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Heat Exchanger Bypass Control to Mitigate the Cost of Fouling in Refinery Preheat Trains

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Heat exchangers in refineries are usually designed with oversized exchange area to compensate for the gradual loss in thermal performance due to fouling. The control of bypasses during the initial stages of operation (clean conditions) represents a common strategy. This work focuses on the simulation of a preheat train heat exchanger undergoing fouling, equipped with a control of tube-side bypass, and subject to thermal and hydraulic limits. An advanced dynamic model of heat exchangers undergoing fouling, capable to accurately capture both the thermal and hydraulic impact of fouling, is used to simulate the behavior of the exchanger. The study explores the use of bypasses to counter not only thermal over-performance during initial stages of operation, but also to avoid (or minimize) throughput reduction when the maximum allowable pressure drop is reached in late stages of operation. Dynamic simulations of the system, including models for bypass control and cost evaluation, are run to find the optimal time profiles of bypass opening that minimize the total cost associated with the gradual loss of performance. The results demonstrate the potential application of these strategies to guarantee operation within both thermal and hydraulic limits and prolong operation time.

1. Introduction

The crude distillation unit (CDU) is one of the largest energy consumers in an oil refinery. A CDU usually comprises a pre-heat train (PHT) followed by a furnace, where the crude oil is heated from storage, and a distillation column where oil is separated. PHTs are extensive heat exchanger networks essential to recover large amounts of energy. Fouling in these facilities reduces heat exchange and flow area, leading to significant energy losses, operational problems, and economic costs. The input temperature to the furnace (i.e. coil inlet temperature, CIT) progressively decreases as the fouling deposit grows. In order to keep the inlet temperature to the distillation column (i.e. coil outlet temperature, COT) constant, the furnace load has to be increased to compensate for the decreasing CIT, resulting in additional fuel consumption and emissions.

In order to partly compensate the loss in thermal performance, heat exchangers are usually over-designed with an excess of exchange area compared to the minimum required to transfer the design duty. When exchangers are initially clean this additional area leads to an initial over-performance. In situations where this is unacceptable (e.g. highly integrated networks for energy efficiency, or streams that must be controlled within certain temperatures to satisfy process constraints downstream) a reduced flowrate of the fluids exchanging heat is required. So as to avoid a reduction in production, a common strategy consists in partially bypassing one of the streams. This strategy involves simple valve control to regulate the flow fraction being bypassed, allowing the outlet temperature or the heat exchanged in the unit to be controlled. When the unit is clean, the bypass is partially open. As fouling builds up, the bypass is progressively closed to compensate for the loss of thermal performance. The optimization of bypasses in heat exchanger networks has been explored in literature. However, only few works consider the dynamics of fouling. Examples are the work by Rodriguez and Smith (2007), who applied an artificial intelligence algorithm to find optimal flow split and bypass control

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together with the optimal cleaning schedule, and the work by Luo *et al.* (2013), who proposed mathematical optimization for design and control of networks with bypasses. Most works do not account for the impact of flow bypass on the fouling behavior. In addition, the focus is typically on the thermal aspects of fouling, ignoring its hydraulic impact. Suitable dynamic, thermo-hydraulic models for exchangers are required in order to accurately evaluate thermal and hydraulic impact, and the interaction between these as a result of fouling dynamics. An advanced model for shell-and-tube heat exchangers undergoing fouling, fulfilling those requirements, is available in the Hexxcell Studio^{TM} software, based on work by Coletti and Macchietto (2011a). This model was applied to comprehensively study the costs of fouling in a refinery preheat train (Coletti and Macchietto 2011b). The study quantified how the gradual degradation of the thermal performance due to fouling leads to increasing fuel consumption in the furnace. The situation becomes severely aggravated when the thermal limit (i.e. maximum capacity of the furnace, or firing limit) is reached. At that point, plant throughput must be reduced, affecting the production of the whole refinery. Reaching the firing limit exponentially increases costs and refinery loss due to fouling.

