Constrained thermohydraulic optimization of the flow rate distribution in crude preheat trains

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Abstract

In the petroleum refining process, a large amount of energy is necessary for the petroleum distillation. The thermal efficiency of this process is strongly dependent on the crude preheat train performance. Crude preheat trains correspond to heat exchanger networks which allow the heating of the oil stream through a set of heat exchangers using hot side streams and pumparound. The final heating step is executed in a furnace. However, during the refinery operation, the heat load of the exchangers in the preheat train may diminish due to fouling. This effect brings economic and environmental penalties due to the necessary additional fuel firing. Associated to the reduction of the thermal effectiveness of the heat exchangers, fouling also involves an increase of the flow resistances along the thermal equipment. In more severe scenarios, the operation staff may be obligated to reduce the refinery throughput due to hydraulic limitations. A potential approach to mitigate these problems is based on the optimization of the distribution of the flow rates of the streams along parallel branches in order to maximize the final train temperature. In this context, this paper presents a constrained nonlinear programming formulation of the problem (a NLP problem). The equality constraints encompass mass, energy and mechanical energy balances and heat exchanger equations in order to describe the thermal and hydraulic behavior of the system. Inequality constraints involve flow velocity bounds, cooler capacity limits and pumparound operational ranges. The performance of the proposed approach is explored using an example based on a real Brazilian refinery.

Keywords: fouling, heat exchanger, petroleum refining, optimization.

1. Introduction

The first main stage of petroleum refining is the atmospheric distillation. In this operation, the crude stream fed to the tower must be heated to about 380 °C. Around 60-70% of the necessary thermal energy is supplied by hot streams from the distillation tower through a heat exchanger network (HEN) called crude preheat train (CPT). The rest of the heating is provided by a fired heater. However, during the operation, the heat load of the CPT diminishes due to fouling. This effect brings economic and environmental penalties because of the necessary additional fuel firing. Due to the
magnitude of this problem, the literature reports several alternatives for fouling mitigation in this kind of system (Panchal and Huangfu, 2000).

One of these approaches involves the optimization of the flow rate distribution among different CPT branches (Oliveira Filho et al., 2009). In a similar way as other papers involving operational optimization of HENs (Lid et al., 2001), the model is based on mass and energy balances without considering hydraulic aspects. However, because of the importance of such effects, this aspect may limit the utilization of the proposed approach in hydraulic constrained networks.

Aiming to avoid this problem, Queiroz et al. (2010) have extended the model of Oliveira Filho et al. (2009) to include hydraulic effects. The solution scheme is based on a two layer structure: a simplex optimization algorithm associated to a thermohydraulic simulator. Despite its robustness, this approach may involve a considerable computational time.

In this context, this paper presents the thermohydraulic optimization of CPTs through a constrained NLP problem. The optimization model encompasses mass, energy and mechanical energy balances. Heat exchanger equations are described using the P-NTU method. The performance of the proposed approach is explored based on a real Brazilian refinery.

### 2. Mathematical formulation

#### 2.1. Network description

The HEN structure is represented by a digraph. The HEN vertices (index $t$) represent the network elements: heat exchangers (set $HE$), mixers (set $MX$), splitters (set $SP$), supply units (set $PS$), demand units (set $PD$) and desalters (set $DS$). These vertices are interlinked by $k$ edges which represent the material streams. The edges are distributed in different branches (index $r$) upstream and downstream the desalter (sets $UD$ and $DD$).

#### 2.2. Objective function

The optimization problem corresponds to maximize the final CPT temperature in order to reduce fuel consumption and carbon emissions:

$$\max T_{final}$$

where $final$ is the index of the CPT outlet.

#### 2.3. Constraints

**2.3.1. Mass balances**

The mass conservation along the HEN is represented by the following equations:

$$\sum_{k \in S_t^{in}} m_k - \sum_{k \in S_t^{out}} m_k = 0 \quad \text{for} \quad t \in (HE \cup MX \cup SP \cup DS)$$

$$\sum_{k \in S_t^{in}} m_k - \sum_{k \in S_t^{out}} m_k + n_t = 0 \quad \text{for} \quad t \in (PS \cup PD)$$

$$n_t - n_t^{esp} = 0 \quad \text{for} \quad t \in PS$$

where $S_t^{in}$ is the set of edges $k$ directed to vertex $t$, $S_t^{out}$ is the set of edges $k$ directed from vertex $t$, $m_k$ is the mass flow of the edge $k$, $n_t$ is the external network flow rate at vertex $t$, and $n_t^{esp}$ is the corresponding flow rate specification.

