TARGETING FOR ENERGY INTEGRATION OF MULTIPLE FIRED HEATERS

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ABSTRACT

Fired heaters are both energy and capital intensive process equipment. Energy integration of fired heaters with the background process helps in targeting fuel requirement and air preheat temperature prior to its detailed design. Existing integration procedures are applicable for processes with single fired heater only. However, in certain processes, multiple fired heaters are required to satisfy the total hot utility demand. In this paper, a methodology is proposed to target the number of fired heaters. Fuel requirement and air preheat temperature for every fired heater may have to be re-estimated to set achievable targets. With multiple fired heaters, duties of different fired heaters can be varied to simplify the design of the overall heat exchanger network.

Key words: Fired heater; pinch; process integration; heater duty; multiple fired heater

NOMENCLATURE

C	Heat capacity as defined after equation (2) [kJkg^{-1}K^{-1}]
c	Specific heat capacity [kJkg^{-1}K^{-1}],
E	Excess air fraction over stoichiometry
F	Net calorific value [kJkg^{-1}]
GCC	Grand composite curve
H	Heat [kW]
M	Mass flow rate [kgs^{-1}]
Mc	Heat capacity [kJK^{-1}]
Q	Hot utility [kW]
S	Stoichiometric air fuel ratio
T	Temperature [K]

Greek letters

α	Setting losses fraction
Δ	Difference

Subscripts

a	Air
adl	Additional
eff	Effective
FT	Flame condition
f	Fuel
g	Flue gas
gout	Condition at exit of convection section
i	Intermediate
in	Inlet
j	Interval above pinch
min	Minimum
max	Maximum
mix	Mixture
n	Actual condition
out	Outlet
p	Pinch
s	Stack
t	Target
0	Ambient
1, 2	Streams

1. INTRODUCTION

Energy saving and capital investment are two important factors during conceptual design of a process. Effective energy integration of various equipments into the process is a challenge before the process designer. Pinch technology helps to target the energy requirements prior to detailed design of process equipments and associated heat recovery network. Fired heaters supply the heat required by process streams at elevated temperature. Fired heaters are both capital and energy intensive process equipment. Primary objective of this paper is to develop energy integration procedure, based on pinch technology, for integrating fired heaters with the background process.

Linnhoff and de Leur [1] had proposed an iterative procedure for fired heater integration by

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matching the process grand composite curve (GCC) against the linear (in temperature–heat duty diagram) flue gas line. A graphical method for integrating fired heater has been proposed by Hall and Linnhoff [2] based on the concept of utility grand composite curve. 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. 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 Jegla et al. [4]. Varghese and Bandyopadhyay [5] have proposed an analytical and algorithmic procedure for integration of fired heater with background process.

In many applications, such as combined crude and vacuum distillation units in refinery, multiple fired heaters are required to meet the local hot utility requirement. In such applications, it is important to estimate the minimum number of fired heaters required to supply the heat demand. Since fired heaters are capital intensive equipment, estimation of minimum number of fired heaters is important for estimating total capital investment in designing a process plant. In this paper, a methodology is proposed to target minimum number of fired heaters.

Based on the analytical procedure proposed by Varghese and Bandyopadhyay [5], fuel requirement and air preheat temperature can be targeted for integrated fired heaters. The heat exchanger network of the overall process may be synthesized using the tools of pinch technology. Heat exchanger network that satisfies targets such as fuel requirement and air preheat temperature, may be complex in nature involving complex design of the fired heater convection and radiation sections. Existing network-evolution principles cannot be applied directly on such networks as fired heaters are connected utility. Different network-evolution schemes with associated energy penalties are analyzed and discussed in detail. For example, simplified heat exchanger networks with once through fired heaters result in increase in fuel requirements and hence, reduction in efficiency. Simplifications during evolutions of network from GCC structure may result in increasing the duty of heaters. However, this may reduce the number of heaters.

2. FIRED HEATER TARGETS

Procedure for targeting and energy integration of fired heater is reviewed briefly [5]. The process GCC is matched against the utility grand composite curve consisting flue gas and air preheating as shown in Figure 2. Two zone model for fired heater is employed here. Ambient air is initially heated to an intermediate temperature T_i using process heat and then it is further heated to a final temperature of T_a. Flue gas leaves the fired heater convection section after supplying the required heat at T_{gout} and leaves to the stack at temperature T_s after preheating the combustion air.