Fouling also reduces the flow area and leads to an increased pressure drop (hydraulic performance). In the above study, (Coletti and Macchietto, 2011b), the pumping system was assumed to be flexible and to gradually increase the inlet pressure to compensate the increased pressure drop whilst maintaining the throughput. This results in increased pump power, which increases the operation costs. In most refineries, however, the mass flowrate in preheat trains is controlled by back-pressure (Coletti et al. 2014). The pump operates applying a constant differential pressure, and the flowrate is regulated by a valve at the end of the train. Initially, the valve is partially closed to maintain the flowrate to the target throughput. As fouling builds up, the valve is progressively opened to compensate for the increase in pressure drop. At some point, depending on the pumping capacity, the situation may occur in which the valve is completely open while fouling keeps progressing. Flowrate will gradually decrease due to the high resistance to flow. This hydraulic limit (HL) is only avoided by oversizing pumps at the design stage, thus increasing the capital and operating costs.

In this paper, the heat exchanger model in Hexxcell Studio^{TM} is applied to simulate the behavior of a single unit considering both thermal and hydraulic limits. A similar cost model to that in (Coletti and Macchietto 2011b) is applied to estimate the operating costs under a number of cases. The introduction of a bypass on the tube-side in order to compensate the initial over-performance of the unit is considered. Finally, the application of bypass to compensate for the high pressure drop at later stages of operation is explored.

2. Modelling Approach

2.1 Heat Exchanger Undergoing Fouling and Physical Properties

The exchanger model in Hexxcell Studio^{TM} is distributed, dynamic, and accounts for the local growth and ageing of the fouling deposit, and the derived impact on heat exchange and pressure drop. The reader is referred to (Coletti and Macchietto 2011a) for a detailed description of the model equations, which are not reported here. The tube-side pressure drop in the reference paper, which is restricted to the pressure drop due to friction through the tubes, is extended to account for the losses at the headers according to recommended values (Sinnot 1999). The models are implemented and solved in gPROMS (PSE 2014), a commercial dynamic simulation environment. The physical properties of the fluids (density, viscosity, conductivity, and heat capacity (cp)) are calculated as function of characteristic parameters and local operating conditions, as described in (Coletti and Macchietto 2011a).

2.2 Modelling of Normal Operation and Operation under Thermal and Hydraulic Limits (TL and HL)

The type of operation influences the way the oil mass flowrate (m_{oil}) is calculated. Here this is simply modelled as a different choice of degrees of freedom. Under normal operation the mass flowrate is equal to the maximum established ($m_{oil,max}$). Two conditions must be satisfied: i) the pressure drop through the PHT (ΔP_{PHT}) must be lower than the maximum allowable (called hydraulic limit, *HL*); ii) the furnace duty (Q_f) must be below its maximum capacity (also called thermal limit, *TL*). Once either *HL* or *TL* is reached, the degree of freedom is changed based on logical conditions (Table 1), and m_{oil} becomes a calculated variable.

2.3 Modelling of Bypass

The bypass is simply modelled by including a flow split with the mass balance below:

$$m_{oil} = m_{oil,HEX} + m_{oil,bypass} = (1-K)m_{oil} + K\, m_{oil} \quad (1)$$

Where $m_{oil,HEX}$ is the mass flowrate of oil going through the tube-side of the exchanger, $m_{oil,bypass}$ is the flowrate through the bypass, and K , the bypass fraction, varies between 0 (fully closed) and 1 (fully open).

Table 1: Choice of degrees of freedom for normal operation and operation under thermal and hydraulic limits

Case	Fixed variable	Holds whilst	Calculated variables
Normal	$m_{oil} = m_{oil,max}$	$Q_f \leq TL$ and $\Delta P_{PHT} \leq HL$	Q_f, ΔP_{PHT}
Thermal limit	$Q_f = TL$	$m_{oil} \leq m_{oil,max}$ and $\Delta P_{PHT} \leq HL$	m_{oil}, ΔP_{PHT}
Hydraulic limit	$\Delta P_{PHT} = HL$	$m_{oil} \leq m_{oil,max}$ and $Q_f \leq TL$	m_{oil}, Q_f

The pressure drop on the bypass pipe is neglected. The outlet stream from the exchanger and the bypassed stream are mixed. The outlet temperature and mass flowrate of the resulting stream are calculated from the corresponding heat and mass balances. In a real system, *K* would depend on the opening of the bypass valve. Here, for simplicity, *K* is the controlled variable, and the pressure of the outlet stream is considered equal to the outlet pressure from the exchanger.