**2.3.2. Energy balances**

The model involves an energy balance equation for each vertex:

$$\sum_{k \in S_t^{in}} m_k C_p T_k - \sum_{k \in S_t^{out}} m_k C_p T_k = 0 \quad \text{for} \quad t \in (HE \cup MX \cup SP \cup DS)$$
Constrained thermohydraulic optimization of the flow rate distribution in crude preheat trains

\[ \sum_{k \in S^i} m_i C_p T_k - \sum_{k \in S^o} m_i C_p T_k + n_i C_p V_i = 0 \quad \text{for } t \in (PS \cup PD) \quad (6) \]

\[ V_i - V_i^{out} = 0 \quad \text{for } t \in PS \quad (7) \]

where \( C_p \) and \( T_k \) are the heat capacity and temperature of the stream related to edge \( k \), and \( C_p \) and \( V_i \) are the heat capacity and temperature of the external stream associated to the vertex \( t \).

### 2.3.3. Heat transfer equations

The heat transfer in the heat exchangers is described based on the P-NTU method that works with relations equivalent to the \( \epsilon \)-NTU method, but always directed to one of the streams (without depend on, as in \( \epsilon \)-NTU method, which stream is the minimum and maximum fluid). In this paper, these equations are written in relation to the hot stream.

Therefore, the P-NTU equations become, for \( t \in HE \):

\[ CR_t = (m_i C_p) / (m_i C_p) \quad (8) \]

\[ NTU_t = U_t A_t / C_h \quad (9) \]

\[ P_t = c_t \left[ \frac{1 - \exp[-NTU_t (1 - CR_t)]}{1 - CR_t \exp[-NTU_t (1 - CR_t)]} \right] + (1 - c_t) \frac{2}{1 + CR_t + \sqrt{1 + CR_t^2} \coth[(1 + CR_t) NTU_t / 2]} \quad (10) \]

where \( CR_t \) is the ratio between the heat capacity flow rates, \( NTU_t \) is the number of transfer units, \( P_t \) is the temperature effectiveness, \( c_t \) is a parameter that is equal to 1 if the heat exchanger \( t \) is countercurrent or equal to 0 if the heat exchanger \( t \) has an even number of tube passes, indexes \( h \) and \( c \) correspond to the hot and cold streams related to the heat exchanger vertex \( t \), \( U_t \) and \( A_t \) are the overall heat transfer coefficient and heat transfer area.

The relation between the temperature effectiveness and the network temperatures are:

\[ T_{in}^h - T_{out}^h - PT_{in}^h + PT_{out}^h = 0 \quad \text{for } t \in HE \quad (11) \]

where the superscripts \( in \) and \( out \) represent the inlet and outlet streams.

The overall heat transfer coefficient is described by the following model equation:

\[ U_t = [(1 / h_{i,t}) (D_{i,t} / D_{i,t}) + D_{i,t} \log(D_{i,t} / D_{i,t}) / 2k + (1 / h_{i,t}) + R_f]^{-1} \quad \text{for } t \in HE \quad (12) \]

where \( h_{i,t} \) and \( h_{e,t} \) are the tube-side and shell-side film coefficients, \( D_{i,t} \) and \( D_{e,t} \) are the inner and outer tube diameter, \( R_f \) is the fouling resistance, and \( k \) is the thermal conductivity of the tube wall.

The model adopted in this paper considers the following equations to predict the variation of film coefficients for the tube-side and shell-side:

\[ h_{i,t} = h_{i,t}^{base} (m_t / m_{i,t}^{base})^{0.8} \quad \text{for } t \in HE \quad (13) \]

\[ h_{e,t} = h_{e,t}^{base} (m_t / m_{i,t}^{base})^{0.6} \quad \text{for } t \in HE \quad (14) \]

where \( m_{i,t}^{base} \) and \( h_{i,t}^{base} \) are the previously known values of mass flow rate and film coefficient at a determined base case.