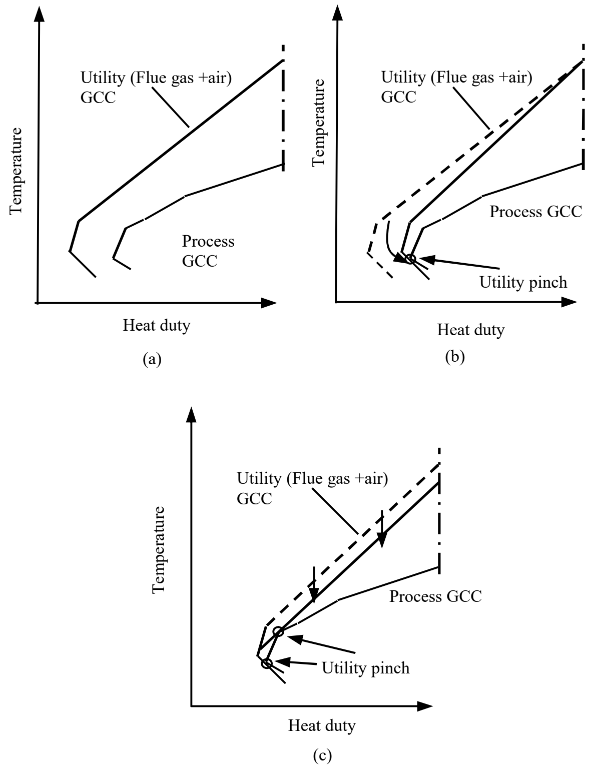

Figure 1: Graphical integration of fired heater with background process. (a) Utility GCC matched against process GCC with high air preheat temperature and fuel firing. (b) Targeting minimum fuel requirement. (c) Targeting minimum air preheat temperature.

Energy balance for the air preheater may be expressed as

$$C_g(T_{gout} - T_s) = C_a(T_a - T_0) \tag{1}$$

Combining equation (1) with process hot utility requirement and the energy balance of the combustion process, mass flow rate of the fuel can be expressed as

$$M_f = \frac{Q}{F_{eff} - C_g(T_s - T_0) + C_a(T_i - T_0)} \tag{2}$$

where $C_a = c_a S(1+E)$, $C_g = c_g[1 + S(1+E)]$ and $F_{eff} = (1-\alpha)F$. Based on the utility pinch, intermediate air preheat temperature using process heat may be calculated:

$$\begin{aligned} T_i &= \frac{QC_g[C_gT_s - C_a\Delta T_{ga}]}{QC_aC_g - H_jC_a\Delta C} \\ &- \frac{\Delta CC_g(QT_{jn} + H_jT_s)}{QC_aC_g - H_jC_a\Delta C} \\ &+ \frac{\Delta CH_j(F_{eff} + T_0\Delta C)}{QC_aC_g - H_jC_a\Delta C} \end{aligned} \tag{3}$$

with $T_{jn} = T_j + 0.5\Delta T + \Delta T_{adl}$, $\Delta C = C_g - C_a$, and $\Delta T_{ga} = T_{gout} - T_a$.

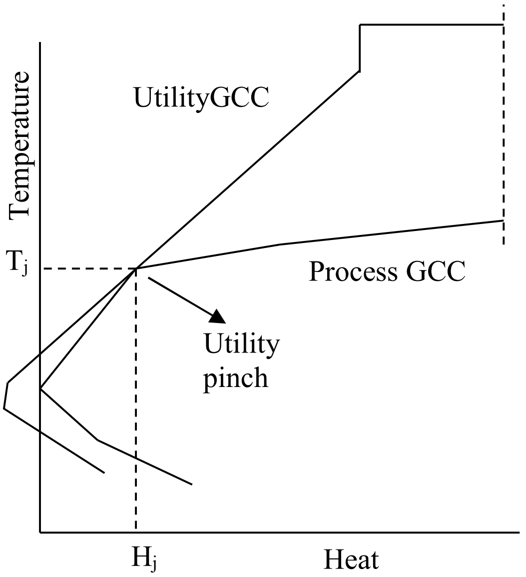

Figure 2. Fired heater integrated into the process.

