THERMO–ECONOMIC OPTIMIZATION OF FIRED HEATER INTEGRATED PROCESSES

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ABSTRACT

Fired heaters supply heat to process streams at elevated temperature. These equipments are energy as well as capital intensive. Energy integration of a fired heater is important for optimization of the entire process plant. In this paper, issues related to the thermo-economic optimization of fired heater integrated processes are studied. Performance of a fired heater is affected by variables such as fuel fired and air preheat temperature. These variables along with the minimum approach temperature difference for the heat recovery of the background process, affect the thermo-economic performances of the overall system. Using the proposed methodology the fuel fired, air preheat temperature and the heat recovery network associated with the background process are optimized simultaneously.

Key words: Process Integration, Fired Heater, Optimization, Pinch, Heat Exchanger Network.

NOMENCLATURE

A	Area [m^2]
C	Cost [$]
c	Specific heat capacity [$kJkg^{-1}K^{-1}$], specific cost
CRF	Capital recovery factor
CV	Net calorific value [$kJkg^{-1}$]
d	Degree of stirring
E	Excess air fraction over stoichiometry
F	Overall heat transfer factor
h	Heat transfer coefficient [$kWm^{-2}K^{-1}$]
K	Cost coefficient
m	Mass flow rate [kgs^{-1}]
n	Life [y]
p	Discount rate
Q	Heat duty [kW]
q	Heat flux
S	Stoichiometric air fuel ratio
T	Temperature [K]
t	Plant operating time [h/y]
U	Heat transfer coefficient [$kWm^{-2}K^{-1}$]
Δ	Difference
α	Setting losses fraction
σ	Stefan-Boltzmann constant

Subscripts

a	Air
ap	Air preheater
bw	Bridge wall
c	Convection fraction
cap	Capital
capann	Annualized capital
cu	Cold utility
d	dew point
FT	Flame condition
f	Fuel
fanpow	Fan power
fh	Fired heater
g	Flue gas
i	Interval
in	Inlet
lm	Logarithmic mean
min	Minimum
ph	Process to process heat exchanger
p	Process
out	Outlet
oprt	Operating
r	Radiation fraction
s	Stack
TAC	Total annualized capital
0	Ambient
1	Sink

INTRODUCTION

Energy saving and capital investments are two important factors during conceptual design of a process. Effective integration of various

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equipments to the process is the challenge before the process designer. Pinch technology helps to target the energy requirements prior to design and evolution of the heat exchanger network. Minimization of the total annualized cost combines the interaction of the operating and capital cost effects. Fired heaters supply heat to process streams at elevated temperature. Fired heaters are considered both capital and energy intensive process equipment.

Linnhoff and de Leur [1] had proposed a simple procedure for fired heater integration based on simple assumptions. Air preheating is considered using the flue gas heat after the process heating and the fuel fired is optimized by matching the process grand composite curve (GCC) against the linear (in temperature–heat duty diagram) flue gas line through an iterative procedure. Integration of fired heater has been proposed by Hall and Linnhoff [2] considering fuel quantity and air preheat temperature as variables. The simple linear profile of the flue gas as proposed by Linnhoff and de Leur[1] has been used in the analysis. The concept of utility grand composite curve has been utilized to simplify the integration procedure. The proposed graphical methodology avoids the iteration procedure as otherwise required for integration of fired heater with air preheating. The procedure essentially minimizes the operating costs. Effect of capital cost has not been considered during optimization. Figure 1 illustrates the procedure for integration.

A two-zone model of a fired heater has been proposed by Stehlik et al. [3] for integration of the fired heater system. Algorithms have been suggested to optimize the air preheat temperature and the stack temperature considering fuel and capital cost of the convection section only. The optimization of air preheating system has been presented for retrofit cases by Stehlik et al. [4] and Jegla et al. [5].

Varghese and Bandyopadhyay [6] have proposed an analytical and algorithmic procedure for integration of fired heater with background process. The stirred reactor-based model proposed by Varghese and Bandyopadhyay [6] can determine the duty split between the radiation and the convection section of a fired heater. This model is utilized in this paper for the thermo-economic optimization of a network with fired heater involving energy–economic tradeoff. A methodology is presented for the optimization of the fired heater parameters along with the heat recovery network of the background process. A two-part cost model for the fired heater is proposed in this paper for the thermo–economic optimization of the overall fired heater integrated process.