### 2.3.4. Mechanical energy balances

The mechanical energy balances for the branches upstream the desalter and downstream the desalter are:

\[ \Delta P_u = \Delta P_u^{base} (m_t / m_{i,t}^{base})^{1.8} + \Delta P_{CV,r} \quad \text{for } r \in UD \quad (15) \]

\[ \Delta P_d = \Delta P_d^{base} (m_t / m_{i,t}^{base})^{1.8} + \Delta P_{CV,r} \quad \text{for } r \in DD \quad (16) \]

where \( \Delta P_u \) and \( \Delta P_d \) are the pressure drops upstream and downstream the desalter, \( \Delta P_u^{base} \) is the pressure drop of the branch \( r \) at the base case, and \( \Delta P_{CV,r} \) is the pressure drop of the control valve of the branch \( r \).
The pressure drop along the entire CPT must be limited according to the available pressure drop, $\Delta P_{av}$:
\[ \Delta P_v + \Delta P_p \leq \Delta P_{av} \]  \hspace{1cm} (17)

2.3.5. Bounds on variables
Constraints related to flow velocity and cooler capacity limits, and pumparounds operational ranges can be represented by bounds on certain temperatures and flow rates:

\[ m_{k}^{LB} \leq m_k \leq m_{k}^{UB} \quad \text{for} \quad k \in ESPm \]  \hspace{1cm} (18)

\[ T_{r}^{LB} \leq T_r \leq T_{r}^{UB} \quad \text{for} \quad r \in ESPT \]  \hspace{1cm} (19)

where $ESPm$ and $ESPT$ are the sets of the specifications

3. Initialization
Problems of non-convergence were eliminated using a systematic procedure for initial estimate generation based on two linear programming (LP) problems: (i) the initialization of the mass balance and (ii) the initialization of the energy and mechanical energy balances. In the first LP problem, the initial estimates of flow rates were generated through the solution of Equations (2) to (4) complemented by split flow specifications. In the second LP problem, with the flow rates estimated in the first problem, the temperatures and pressure drops were generated by solving Equations (5) to (16).

4. Results
The potentiality of the proposed optimization approach is illustrated based on a CPT example of a real Brazilian refinery. This CPT has three parallel branches upstream the desalter and two other branches downstream the desalter. Figure 1 presents a general overview of the CPT structure. The entire network has 11 process supply nodes, 16 process demand nodes, 35 heat exchangers, 6 mixers, 12 splitters and 1 desalter. The detailed description of this system can be found in Oliveira Filho et al. (2009).

Fig. 1. Crude preheat train example investigated

These set of data were complemented with additional hydraulic parameters. The pressure drop at the base case for branches A, B, C, D and E are equal to 13 bar, 8 bar, 6 bar, 10 bar, and 10 bar, respectively. The corresponding mass flow rates are 103 kg/s,
Constrained thermohydraulic optimization of the flow rate distribution in crude preheat trains

78 kg/s, 93 kg/s, 138 kg/s, and 137 kg/s. The total pressure drop available supplied by the pump is equal to 25 bar.

The optimization model was implemented in the GAMS software and the resultant NLP problem was solved using the CONOPT solver. The LP problems for generation of initial estimates were solved using the CPLEX solver.

This optimization scheme was applied to two situations: the original CPT example complemented by the hydraulic data and a similar problem but with a crude flow rate 13% higher and lower available pressure drop equal to 23 bar, related to the profile of the pump characteristic curve. The optimal values of the final temperature are presented in Table 1, together with the corresponding results of the pure thermal optimization (i.e. without mechanical energy balances).

Table 1. Final temperature of cold stream in the optimization.

<table>
<thead>
<tr>
<th>Case</th>
<th>Thermohydraulic</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>266.2 ºC</td>
<td>266.2 ºC</td>
</tr>
<tr>
<td>Increased flow rate</td>
<td>263.9 ºC</td>
<td>264.4 ºC</td>
</tr>
</tbody>
</table>

In the original problem, the thermohydraulic results were identical to the thermal results, thus indicating that the hydraulic facilities did not constrained the optimization search. However, in the increased flow rate scenario, there is a gap of 0.5 ºC, which is a considerable economic impact due to the large flow rates involved. This gap indicates that the actual optimization gain is limited by the available pump power, i.e., in this case, the pure thermal approach indicated a nonrealistic solution.

5. Conclusions

This paper presented the thermohydraulic optimization of the flow rate distribution in CPT for fouling mitigation. The resultant mathematical model corresponds to a NLP problem. Convergences problems are avoided through an automatic procedure for initial estimate generation based on two LP problems.

The application of the proposed procedure to an example based on a real Brazilian refinery illustrated the importance of the hydraulic energy balances in order to identify feasible operational set-points considering the available hydraulic equipment.

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References