Since the utility pinch point is not known a priori, the intermediate air preheat temperature is calculated for all possible vertices on the process GCC. The minimum of all the calculated temperatures, defines the actual utility pinch (H_P, T_P) as well as the maximum possible intermediate air preheat temperature, T_i. From the energy balance of the utility pinch, the final air preheat temperature may be expressed:

$$T_a = T_i + \frac{C_g(T_{p,n} - T_s)}{C_a} - \frac{H_p}{M_fC_a} \tag{4}$$

It may be noted that as the process pinch temperature increases, the intermediate air preheat temperature decreases and thereby increases the fuel requirement (or decrease in heater efficiency).

3. TARGETING FIRED HEATER NUMBER

The synthesis of network involving fired heater give importance to translate the target set based on GCC to achievable reality. To control the terminal temperature (or coil outlet temperature from the fired heater) of a process stream, fuel fired in the heater can be varied. Since, there is one manipulated variable there can only be one control variable. Therefore, every fired heater can have only one process stream to transfer the heat. Based on this, we may proceed to target required number of fired heater.

The process stream that exchanges heat with the fired heater, can also be represented on a temperature-enthalpy diagram. There are three cases to consider: Stream line cuts the process GCC, stream line cuts the utility GCC, and the stream line is contained in the space between the process GCC and utility GCC. These cases are discussed in details.

Case(i): Process stream intersects the GCC

When the steam line cuts the process GCC (Figure 3), it will have two consequences: increase in hot utility requirement and shift of pinch location. As the stream does not have enough heat capacity (*Mc*), total heat requirement at required temperature cannot be met. The largest distance between the process GCC and the stream line will signify the additional hot utility requirement (*ΔH*). The pinch point shifts to a location that determines the additional hot utility requirement (Figure 3). This leads to increase in utility demand and reduction in fired heater efficiency due to increase in pinch temperature. Therefore, this is not a desirable option. To eliminate the energy penalty, multiple streams should be chosen (starting with the maximum heat capacity one first) such that the combined composite line should be above the process GCC line.

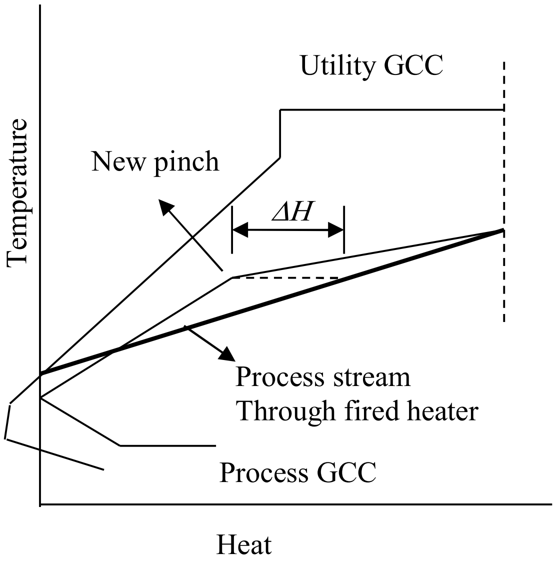

Figure 3. Stream line cutting the process GCC.

Case (ii): Stream intersecting the utility GCC

If the stream line (or the stream composite line) intersects the utility GCC, process heat requirement can be satisfied with the targeted value. However, the inlet temperature of the stream line forms a utility pinch above the process pinch (Figure 4). This results in decreasing the efficiency of the fired heater. Fired heater targets need to be revised with respect to the new utility pinch formed by the process streams as it intersects utility GCC.

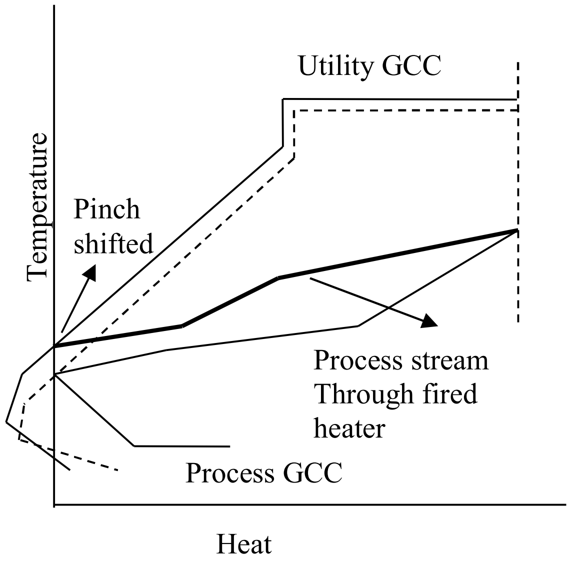

Figure 4 Stream line cutting the utility GCC.