2.4 Control of Bypass: strict constraints for over-performance and maximum pressure drop

The bypassed fraction (*K*) can be externally imposed (for instance, when performing a dynamic optimization) or calculated to satisfy certain conditions. In this paper, the second option is chosen, and 3 possible scenarios are considered: i) bypass fully closed (*K*=0), in which the oil flow is directed entirely through the exchanger; ii) automatic bypass control to avoid over-performance, that is, prevent the heat duty from exceeding the target value ($Q_{HEX,target}$) (*K* is calculated); iii) automatic control to prevent the pressure drop (ΔP) from exceeding a set limit (ΔP_{max}) (K is calculated). The transition between scenarios is simply performed by changing the choice of assigned degrees of freedom according to logical conditions, as shown below.

2.5 Cost Model

The cost model is based on the one reported in (Coletti and Macchietto 2011b). The total cumulative cost (C) is the sum of fuel consumption in the furnace (C_f), CO_2 emissions (C_e), and loss in production (C_{pr}).

$$C = C_f + C_e + C_{pr} = \left(P_{fuel} + P_{CO_2} \cdot m_{CO_2}\right) \frac{1}{\eta_{furnace}} \int_0^t Q_f dt + P_{kg} \int_0^t \left(m_{oil,max} - m_{oil}\right) dt \quad (2)$$

where P_{fuel} is the price of fuel, P_{CO2} the price of CO_2 emissions, m_{CO2} the carbon emissions per joule of energy consumed, $\eta_{furnace}$ the efficiency of the furnace, and P_{kg} the operating margin per kg of oil, with values as reported in (Coletti and Macchietto 2011b). Differently from that work, the total heat supplied in the furnace to raise oil temperature from CIT to COT is accounted for, rather than the amount due to fouling.

3. Case Study

A simplified PHT is considered consisting of a single-shell heat exchanger, working under conditions typical of a PHT hot end (Coletti and Macchietto 2011a) and equipped with a bypass (Figure 1). The mass flowrate of the crude oil (tube-side fluid) is calculated as described in Section 2.2. The maximum value is here set to 88 kg/s. The shell-side fluid is a stream from the distillation column, where crude oil is fractionated. The flowrate of this stream will vary with the crude oil throughput. Its flowrate is assumed to be 40% that of the crude oil. Both streams are assumed to enter the system at a constant pressure. Since a single unit is considered and the inlet pressure is kept constant, the hydraulic limit for the preheat train is equal to the maximum pressure drop for the exchanger (HL=ΔP_{max}). The target performance for the heat exchanger ($Q_{HEX,target}$) is assumed to be 6.15MW, which is the heat duty exchanged for a fouling resistance (R_f) of 3 $m^2K\ kW^{-1}$ and maximum throughput. Typical geometric and fouling parameters are used in the simulation. Operating conditions are shown in Figure 1.
Three scenarios are studied: (i) Initial over-performance is acceptable, the influence of the level of the limits on the cost is studied; (ii) Initial over-performance is unacceptable, and the bypass is used to initially reduce the flow through the unit and prevent exceeding $Q_{HEX,target}$; (iii) The bypass is used to compensate over-performance and excessive pressure drop. A total of 9 sets with different combinations of thermal and hydraulic limits are considered and referred to as Thermo-hydraulic limit stets (THL sets), as summarised in Table 3. One year of operation, starting from clean conditions, is simulated in all cases.

Table 2: Choice of degrees of freedom for automatic bypass control

Case	Description	Fixed variable	Holds whilst	Calculated variables
A	Bypass fully closed	$K = 0$	$Q_{HEX} \leq Q_{HEX,target}$ and $\Delta P \leq \Delta P_{max}$	Q_{HEX}, ΔP
B	Avoid Over-performance	Q_{HEX}=$Q_{HEX,target}$	$K \geq 0$ and and $\Delta P \leq \Delta P_{max}$	K, ΔP
C	Avoid Hydraulic limit	ΔP=ΔP_{max}	$K \geq 0$ and $Q_{HEX} \leq Q_{HEX,target}$	K, Q_{HEX}

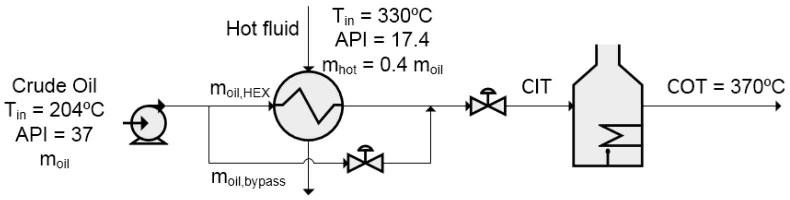

Figure 1: Schematic representation of the system under study

Table 3: Thermal and hydraulic limit sets (THL sets).

