tag{3}$$

The complete system of equations for the differential method for calculating furnaces, the specifics of setting boundary conditions and methods for the numerical solution of the system of finite-difference analogs of the original equations are available in [2-4]. The application of this method to the calculation of the ethane pyrolysis furnace, which does not fundamentally differ from the analyzed furnace, was shown in [5]. Therefore, we present some results of a numerical analysis of the features of heat and mass transfer in the radiation chamber of a tubular propane pyrolysis furnace.

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DISCUSSION

The flue gas temperature field is already shown in Fig. 1 b. The temperature of the fuel gas and combustion air was taken equal to 300 K. The temperature of the outer surface of the radiation chamber was taken equal to 315 K. The change in the temperature of the combustion products, the temperature of the inner surface of the side wall and the temperature of the outer surface of the outlet pipe of the coil along the height of the radiation chamber obtained as a result of the calculations is shown in Fig. 2.

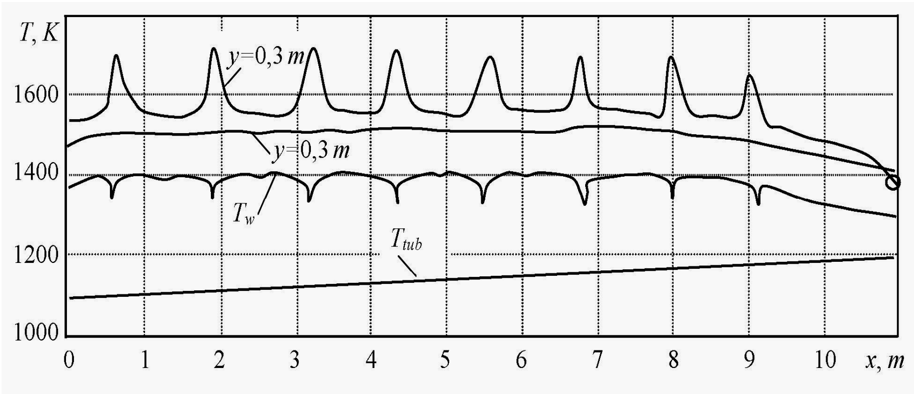

Figure 2. Change in temperature along the height of the radiation chamber: T_w – internal lined surface of the side wall; T_{tub} – the outer wall of the coil outlet pipe; **O** – flue gas temperature at the xit from the radiation chamber according to the thermocouple readings

As can be seen from the figures, near the locations of wall-mounted burners, a large non-isothermal flow is observed. At the same time, in the area closer to the tubular screen, a fairly uniform temperature distribution of the flue gases is formed. Immediately near the tubular screen outside the thermal boundary layer, the temperature of the combustion products varies within the range of 1420..1460 K (1150 ... 1190 °C). At distances of about 0.25 ... 0.4 m from the tubular screen, the temperature is at the level of 1500 ... 1600 K (1230 ... 1330 oC). Closer to the roof and to the transition to the convection part, the flue gas temperature drops to 1420 K, which practically coincides with the readings of the T3 thermocouples (1146 °C) obtained during the commissioning tests of the furnace. The temperature of the inner surface of the side wall of the combustion chamber is about 1400K, slightly decreasing near the arch of the furnace and towards to the exit from the radiation chamber, as well as near the locations of the burners. The temperature of the outer wall of the coil outlet pipe rises from 1100K to 1200K. The temperature of the mixture of propane and dilution steam was T1 = 650 °C, and the temperature of the pyrolysis gas at the outlet from the tubular screen according to the readings of the standard thermocouple was T2 = 815 °C. The ethylene content in the pyrolysis gas is 31% at a propane flow rate of 4.53 kg / s.

Fig. 3 shows the view of the isolines of the stream functions, in the *xy* section, passing through the axes of the wall burners.

Fig.3 shows that a rather complex flow field is formed in the radiation chamber with the presence of reverse flows zones between the burner rows. The presence of reverse flows near the mouth of the burners should contribute to the stability of combustion. Attention is drawn to the presence of reverse flow zones at the bottom of the furnace and near the tubular screen at the level of the third row of burners at the bottom of the radiation chamber. This zone, apparently, provides a relatively uniform temperature field in the lower part of the furnace near the tubular screen. The absolute velocities of flue gases in most of the combustion chamber are within 0.5 ... 1.5 m. Despite this, there is some similarity between the temperature and velocity fields. This confirms the influence of convective heat transfer on the formation of the temperature field.

Fig. 4 shows the change in molar (volumetric) fractions of the main components of combustion products υ along the height of the radiation chamber.