Case (iii): Process stream within utility GCC and process GCC

The stream line, contained within the utility GCC and the process GCC (Figure 5), ensures that the energy targets can be satisfied. However, this may result in a complex network involving multiple entries of the process streams into the fired heater. Based on the above discussion, the minimum number of fired heaters required to satisfy the minimum energy requirement can be targeted. The procedure starts from the terminal point of the process GCC and the stream line is drawn at the terminal point with slope corresponding to the largest heat capacity of the cold stream present at the terminal point (Figure 6).

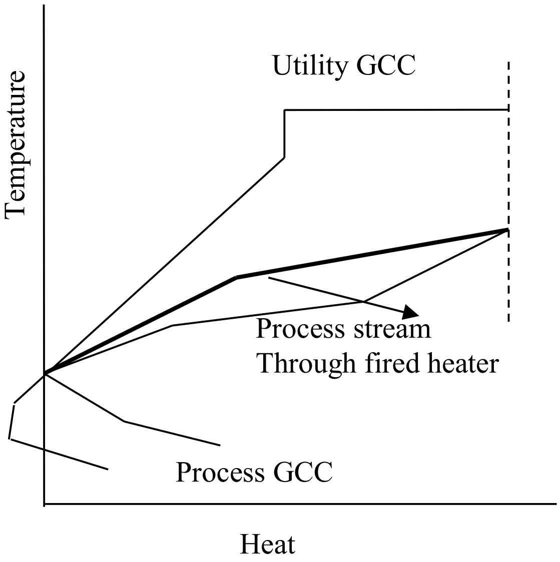

Figure 5. Fired heater integrated with the process

If this line intersects the process GCC above the process pinch, another stream with second largest *Mc* is chosen and the composite line is drawn. The same procedure is continued till the composite line lies entirely above the process GCC. It has also to be ensured that the composite line should be able to absorb the total heat requirement of the process. More number of streams may be added to ensure that the composite line intersects the temperature axis at or above the process pinch (Figure 6). Minimum number of streams required to form a composite line that lies entirely above the process GCC and intersects the temperature axis at or above the process pinch represents the minimum number of fired heater required.

4. NETWORK SYNTHESIS WITH SINGLE FIRED HEATER

When the stream line (for cold stream with largest *Mc*) passes above the process GCC and the stream is present at the process pinch, only one fired heater is sufficient to satisfy the required heat duty. It is now possible to have a simplified once through condition for the fired heater. In once through case, the process stream enters the fired heater convection section and leaves the fired heater from the radiation section at the required temperature. This is the preferred practice in the industry owing to the simplicity and controllability of associated heat exchanger network. Since the stream line intersects the utility GCC and causes a utility pinch above the process pinch, the efficiency of the fired heater reduces. Penalty in fuel consumption can reduce the capital investment. This implies capital-energy tradeoffs.

To achieve the targeted energy recovery, the stream line should be such that it is confined entirely between the process GCC and the utility GCC and intersects both of them at the process pinch. This calls for reduced mass flow rate for the process stream at the fired heater entry. Therefore, the process stream is split with one portion of the stream entering the fired heater. The other portion of the cold process stream exchanges heat with hot process streams and re-enters the fired heater after completing required process heat recovery. However, there exit limits on the heat capacity of the split portion that enters the fired heater. The maximum heat capacity flow rate (Mc_{max}) depends on the process GCC where as its minimum value (Mc_{min}) depends on the utility GCC. As long as the heat capacity flow rate of the fraction of cold process stream that enters the fired heater, energy target can be satisfied (Figure 7).

Example 1

The following example illustrates the methodology of integration of fired heater into the process. Stream data is given in the Table 1. Fired heater data is given in Table 2.

Table 1 Stream data of the example

Stream	Mc (kWK^{-1})	T_{in}(K)	T_{out}(K)
H1	4	600	350
H2	4	450	300
C3	4	300	700
C4	2	350	450

Table 2. Data related to the fired heater.