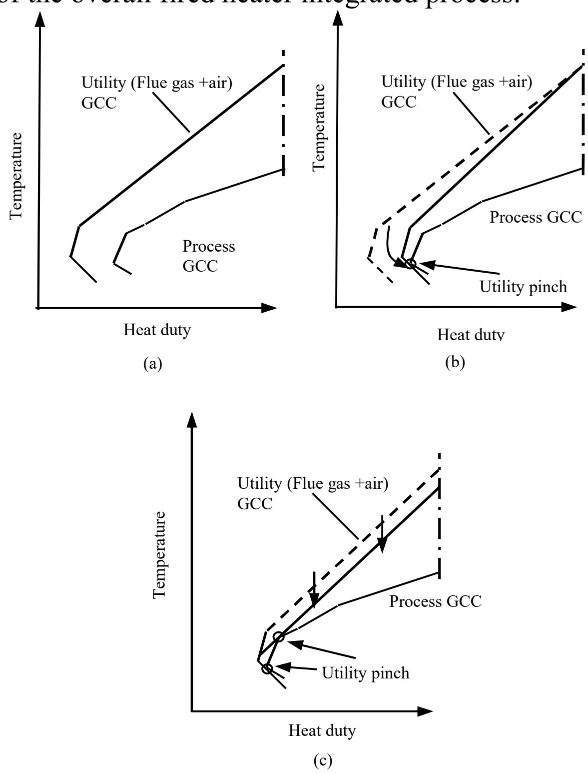

Figure 1: Integration of fired heater with background process. (a) Utility GCC matched against process GCC with high air preheat and fuel firing. (b) Reduction of fuel fired up to utility pinch. (c) Targeting minimum air preheat temperature.

COST OPTIMIZATION PROCEDURE

The energy targets for process streams corresponding to a minimum approach temperature (ΔT_{min}) may be targeted using the pinch procedure (composite and grand composite curves). The overhang of the composite curves gives the hot utility (Q) and cold utility (Q_{cu}) requirements (see Figure 2). The fired heater supplies the required hot utility. Process streams enter into the fired heater convection section after completing possible process to process heat recovery. Streams flows from the convection section to the radiation section and leaves the fired heater after picking up the required amount of heat duty. Schematic of a fired heater is shown in Figure 3.

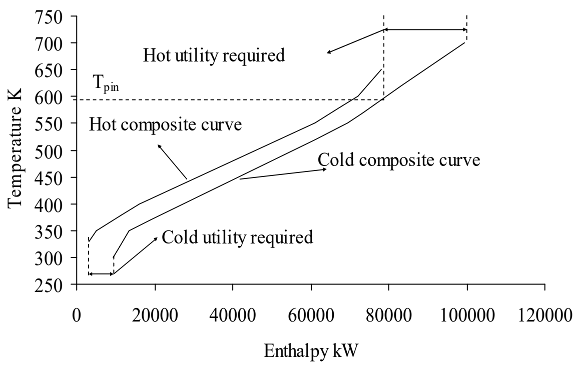

Figure 2: Composite curves for the example.

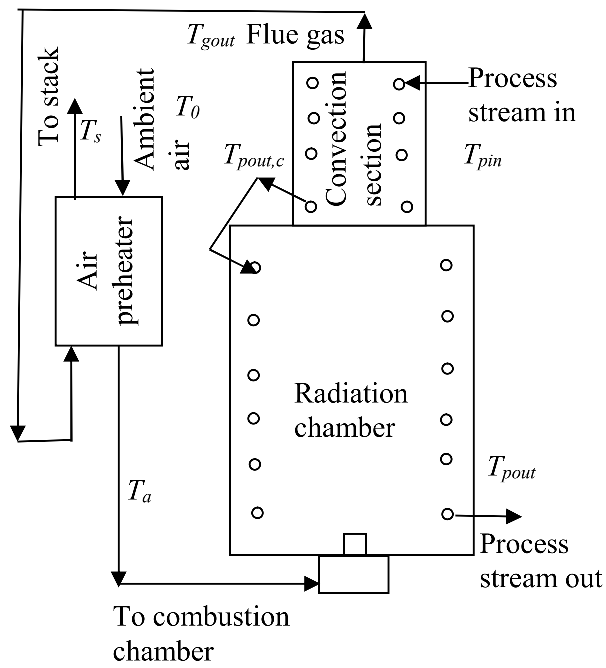

Figure 3: Schematic of a fired heater.

