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Investigation on steam injection condition in refining vacuum furnace

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HIGHLIGHTS

- Injecting steam inside the radiant section is superior to the entrance.
- The optimal steam injection location is at the oil bubble point area.
- Excessive steam brings no benefits but unnecessary pressure drop.
- Heavy crude process and deep-cut operation need earlier and more steam injection.

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ABSTRACT

As worldwide petroleum reserves evolve toward heavier crude oils, crude distillation units encounter historically high coking risk, and this problem is further exacerbated by cutting deeper into the bottom for higher HVGO yield. In this work, we aimed to optimize the steam injection condition for coking prevention purpose in refining vacuum furnace. A new technology that injecting steam inside the radiant section was proposed and comparison was made with steam injection at the entrance. Variable steam injection location and rate were examined according different operating cases, and the flow patterns in vaporizing tubes and coking tendency curves were present. All the calculations were performed using the commercial software Petro-SIM and the calculation model was validated against on-site data. The criterion was proposed for the optimal steam injection condition. The results showed that steam injection inside the radiant section was superior to the entrance.

1. Introduction

Many refining vacuum furnaces have problems of coke formation and short life cycles, especially in deep-cut units. The coke layer reduces heat transfer coefficient, and increases the tube metal temperatures (TMTs) progressively. As the TMTs getting close to the tube metallurgical temperature limit, the furnace must be shut down for coke cleaning (Martin and Barletta, 2001). Rapid coke formation is usually caused by a combination of high oil film temperature, long oil residence time, and inherent instability of the oil (Mahulkar et al., 2014; Radmanesh et al., 2008; Souza et al., 2006; Wang and Anthony, 2003). Taking into consideration the first two factors, the coke formation can be relieved by optimized designs, such as proper radiant coil size and layout, combustion control and using steam injection. Steam injection which has long been used in delayed coking furnace (Elliot, 1996) can remarkably improve the flow pattern by adjusting the velocity and vaporization of the fluid. Correct flow pattern is beneficial to eliminate hot spots and avoid rapid coke formation, thus extend life cycles (Qian et al., 2003).

Flow pattern in horizontal tube has the following forms: bubble flow, plug flow, stratified flow, wavy (or cresting) flow, slug flow, annular flow and mist flow (Baker, 1954; Fouilland et al., 2010; Geraci et al., 2007; Gregorc and Zun, 2013; Strazza et al., 2011; Vianna and Nichele, 2010). For vertical flow, only four types of flow pattern, Bubble → Slug → Annular → Mist, have been observed in order of increasing vaporization (Abdulkadir et al., 2014; Guet et al., 2006; Hewitt, 2012; Russell and Pratt, 1979; Taha and Cui, 2006; Wolf et al., 2001).

Bubble flow and slug flow usually occur at the beginning of oil vaporization, where vapor fraction is relatively low. Mist flow usually occurs near the outlet where vapor fraction is high. In most cases, annular flow dominates in the tube pass, which means the liquid coats the inner wall of the tube and there is vapor through

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the middle. Generally, the annular flow pattern is desirable because it prevents the droplets from hitting the very hot tube wall, and thus prevents rapid coke formation. Bubble flow is also acceptable, but slug flow, mist flow and other patterns should be avoided (Qian et al., 2003). Slug flow will cause water hammer and vibration, simultaneously produce great noise even damage the tubes in severe cases. In mist flow region, the droplets sticking to the hot tube wall will increase localized oil residence time if not washed away by the liquid quickly, thus leading to localized hot spots and consequent rapid coke formation.

In this work, we aimed to find out the optimal steam injection condition for the radiant coil. Variable steam injection location and rate were examined according different operating cases. The research was based on a newly installed vacuum furnace in China. Calculations were performed using the commercial software Petro-SIM in which the Furnace model was already implemented. The model was calibrated using on-site data.

2. Model description and experiments

2.1. Model description

All the calculations were performed using Petro-SIM which is robust for refining oil assay synthesis and process simulation. The fluid properties were calculated and propagated through the flowsheet, many of them specific to the refinery industry. In this paper, the Furnace model implemented in Petro-SIM was used to perform process side calculation in a refinery vacuum furnace, while the flue gas side was not considered. The vacuum furnace flowsheet and calculation model are shown in Fig. 1. The vacuum furnace must raise the atmospheric residuum temperature high enough to meet the vacuum gas oil (VGO) yield target, and supply sufficient wash oil flow to prevent the wash section packing from coking. The calculation mainly focuses on the radiant section since the high peak TMTs in this section are far higher than in the convection section.

Oil is fed into the furnace and travels through tubing that is exposed to the heat source. As the tubing heats up, the oil viscosity decreases allowing for ease of transportation of the oil through the tubing. There are two common tubing sections in the furnace: the Convection Section in which the tubing is heated by convective currents generated by the flue gas; and the Radiant Section in which the tubing is heated directly by radiation from the heat source.