Net calorific value of fuel (kJ/kg)	41000
Stoichiometric air fuel ratio	15
Excess air recommended	10 %
Ambient temperature	300 K
Specific heat of air (kJ/kgK)	1.005
Specific heat of flue gas (kJ/kgK)	1.148
Dew point temperature (K)	433
Setting losses (α)	2%

The hot utility requirement of 580 kW corresponding to a ΔT_p of 30 K is obtained from the problem table algorithm. The pinch corresponds to 450K on the hot side and 420K on the cold side. Inlet temperature of the hot process stream H2 holds the pinch. An additional temperature potential□□ ΔT_{adl} of 20K between the flue gas and process streams is assumed. The temperature potential between air-preheat and flue gas outlet is assumed to be 70 K. The maximum intermediate temperature up to which the process heating possible is calculated as 355.2 K, the air preheat temperature required is 400K and the corresponding adiabatic flame temperature is 2382.5K, corresponding to this the fuel required is 0.0151 kg/s (i.e., 54.34 kg/h). The fired heater efficiency is calculated as 93.7 %.

The detailed heat exchanger network synthesized is shown in Figure 8. The network synthesized shows the stream (C3) enters twice into the fired heater. Modified once through case is shown in Figure 9. Now the process streams enter the fired heater at 555 K, and hence, the pinch point becomes 570 K. Fuel required is increased to 0.01528 kg/s (i.e, 55.02 kg/h). The fired heater efficiency is calculated as 92.5 % and the

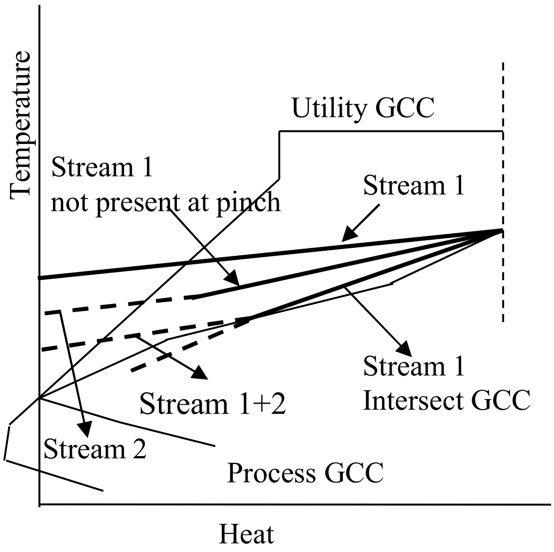

Figure 6. Fired heater number and duty targeting

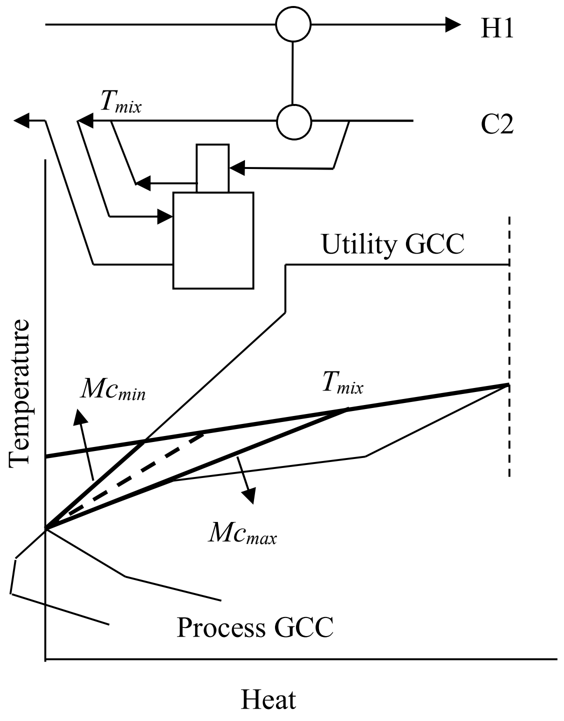

Figure 7. Fired heater network options

minimum air preheat temperature required is 535 K. The reduction in efficiency is due to the reduction in process heating for air preheating and thus, resulting an increased fuel flow. From the fired heater integration the minimum and maximum values of heat capacity of the fraction of C3 that enters the fired heater are found to be between 0.31 and 0.4.