Theoretical flame temperature (T_{FT}) may be obtained from the energy balance of the combustion assuming appropriate setting losses.

$$T_{FT} = T_0 + \left[\frac{Sc_a(1+E)(T_a - T_0) + (1-\alpha)CV}{c_g[S(1+E)+1]} \right] \quad (1)$$

The total hot utility requirement is divided between the radiation chamber and the convection section. The flue gases in the radiation chamber give Q_r amount of heat to the process fluid and the flue gas temperature come down to the bridge wall temperature T_{bw} from the flame temperature

Stirred reactor model

The stirred reactor model predicts the overall heat transfer mechanism and performance of a fired heater more accurately [7]. This model can be applied to any type of combustion chamber configurations and to all fuels. In this model the furnace chamber is modeled using three zones, a single gas zone which is at a uniform effective temperature, the heat sink which absorbs the heat from gases and the refractory respectively. Based on this concept, a simplified model for a fired heater has been proposed by Varghese and Bandyopadhyay [6]. The hot gas is assigned a mean effective radiating temperature T_g, and the refractory surface is radiating adiabatically. Radiation losses through the openings and surfaces are neglected. From the energy balance of the net heat transfer from the combustion gases to the heat sink, the tubes carrying the process fluid at the mean metal temperature T_1 by radiation and convection, the radiation flux could be determined.

$$q = F_r \sigma (T_g^4 - T_1^4) + F_c (T_g - T_1) \quad (2)$$

Where F_r combines the overall radiation view factor of the radiation chamber and F_c is the convection coefficient in the radiation chamber.

The bridge wall temperature, the temperature of the flue gas leaving the radiation chamber and the mean radiating temperature are related with an allowance for imperfect stirring.

$$T_{bw} = dT_g - (d-1)T_{FT} \quad (3)$$

Based on the actual data presented by Berman [8], it is reported that for the vertical cylindrical and horizontal tube heater, F_r = 0.201, F_c = 0.02197, and d = 1.07 [6].

The radiation fraction of the total duty could be determined assuming constant specific heat of the flue gas.

$$Q_r = Q(T_{FT} - T_{bw}) / (T_{FT} - T_{gout}) \quad (4)$$

Convection section of the fired heater supplies the remaining heat duty Q_c to the process streams and the flue gases leaves the convection section at temperature T_{gout}.

$$Q_c = Q - Q_r \quad (5)$$

$$T_{gout} = T_{TF} - Q / m_g c_g \quad (6)$$

The process stream enters the convection section at a temperature T_{pin} (obtained from the composite curve) after completing the process to process heat recovery and leaves at higher temperature $T_{pout,c}$.

$$T_{pout,c} = T_{pin} + Q_c / m_c c_c \quad (7)$$

The heat transfer area requirement for the fired heater convection section and the air preheater can be determined. For the fired heater convection section, the mean temperature and the overall heat transfer coefficient with process stream heat transfer coefficient h_p and the flue gas with h_g can be found as

$$U_{gp} = [h_p^{-1} + h_g^{-1}]^{-1} \quad (8)$$

$$\Delta T_{lm} = \frac{(T_{bw} - T_{pout,c}) - (T_{gout} - T_{pin})}{\ln\left[\dfrac{T_{bw} - T_{pout,c}}{T_{gout} - T_{pin}}\right]} \quad (9)$$

$$A_c = Q_c / \Delta T_{lm} U_{gp} \quad (10)$$

The flue gas, after the process stream heating is used to preheat the combustion air. Considering the energy balance of the air preheater the stack temperature T_s may be calculated.

$$T_s = T_{gout} - \frac{(1+E)Sc_a(T_a - T_0)}{[1+(1+E)S]c_g} \quad (11)$$

Air preheater area A_{ap} can be calculated in a similar way.

$$A_{ap} = m_a c_a (T_a - T_0)/(\Delta T_{lm} U_{ga}) \quad (12)$$

The process to process and process to cold utility heat exchanger area A_{ph} can be calculated from the balanced composite curves. The temperatures at the vertex of the composite curves (change of slope) and heat transfer in the interval i are used to target the heat exchanger area in that interval.

$$A_{ph} = \sum_i Q_i / \Delta T_{lm,i} U_i \quad (13)$$

The number of heat exchanger units for the heat recovery network can be targeted using the Euler's formula, used in graph theory.