In the Furnace model, tubes are numbered in the reverse order to the process flow, so Tube #1 is the final outlet tube. The model is based on actual geometry and configuration modeled, performs tube-by-tube calculations which is an iterative procedure, works in the reverse order from the outlet (Tube #1) to the entrance (Tube #n). To accurately model the furnace, the detailed data sheet and the drawings as well as operating conditions are required to specify the model. It also requires an estimated pressure drop and the final will be a calculated value.

2.2. Calculation models

2.2.1. Heat transfer calculation

Various methods and tuning factors were used when calculating heat transfer within the furnace to improve the accuracy of the model. Maximum heat flux ($q_{\max}$) for each single tube was introduced to calculate the outside skin temperature of each tube.

$$q_{\max} = q_{\text{average}} \times K_1 \times K_2 \times K_3 \tag{1}$$

where q_{average} was the average radiant heat flux, K_1 was the correction factor for the irregularities in vertical or horizontal distribution of the radiant section, K_2 was the tube irregular layout correction factor, K_3 was the flame type correction factor. These correction factors can be calibrated according the furnace type during the validation procedure. q_{average} was specified by a fixed heat flux profile and adjusted during the calibration procedure.

Table 1
Design parameters of the furnace.

Items	Convection section	Radiant section
Diameter (mm)	152	152/168/219/273/325
Thickness (mm)	8	8/8/10/12/14
Length (mm)	9000	12000
Number	108	102/12/12/12/6
Pass	6	6
Tube pitch (mm)	304	304/336/438/546/650
Row pitch (mm)	263	
Total flow rate (t/h)	417.8	417.8
Inlet temperature (°C)	354	374
Outlet temperature (°C)	374	410
Inlet absolute pressure (kPa)	501	501
Outlet absolute pressure (kPa)	501	43
Coil steam injection rate (kg/h)		450[a]

[a] Total rate of the 6 passes injected at Location I.

The outer skin temperature (T_{skin}) of the tube was calculated by:

$$T_{\text{skin}} = T_{\text{bulk}} + \Delta T_{\text{film}} + \Delta T_{\text{coke}} + \Delta T_{\text{metal}} \tag{2}$$

with

$$\Delta T_{\text{film}} = \frac{1}{h_{\text{i}}} \times \frac{D_{\text{ext}}}{D_{\text{intcoke}}} \times q_{\max} \tag{3}$$

$$\Delta T_{\text{coke}} = \frac{m_{\text{coke}}}{k_{\text{coke}}} \times \frac{2D_{\text{ext}}}{D_{\text{int}} + D_{\text{intcoke}}} \times q_{\max} \tag{4}$$

$$\Delta T_{\text{metal}} = \frac{m_{\text{tube}}}{k_{\text{metal}}} \times \frac{2D_{\text{ext}}}{D_{\text{ext}} + D_{\text{int}}} \times q_{\max} \tag{5}$$

where T_{bulk} was the oil bulk temperature, ΔT_{film}, ΔT_{coke} and ΔT_{metal} were the temperature increase across the oil film, inside the coke layer, and tube metal, respectively. D_{ext}, D_{int} and D_{intcoke} referred to external diameter of tube, internal diameter of tube and internal diameter of coke layer respectively, m_{coke} and m_{tube} were the coke layer thickness and tube wall thickness respectively, k_{coke} and k_{metal} were the thermal conductivity coefficients of coke and tube metal respectively. h_{i} was the inside oil film heat transfer coefficient, and it was calculated using the Sieder–Tate correlation. Sieder and Tate made a correlation of both heating and cooling a number of fluids, principally petroleum fractions, in horizontal and vertical tubes and arrived at an equation for laminar flow where $Re < 2100$:

$$\frac{h_i D}{k_{oil}} = 1.86\left(\text{RePr}\frac{D}{L}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{6}$$

where k_{oil} was the thermal conductivity coefficients of oil, L was the tube length. μ and μ_{w} were the fluid viscosity at the bulk fluid temperature and the inner wall temperature respectively. $\phi_w = \left(\frac{\mu}{\mu_w}\right)^{0.14}$ corrected for the heat transfer direction. Re and Pr were the Reynolds number and Prandtl number respectively. Eq. (6) gave maximum mean deviations of approximately ±12% from $Re = 100$ to $Re = 2100$. Beyond the transition range, the data was extended to turbulent flow as:

$$\frac{h_i D}{k_{oil}} = 0.027\text{Re}^{0.8}\text{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{7}$$

Eqs. (6) and (7) were used cooperated with working plot by Kern (1950) in the model. The working plot used j_H on the vertical ordinate and the Re on the horizontal ordinate. By using L/D as a