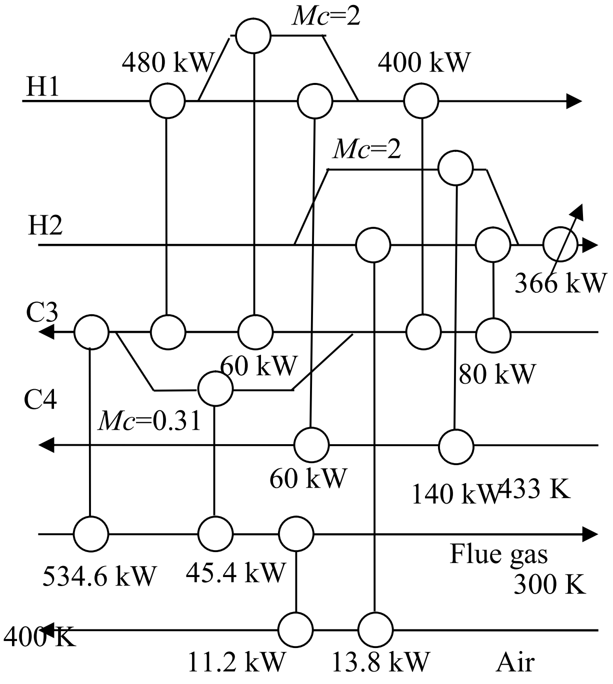

Figure 8. Network synthesized for example with process heating.

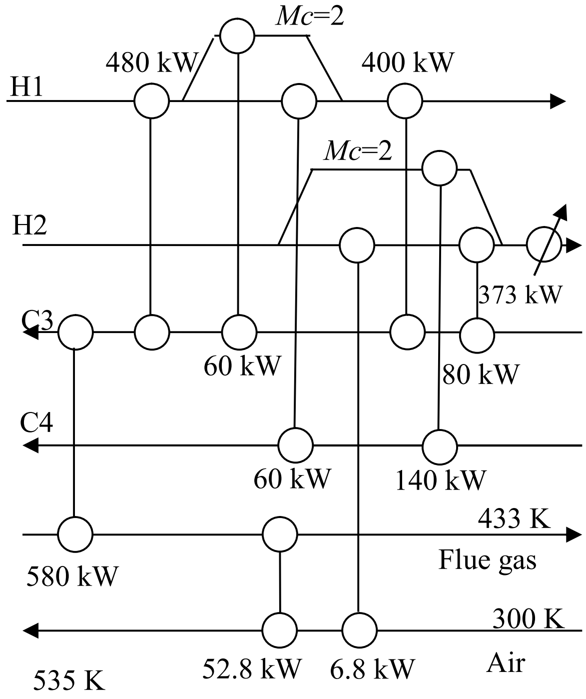

Figure 9. Network synthesized for example involving once through case.

It is to be noted that both these networks have the same heater efficiency and heat loads. It can be concluded that any value of heat capacity between 0.31 and 0.4 would satisfy the network and fuel target requirements. The minimum value of heat capacity 0.31 corresponds to the heat capacity of the flue gas. The range of heat capacity changes the exit temperature of the fraction from the fired heater and through the process heater, this changes the area requirement of the fired heater convection section and the process heater involved with the fraction. Economic considerations could optimize the heat capacity required for the split.

5. NETWORK WITH MULTIPLE HEATERS

In a network with multiple fired heaters and with the streams present at the pinch, the individual fired heater duty can vary within a range. However, the total fired heaters duty remains the total hot utility requirement. This is shown in Figure 10 with multiple fired heaters required to meet the total duty. The sum of the heat capacities entering fired heaters is determined using the above procedure. The minimum of the combined heat capacity is the flue gas heat capacity and the maximum is found from the process GCC limit. For each fired heater the cold stream is split at the pinch to the fired heater and for process heat recovery. The streams combine after completing the process heat recovery and at the mixed temperature T_{mix} re-enter to the fired heater to complete the heat requirement.

Consider a case where two fired heater are required meet the hot utility requirement of Q. The cold streams are both present at the pinch and they are split into $Mc1_{in}$ and $Mc2_{in}$ fractions passing through the fired heater. The combined heat capacities $Mc1_{in}$ and $Mc2_{in}$ are to be between the minimum and maximum range set. The sum of the duties of the fired heater matches to the hot utility requirement targeted. Referring to Figure 10, consider the fired heater 1 is supplying heat to the stream C3 with heat capacity $Mc1$ and the fired heater 2 is supplying heat to C4 with heat capacity $Mc2$. At the pinch $Mc1_{in}$ fraction of C3 enter the fired heater 1 and $Mc2_{in}$ fraction of C4 enter fired heater 2. The streams are at T_{mix} after mixing the heat recovery stream and the fraction which received part of the heat from fired heater. Both the streams reach target temperature of T_t and the total heat supplied by the fired heaters up to the temperature T_t:

$$\begin{aligned} Q &= (Mc1_{in} + Mc2_{in})(T_{mix} - T_p) \\ &+ (Mc1 + Mc2)(T_t - T_{mix}) \end{aligned} \qquad (5)$$

with $M_f C_g \leq Mc1_{in} + Mc2_{in} \leq Mc_{max}$

This range of heat capacities of the fractions $Mc1_{in}$ and $Mc2_{in}$ results a permissible fired heater heat duty range as evident from the equation Eq (5). This gives flexibility on design of the network. Economic considerations can further optimize the duty split between fired heaters. Many cases it is possible to have many fired heaters with once through design with appropriate choice of different heat capacities.

In the case with multiple fired heaters, if the stream is not present at the pinch, to meet the total hot utility requirement more than one fired heater is required. For the stream with the higher entry temperature than the pinch temperature the fired heater parameters need to be retargeted corresponding to the shifted pinch location of this stream. In this case the GCC target could not be met. An example to illustrate the fired heater duty range is given below.

Example 2

The stream data is given in Table 4.The pinch is at 450 K and the hot utility requirement is found to be 1700 kW with cold utility requirement of 1400 kW. It is found that one fired heater is not sufficient to supply the hot utility requirement. The largest heat capacity 8 kW/K line present at the terminal point is found to intersect the GCC and the next stream is added and the fired heater segments are completed. Thus for this network two fired heaters are required to supply the 1700 kW requirement. The possible network options are initiated using the GCC as in Figure 11. The minimum heat capacity fraction of the cold streams combined to be admitted to the fired heaters is 0.9 kW/K and the maximum possible is 2 kW/K. Thus the sum of the fractions of $Mc1_{in}$ and $Mc2_{in}$ at the entry points of fired heater 1 and the fired heater 2 must be within these limits.

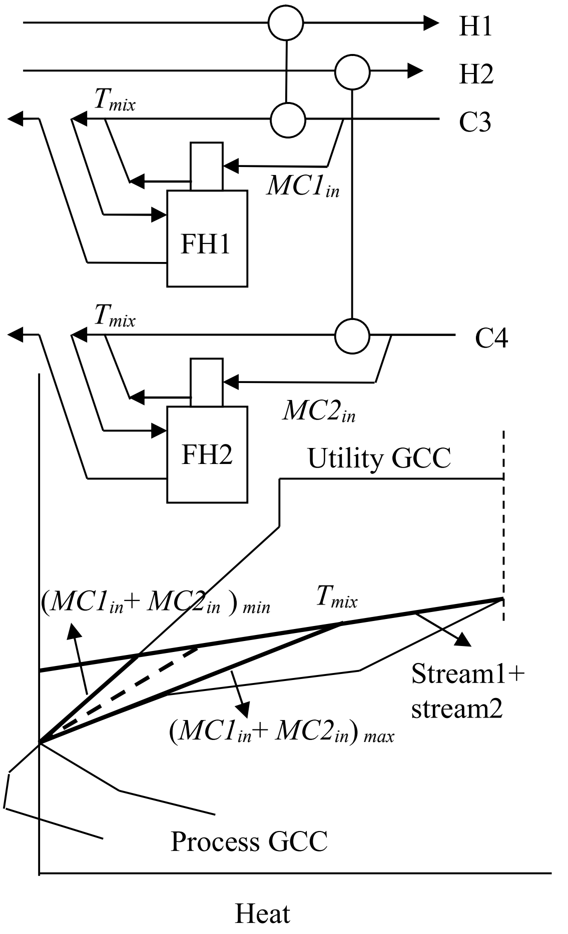

Figure 10. Multiple fired heaters

Table 3. Stream data

Stream	Mc(kW/K)	T_{in} (K)	T_{out}(K)
H1	12	650	350
H2	4	550	350
C3	10	450	620
C4	8	300	700

In Figure 11 the cold streams fractions range at the entry and the possible duty range are determined. With $MC1_{in}$=0.3 and $MC2_{in}$=0.6, mixing temperature is 567K and the duty of fired heater 1 is 566 kW and for fired heater 2 the duty is 1134 kW In the case with $MC1_{in}$=1.2. and $MC2_{in}$=0.8, mixing temperature is 575K (Figure 12) and the duty of fired heater 1 is 600 kW and for fired heater 2 the duty is 1100 kW. The air preheat temperature is 450 K corresponding adiabatic flame temperature, the mean radiating temperature, bridge wall temperature, skin temperature and the radiation fraction are 2424K,1146K, 1108K, 651K, and 0.684, respectively. The network structure remains the same while the mixing temperature and the duties changed.