Capital cost

The capital cost of different heat exchangers are estimated to be proportional to its heat transfer area.

$$C = K\,A \quad (14)$$

Fans are required to overcome the increase in air pressure drop due to the air preheater. The capital cost of fan is assumed to be proportional to the mass flow rate of flue gas.

$$C_{fan} = 5460 m_g \quad (15)$$

Cost of a fired heater is the predominant factor of the overall capital investment. Existing cost correlation for a fired heater is proportional to its heat duty. However, the existing correlation fails to optimize the temperature driving force between the flue gas and the process streams. A new two-part cost model has been proposed in this paper to overcome this limitation. It may be noted that the heat transfer area in the radiation section is a function of the effective heat flux in the radiation chamber (typically specified during design stage) and does not depends on the temperature driving potential. On the other hand, heat transfer area in the convection section is influenced by the temperature potential due to the lower temperatures involved. Therefore, it may be assumed that the cost of the radiation section of a fired heater is a function of its heat duty and the convection section of the fired heater is a function of its heat transfer area.

$$C_{fh} = K_r Q_r + K_c A_c \quad (16)$$

The total capital cost can be estimated as a sum of the cost of all components.

$$C_{cap} = C_{fh} + C_{ph} + C_{ap} + C_{fan} \quad (17)$$

$$C_{capann} = C_{cap} CRF \quad (18)$$

Where, capital recovery factor is used ($p(1+p)^n / [(1+p)^n - 1]$) to annualize the total capital cost.

Operating cost.

The total operating cost of the overall fired heater integrated system includes the fuel cost, cold utility cost and fan power cost. The total plant utilization of t hours is considered annually for the calculation. The fan power is calculated based on the mass flow rate of flue gas.

$$C_f = 3600 m_f t c_f \quad (19)$$

$$C_{cu} = Q_{cu} c_{cu} \quad (20)$$

$$C_{fanpow} = 0.62 m_g t \quad (21)$$

The total operating cost is found to be

$$C_{oprt} = C_{cu} + C_{fanpow} + C_f \quad (22)$$

THERMO–ECONOMIC OPTIMIZATION

The objective function for the optimization is the total annualized cost of the system.

$$C_{TAC} = C_{capann} + C_{oprt} \quad (23)$$

This objective function is to be minimized with respect to the air preheat temperature T_a, and mass flow rate of the fuel m_f. The optimization process can be done with any search method and starts with a high value for the fuel quantity, air preheat temperature. The constraints for the optimization are,

(1) The air preheat temperature $T_a \geq T_0$. This is a practical limit as in some cases the air preheat temperature may tend to minimize during the iterations.

(2) The stack temperature must be $T_s \geq T_d$ The stack temperature cannot be allowed to come below the acid dew point to prevent any possibility of acid formation on the stack resulting corrosion.

Fuel quantity

Quantity of fuel fired in the fired heater is an important variable for the overall integration. It may be observed that an increase of the fuel quantity increases the mass flow rate as well as the temperature of the flue gas leaving the convection section of the fired heater, bringing down the area requirement in the convection section and its cost. Furthermore, the stack temperature will increase corresponding to an increase of fuel fired; thereby reducing the air preheater area requirement. Thus, the total capital will be reduced for an increase in fuel quantity. But this will lead to an increase of operating cost, so we can have an optimum range for the fuel quantity fired.

Air preheating

We have considered recovering part of the flue gas heat by employing an air preheater. Air preheat temperature is a variable for the optimization. For an increase in air preheat temperature, the flame temperature increases as well as it leads to a possible reduction in the stack temperature. This leads to a reduction in the fuel consumption. Additionally, the higher temperatures reduce the capital of fired heater. But a higher air preheat temperature increases the air preheater area requirement and the air preheater capital will be increased. This leads to an optimum range of air preheat temperature.

We can optimize the C_{TAC} by repeating the procedure for various values of process ΔT_{min} and the optimum range ΔT_{min} corresponding to minimum *TAC* can be arrived at. Thus, using this method the fired heater got integrates with the process effectively optimizing the total cost involved. It may be noted that this optimization is a nonlinear optimization problem and *not* a mixed integer nonlinear optimization problem due to linear cost correlations are assumed, neglecting fixed installation cost for every component.

ILLUSTRATIVE EXAMPLE

The proposed methodology is illustrated with the following example. The stream data for the example is given in Table 1.