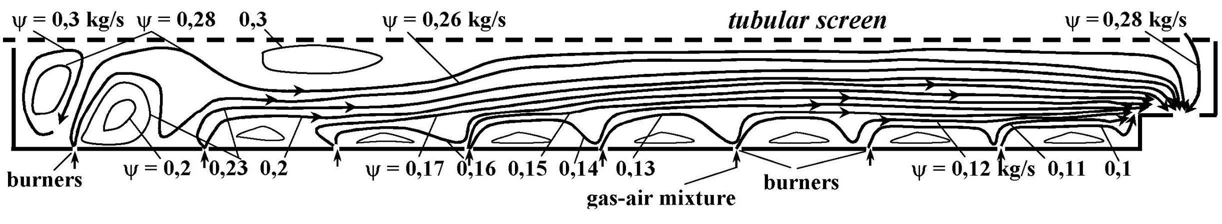

Figure 3.View of streamline functions in the radiation chamber.

Fig. 4 shows that the main changes in the concentration of combustion products occur only in the areas of combustion of the fuel - air mixture, and in the rest of the volume of the combustion chamber, there are practically constant values of the concentrations of components of flue gases. When leaving the radiation chamber, the volume fraction of CO_2 is about 14.5%, and O_2 is 2.5%, which is in good agreement with the data of chromatographic analysis of the composition of flue gases. The CO concentration is noticeable only in the combustion area, and at the exit from the furnace it is 0.0004 ppm. The concentration of nitrogen oxide NO in flue gases is 0.0044 ppm.

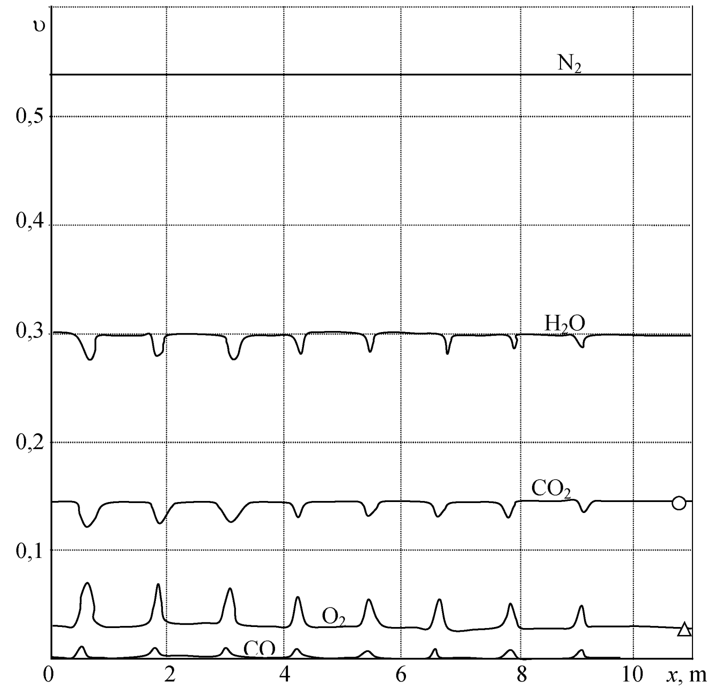

FIGURE 4. Change in volume fractions of combustion products components along the radiation chamber height.

CONCLUSION

As a result of calculations, it was found that the power of heat transfer to the cracking product in the radiation chamber at a given gas consumption for combustion is 21.03 MW with a specific energy of propane pyrolysis of 39.4 kJ / mol. This corresponds to the consumption of methane for combustion of 274 kg / (ton of raw materials). With some changes in the operating mode of the furnace according to the readings of the metering devices, the heat transfer power in the radiation section is in the range of 20.4 ... 22.5 MW. Heat transfer in the convection part of the furnace is 19.2 ... 20.53 MW. Heat loss through the walls of the furnace is 0.453 MW, and with flue gases, 0.476 MW. The flue gas temperature is 276 ... 279 °C. As a rule, an increase in the excess air ratio α by 0.1 leads to an increase in losses with flue gases from 0.4 to 0.8%. The thermal efficiency of the furnace is 92.3%.

As can be seen from the calculations, although the use of a large number of wall burners does not provide a completely uniform temperature field, the temperature field in the radiation chamber of a tubular furnace is more uniform than when using more powerful floor burners of the same total heat output. When using small burners, areas with high temperatures are also reduced, which leads to a decrease in nitrogen oxides in the flue gases.

Calculations carried out with reduced or increased fuel gas consumption have shown that this leads to a decrease or increase in the temperature of flue gases at the exit from the radiation chamber of the furnace. As a consequence, the yield of ethylene decreases. Therefore, it is necessary to ensure the temperature of the flue gases at the level of 1420 K. It is necessary to monitor the density of the furnace casing and to eliminate air suction in time, as this leads to an increase in heat loss with flue gases. It is recommended to periodically monitor the temperature of flue gases, as an increase in temperature by 10 ... 15 °C leads to an increase in losses with exhaust gases by 0.6 ... 0.8%. The reason for the increase in the flue gas temperature can be contamination of the outer heating surfaces as a result of chemical underburning of the fuel gas. This, in turn, will lead to a decrease in heat transfer by the raw material and to a decrease in the yield of the target product.

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