[Bar] / [MW]	HL1 1.2	HL2 1.0	HL3 0.8
TL1 41.5	THL 1	THL 2	THL 3
TL2 41.0	THL 4	THL 5	THL 6
TL3 40.5	THL 7	THL 8	THL 9

4. Results

4.1 Scenario (i): The cost of reaching the operating limits

Here, the bypass is simply ignored (only Case A in Table 2 considered). Figure 2 shows the time evolution of the furnace duty (Figure 2a), the pressure drop (Figure 2b), and the oil throughput (Figure 2c) over time for several THL sets with different HL and TL. For an overdesigned system, such as THL 1, the system can operate at full production for the entire year. When the limits are more restrictive, however, as soon as either HL or TL is hit the flowrate starts decreasing. As discussed in (Coletti and Macchietto 2011b), reaching the limits leads to dramatic increase in costs, as shown for case THL 8 in Figure 2d. The results reveal that, for the system in Figure 1, the HL leads to a more dramatic decrease in throughput than the TL. This can be seen, for instance, for set THL 8, where two slopes in the throughput profile are observed: slow decay after heating TL3 (which overlaps with that for set THL 7), followed by faster decay when HL2 is reached. On the other hand, if HL is reached, the system moves away for TL and therefore the latter becomes not limiting. It should be noted that this analysis is specific to this system, and further work is need to extend these conclusions to entire heat exchanger networks. In addition, the relative importance of thermal and hydraulic effects of fouling is heavily influenced by the conductivity of the deposit, which depends on its composition and its coking over time (ageing). The results are summarized in Table 4, which reports which limit is reached first, the operation time until a limit is reached and the costs after 1 year of operation.

4.2 Scenario (ii): Bypass to avoid heat exchanger over-performance and its effect on fouling

In this section, the initial over-performance in clean conditions is assumed to be unacceptable, represented as a strict constraint imposed in the equation system. Cases A and B in Table 3 are considered (C is ignored in this section). The resulting time profile of the bypass fraction is showed in Figure 3b. As expected, part of the fluid is initially bypassed (about 66%). As fouling builds up, the bypass is gradually closed to maintain the heat exchanged to the target value (here showed by a constant value in the furnace duty, Figure 3b). After 40 days, the bypass is fully closed. From that point, the thermal performance inevitably falls below the target as a result of the progression of fouling, and the furnace duty must be gradually increased to compensate.

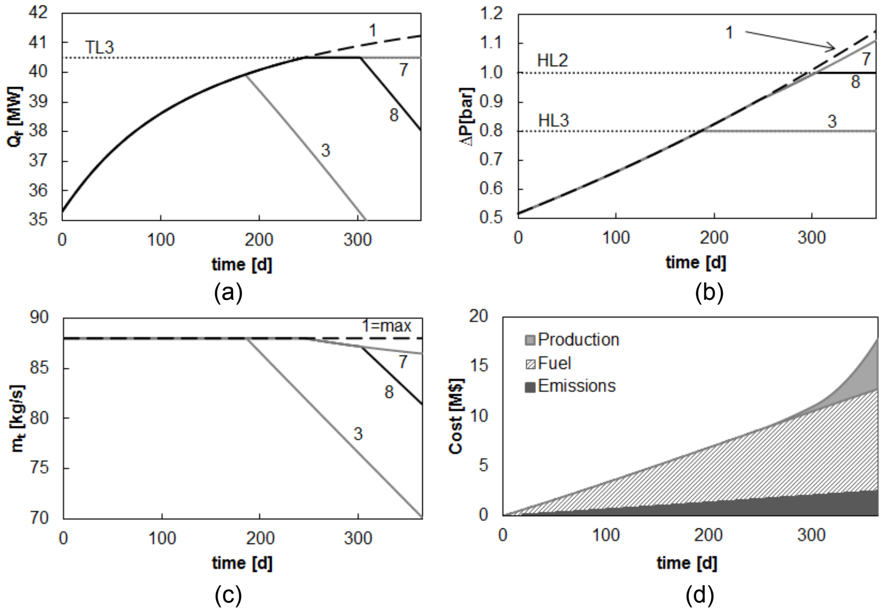

Figure 2: Evolution of furnace duty (a), pressure drop (b) and oil throughput (c) for THL sets 1, 3, 7, 8 and cumulative costs for THL 8 over a year of operation (d).