Table 1: Stream data

Streams	MC_p kW/K	T_{in} K	T_{out} K	h $kWm^{-2}K^{-1}$
H1	100	600	300	1
H2	120	650	350	1
H3	80	550	400	1
C4	200	350	700	2
C5	80	300	550	2

The fuel used is having a net heating value of 41000 kJ/kg. The stoichiometric air-fuel ratio is assumed to be 15 and minimum excess air recommended is 10%. The ambient is at 303 K; average specific heat of air and flue gas are assumed be 1.005 $kJkg^{-1}K^{-1}$ and 1.148 $kJkg^{-1}K^{-1}$, respectively. The limiting dew point temperature of the flue gas is 433 K. and the setting losses (α)

is taken as 2%. The heat transfer coefficient for the flue gas and air are assumed as 0.052 $kWm^{-2}K^{-1}$ and 0.049 $kWm^{-2}K^{-1}$, respectively. The design average radiant tube flux is taken as 29 kWm^{-2}. The plant life, discount rate, and the annual operating hours are taken as 10 y, 10%, and 8000 h/y, respectively. The costing correlations are given in Table 2.

Table 2: Cost coefficients/correlations.

Capital cost correlation		
#	Equipment	Cost ($)
1	Radiation section	$144.0\times Q_r$
2	Convection section	$1000\times A_c$
3	Air preheater	$300\times A_{ap}$
4	Process exchangers	$1100\times A_{ph}$
5	Air preheater fan	$5460\times m_g$
Operating cost		
#	Utility	Cost
1	Fuel (c_f)	$0.03/kg
2	Cold utility (c_{cu})	$10/(kW y)

The hot utility required is determined from the problem table algorithm, and it is supplied by the fired heater. The composite curves for the example is shown in the Figure 2. The total annualized cost is optimized for the air preheat temperature, fuel fired and the optimization is carried out for various minimum process approach temperature ΔT_{min}. Results are shown in the Figure 4. The optimum approach temperature is found to be in the range of 30 K and the corresponding hot utility requirement is 21400 kW. The pinch point is identified as 550 K on the hot side and 520 K on the cold side. The results of the overall integration are given in Table 4. The network corresponding to the optimum process temperature difference of 30 K is shown in Figure 5. It may be noted that the radiation and convection section of the fired heater is shown separately in Figure 5 for clarity.

Sensitivity analysis

The sensitivity of the optimum results to the various capital coefficients on the overall optimization are shown in the Figure 6. For 5% change in the radiation section cost, convection section and air preheater cost, *TAC* is found to change proportionally without a significant change in optimum ΔT_{min}. A small change in optimal ΔT_{min} may be observed from Figure 6. As the capital cost

Table 4: Optimization results for the example.

Optimum ΔT_{min} (K)	30
Pinch temperature (K)	535
Optimum fuel required (kg/s)	0.595
Hot utility required (kW)	21400
Cold utility required (kW)	9400
Opt. air preheat temperature (K)	526.4
Flame temperature (K)	2369
Mean radiating temperature (K)	1292
Bridge wall temperature (K)	1217
Radiation duty fraction	0.68
Fired heater efficiency	87.7%
Total annualized cost ($/y)	1.635×10^6