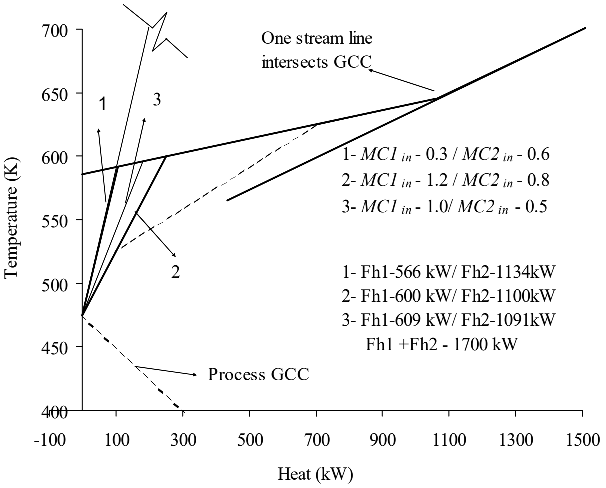

Figure 11 Multiple fired heater duty range.

6. CONCLUSIONS

Fired heater integration procedure with the process GCC helps in targeting fuel requirement and air preheat temperature. For processes with multiple fired heaters it is important to estimate minimum number of fired heaters required to supply the heat demand of the process. In cases where all streams are present at the process pinch, it is possible to meet the minimum energy targets by making some appropriate changes in network design. On the other hand, if all the streams are not present at the process pinch, minimum fuel target cannot be satisfied and new fuel targets have to be estimated. For feasible network, the stream segment passing through the fired heater need to be contained within the utility GCC and the process GCC. The entry conditions of cold stream to the fired heater convection section should be within a certain range as dictated by the flue gas heat capacity and process GCC. Cold streams should enter the fired heater at the pinch condition to meet the energy target. There exists a range of heat capacity for the cold stream entering the fired heater. Techno-economic optimization may be carried to finalize the overall design.

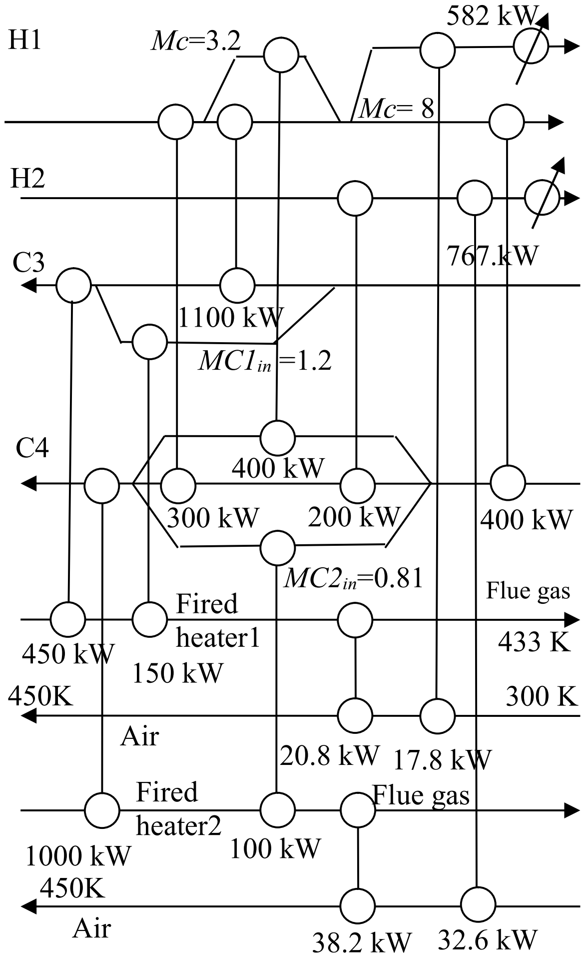

Figure 12 Network with multiple fired heaters

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