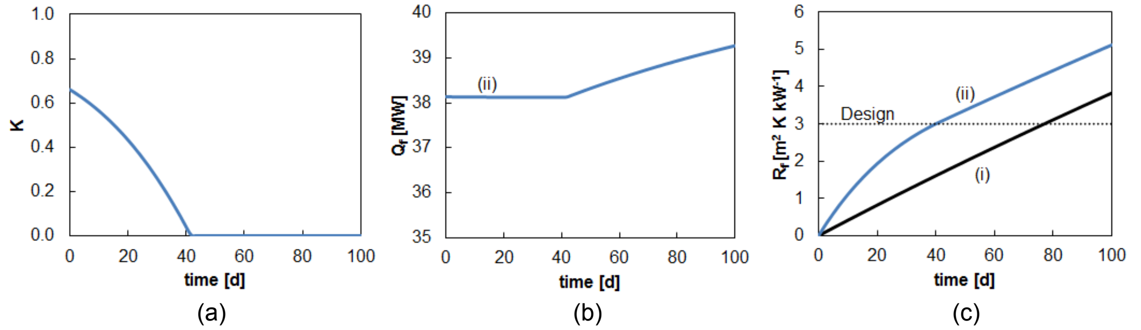

Figure 3: Bypass policy to prevent initial over-performance (Scenario ii) (a), and its impact on furnace duty (b) and fouling resistance (including comparison with Scenario (i)) (c).

By comparing the fouling resistance in scenarios (i) and (ii) (Figure 3c), the results show that the partial bypass of crude oil leads to faster fouling rates (the design R_f is reached 33 days earlier in (ii)) and, consequently, to a faster degradation of the thermal and hydraulic performance and greater fuel consumption at the furnace. As a result, the thermal and hydraulic limits are also reached earlier, increasing the costs compared to the case with full flowrate from clean conditions. This is result of fouling being promoted by low velocities and high local temperatures. The results for THL sets 1-9 are summarized in Table 4. Note that Figure 3 is common to all THL sets, since none of the limits is reached in the timeframe considered.
If the constraint preventing over-performance is strict, as assumed here, the bypass profile showed in the figure is optimal, since it corresponds to the case that maximizes flowrate and minimizes temperature within the heat exchanger. If the over-performance was penalized by some additional cost (e.g. utility consumption), rather than be impeded by a strict constraint, there would be an economic trade-off between cost of over-performance and fuel consumption at the furnace, and more advanced optimization tools would be required. The results highlight the importance of proper exchanger design for minimal oversize, therefore avoiding the need of bypassing, whilst preventing operating conditions that promote fouling.
Alternative configurations, such as bypassing the hot stream (shell-side) instead of the crude oil (tube-side) could be considered, and might be more advantageous if the hot fluid had low or no propensity to foul.

4.3 Scenario (iii): Bypass to avoid hitting the hydraulic limit

Case A, B and C in Table 2 are included. By enabling the constraints in case C, the bypass is opened as soon as the HL is hit, and a reduction in throughput is avoided (Hydraulic limit in Table 1 is never active). The time-profile of bypass fraction is shown in Figure 4(a) for the cases with more restrictive TL (THL sets 7 to 9).
The furnace duty, pressure drop, and throughput time-profiles and cumulative costs are shown in Figure 4(b,c) for THL set 8, and compared to those in Scenario (ii). When the hydraulic limit is hit, part of the oil is bypassed, maintaining the pressure drop constant over time whist avoiding the reduction in throughput. This leads to significant savings from the moment the HL is hit until the end of the operation period (7.8 M$ for THL 8). On the other hand, partial bypassing also leads to lower CIT (due to lower recovery and enhanced fouling rate) and, therefore, greater fuel consumption. Nevertheless, given the clear dominance of the throughput cost over the others, and the greater impact of HL on throughput compared to TL, the results reported for Scenario (iii) can be considered as a near optimum. For instance, in the case of THL 9 (the set of more restrictive limits) the costs due to decreased energy recovery (emissions and fuel) is 0.9 M$ higher in Scenario (iii) than in Scenario (ii), but the savings in cost of production ascend to 41.8 M$.