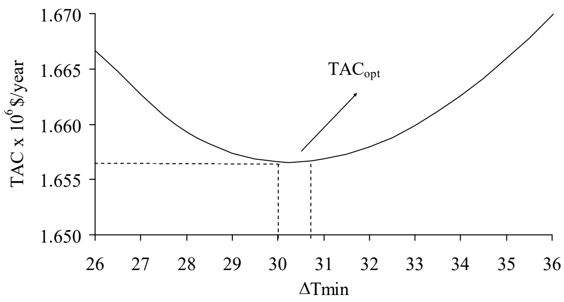

Figure 4: Optimization of ΔT_{min} for the network

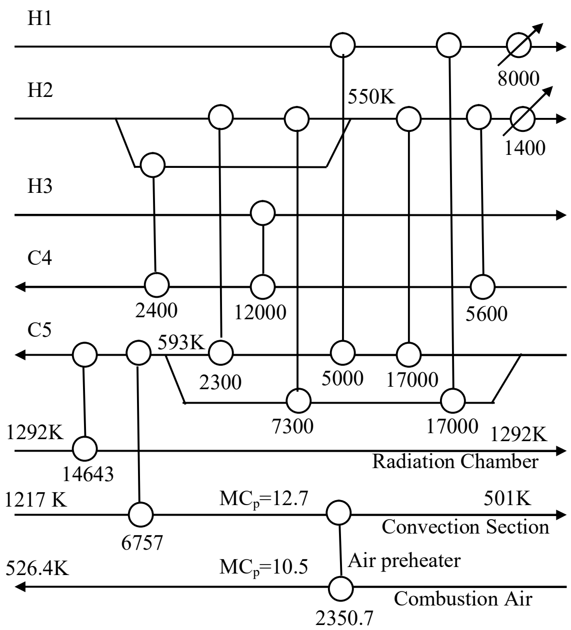

Figure 5: Optimized network for ΔT_{min} = 30K.

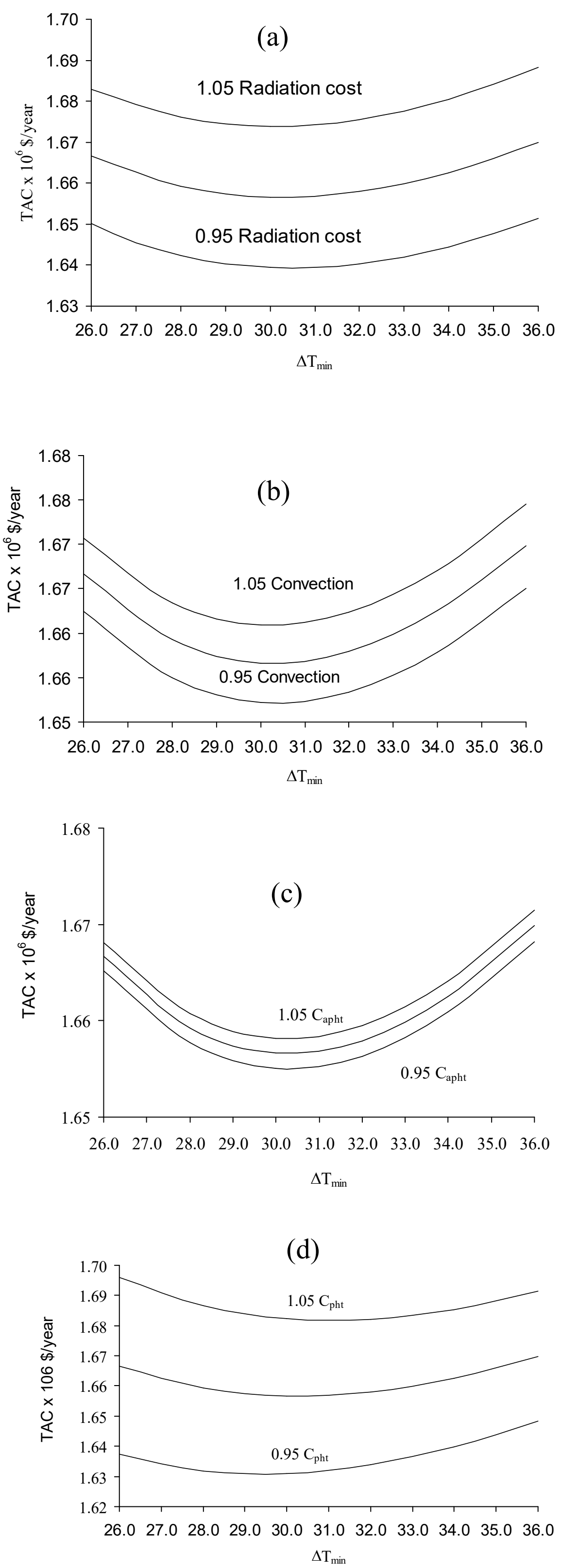

Figure 6. Sensitivity analysis: (a) radiation section cost, (b) convection section cost, (c) air preheater cost, and (d) process exchanger cost.

of the radiation section, convection section, or air preheater is increased, the optimum ΔT_{min} decreases marginally. Change in the capital cost of process heat exchanger influences the optimum value of ΔT_{min}. As the capital cost of process heat exchangers increases, the optimum ΔT_{min} increases.

Increase in capital cost of components directly related to the fired heater essentially makes the overall system more energy efficient. This is expected as the heat duty of the fired heater directly influences its capital cost. On the other hand, decrease in capital cost of the process exchanger makes the overall system energy efficient. In this case, increase in heat duty makes the composite curve to move apart and consequently, the vertical gap between the composite curves increases. This increases the temperature driving force in each interval and reduces the total process to process heat transfer area. Thus reduces the capital investment for the heat recovery network of the background process.

The effects of various operating costs on the overall optimization are shown in Figure 7. For a 5% change in fan power cost, cold utility cost, and fuel cost causes a proportional change in the overall system cost. The optimum ΔT_{min} also changes accordingly. As discussed above, increase in operating cost reduces the overall utility requirement and hence, the overall system becomes more energy efficient.

Form Figures 6 and 7, it may be observed that the capital costs of fired heater (both radiation chamber and convective section) and process heat exchangers influences the overall optimization significantly. Similarly, the operating costs for the cold utility and the fuel have a significant influence on the overall optimization. However, sensitivity of air preheater capital cost and operating cost related to fan power is not significant.

CONCLUSIONS

For an overall optimization of the entire process plant, it is necessary to optimize the heat recovery subsystem along with the utility system. In this paper, a methodology for integrating fired heater with the background heat recovery network has been proposed and discussed. The thermo-economic optimization of a heat exchanger network along with fired heater and air preheater parameters helps to integrate the fired heater effectively with the process. The proposed methodology simultaneously optimizes the approach temperature driving force between the flue gas and process streams, fuel fired in the fired heater and the possible heat recovery achievable through the air preheater. Through the detailed sensitivity of the cost coefficients, important factors for integration of fired heater and optimization of the overall systems has been identified.

It may be noted that in actual practice, cost correlations are non-linear to incorporate the effect of scale of economy. Inclusion of these non-linear cost correlations may increase the mathematical complexity of the optimization problem. In the illustrated example, installation cost for different equipments has been neglected. Inclusion of these fixed charges may bring the effect of number of such equipments into optimization problem. This may make the TAC curves discontinuous and adds further mathematical complexity. However, the proposed methodology is valid for non-linear cost correlations with installation costs.

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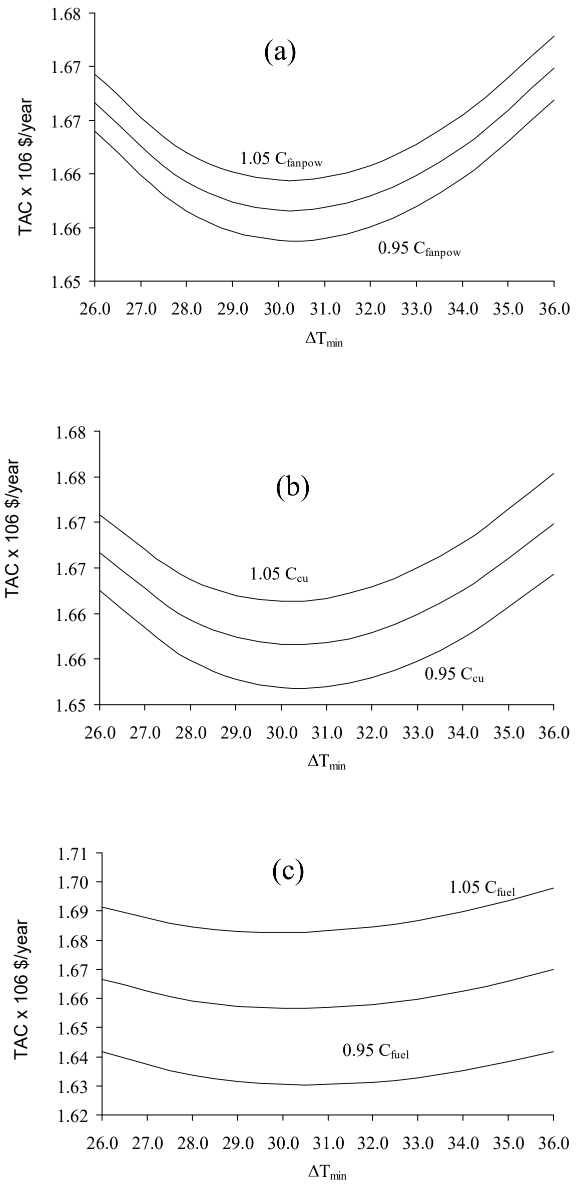

Figure 7. Sensitivity analysis: (a) fan power cost, (b) cold utility cost, and (c) fuel cost.

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