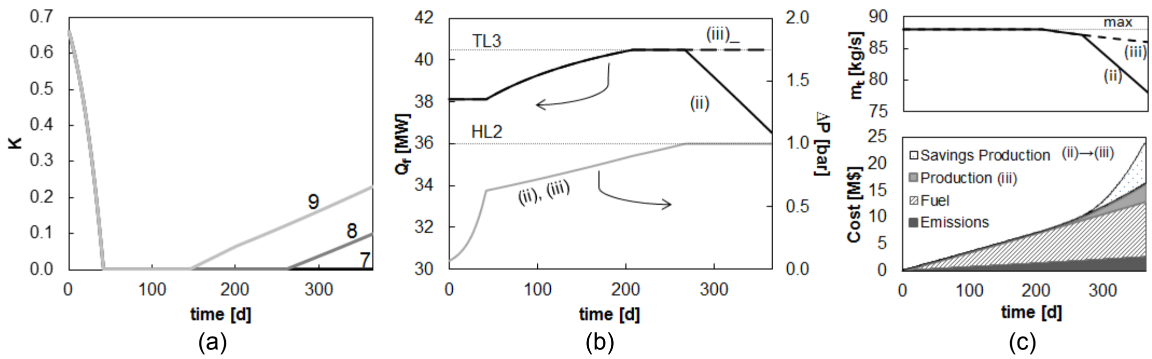

Figure 4: Bypassed fraction over time in scenario (iii) for sets THL 7-9 (a), furnace duty, pressure drop, throughput and cost for Scenarios (ii) and (iii) with THL set 8 in (b,c).

Table 4: Summary of Results. Time to reach operating limits and costs after 1 year

THL set	1			2			3			4			5		
Scenario	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Days to HL	-	355	355	295	253	253	187	150	150	-	364	356	295	253	253
Days to TL	-	-	-	-	-	-	-	-	336	318	281	281	-	-	279
C_f [M$]	10.4	10.5	10.5	10.3	10.3	10.5	9.8	9.7	10.5	10.4	10.5	10.5	10.3	10.3	10.5
C_e [M$]	2.5	2.6	2.6	2.5	2.5	2.6	2.4	2.4	2.6	2.5	2.6	2.6	2.5	2.5	2.6
C_p [M$]	0.0	0.1	0.0	4.6	10.6	0.0	31.7	46.0	0.1	0.2	0.7	0.7	4.6	10.6	0.9
C [M$]	12.9	13.2	13.1	17.3	23.4	13.1	43.9	58.1	13.2	13.1	13.8	13.8	17.3	23.4	13.9
THL set	6			7			8			9					
Scenario	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)			
Days to HL	187	150	150	-	-	-	303	266	266	187	150	150			
Days to TL	-	-	261	246	208	208	246	208	208	-	-	208			
C_f [M$]	9.8	9.7	10.5	10.3	10.5	10.5	10.3	10.3	10.5	9.8	9.7	10.5			
C_e [M$]	2.4	2.4	2.6	2.5	2.5	2.5	2.5	2.5	2.5	2.4	2.4	2.5			
C_p [M$]	31.7	46.0	1.5	2.0	3.2	3.2	5.0	11.1	3.3	31.7	46.0	4.2			
C [M$]	43.9	58.1	14.6	14.8	16.2	16.2	17.8	23.9	16.3	43.9	58.1	17.2			

The bypass profile policy is similar for those sets with the same HL, with slightly greater bypassed fractions as the TL is relaxed (no reduction in throughput due to thermal limitations). The results for all limit sets (THL 1-9) are reported in Table 4.

5. Conclusions

A simple PHT with a single heat exchanger undergoing fouling has been simulated under a number of levels of TL and HL. The results show that reaching the HL leads to larger decrease in throughput and, consequently, to higher costs. Bypass of the stream can be carried out to initially compensate over-design and maintain the heat duty to the desired target. The optimal profile of bypassed fraction, obtained by simulation, consist of an initial diversion of the flow, followed by a gradual reduction as fouling builds up. Tube-side fluid bypass has been shown to lead to greater initial fouling rate, reducing energy recovery and the times to reach the operating limits. Based on this analysis, the use of bypass for this purpose is not recommended and should be avoided when possible. Finally, it has been proposed to use a bypass to compensate the excessive pressure drop derived from deposition. By gradually opening the bypass when the HL is hit, operation at maximum throughput is enabled for longer periods, eliminating the major costs to the refinery. For the cases studied here, the savings achieved by maximising the refinery throughput significantly offset the larger costs due to the additional fuel consumption at the furnace. For more complex cases, e.g. extensive networks with a large number of heat exchangers, additional trade-offs need to be taken into account and formal mathematical optimization would be necessary.

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