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Energy Integration of Fired Heater

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Abstract

Tools of pinch technology help in establishing energy efficient design of a modern process plant prior to its detailed design. Modeling and prediction of the performance of fired heaters are necessary for energy integration of the entire process plant. A simple mathematical model based on the perfect stirred reactor concept is proposed in this paper. In this model, the temperature of the radiation chamber is represented by a mean effective value. The simplified model parameters are estimated from established cases reported in the literature. Effect of different parameters, such as quantity of fuel fired, air preheat temperature and average radiation flux, on the energy integration of the fired heater with the overall process has been studied. An analytical procedure is proposed in this paper, considering air preheat using the flue gas only, to target the adiabatic flame temperature, minimum fuel required and minimum air preheat temperature. The results show that the minimum fuel requirement remains same for air preheat temperature lies between the minimum and the practical maximum limits.

Keywords: fired heater; pinch technology; bridge-wall temperature; process integration; mathematical modeling

Nomenclature

A	area, m^2
Cc	convection heat transfer factor
C_1	fraction of total area covered by heat sink
C_r	overall radiation transfer factor
C_v	lower calorific value, kJ/kg
c_p	specific heat, kJ/kgK
d	degree of stirring
E	excess air fraction
GCC	grand composite curve
$g_{g-1,r}$	total radiation transfer factor from gas to sink
H	enthalpy, kJ
h	heat transfer coefficient , kW/m^2K
k	number of temperature intervals above pinch point

MC_p	heat capacity (kW/K)
m_f	mass flow rate of fuel, kg/s
PTA	problem table algorithm
Q	total hot utility requirement, kJ
Q_1	heat exchanged in the radiation chamber, kJ
q_r	average design radiation flux, kW/m^2
S	stoichiometry air fuel ratio
T	temperature, K
Greek symbols	
ε	emissivity
Δ	difference
σ	Stefan-Boltzmann constant, 5.67×10^{-11} kW/m^2 K^4
Subscripts	
1	heat sink
0	ambient
a	air properties
a,min	minimum air preheat
a,max	practical maximum temperature limit
bw	bridge-wall
c	convection surface
cas	cascaded
FT	flame
g	flue gas
gout	condition of gas after the convection section
int	interval
n	temperature interval from 0 to k
pmin	process minimum
r	radiation
rfr	radiation fraction
stack	stack condition
T	total surface

Introduction

Heat recovery is considered as the most effective way to conserve energy and minimize waste. The energy targeting methods, using the well established pinch technology, are used for maximizing heat recovery for a given set of process conditions. Different equipments along with the entire process need to be optimized to improve the overall energy efficiency of the plant. This necessitates the proper integration of various systems into the process. Process furnaces, also known as fired heaters, supply heat to process streams at elevated temperature directly by burning fuel. Fired heaters are both energy and capital intensive. Schematic of a box type fired heater is shown in Fig.1. Prediction of performance and proper integration of a fired heater is necessary for the overall optimization of the entire plant.

Linnhoff and de Leur [1] had proposed the use of a linear (in temperature-enthalpy diagram) flue gas profile for the integration of the fired heater. The flue gas temperature changes from the adiabatic flame temperature to the stack temperature along a linear path, exchanging heat with process streams and combustion air. Air is preheated using the flue gas after the process heating in the convection section and the fuel fired is optimized. This is done by matching the process grand composite curve (GCC) against the linear flue gas line in the temperature-enthalpy diagram. Three cases had been identified that limit heat recovery from flue gas: the process pinch is above the acid dew point and an in-between utility pinch is formed between the flue gas and the process GCC, the process pinch is above the acid dew point and the process pinch is below the acid dew point.(see Fig.2). This procedure helped to predict fuel consumption in a simplistic way. The integration of fired heater with process was dealt in detail by Hall and Linnhoff [2]. The fuel quantity, air preheat temperature and excess air are considered as the variables for the integration of the fired heater with the back ground process. A new concept of utility grand composite curve with the linear flue gas line is introduced and it simplifies the integration procedure. The variation of the flue gas profile with the variables is utilized for the optimization of the fuel quantity. In the proposed graphical procedure, the utility GCC is matched against the process GCC, and the minimum fuel as well as air preheat are fixed in steps. The procedure is shown in Fig.3. This involves starting the procedure with high values for fuel and air preheat, the process GCC is matched against the utility GCC. In the next step fuel fired is reduced until a utility pinch is formed between the process GCC and the utility GCC, this correspond to the minimum fuel required. The air preheat temperature is reduced next until the process GCC form again a utility pinch against the utility GCC. This graphical methodology is very useful and powerful to predict the furnace energy target and to fix the air preheat parameter. The linear profile is easy to construct with an average constant specific heat for the flue gas. However, the linear profile does not provide the information on the bridge-wall temperature which divides the radiation duty and convection duty split. Also if the air preheat and fuel fired initial values are not high enough then it leads to an iteration of the procedure.

The use of a two zone model for the flue gas profile was proposed by Stehlik et al. [3] with a constant effective temperature of the flue gas in the radiation section, followed by a linear variation for the flue gas profile in the convection section. An algorithm is suggested to optimize the air preheat temperature and the stack temperature considering the capital energy trade off also for the grass root [3] and retrofitting [4] cases.

The stirred reactor model predicts the overall heat transfer mechanism and performance of a fired heater more accurately. Based on this concept, a simplified model for a fired heater is proposed in this paper. The model can be used to target the duty split between the radiation and convection sections of a fired heater. This is useful for targeting multiple streams in the convection section. An analytical procedure for the fired heater integration is also presented here. Compared to the earlier procedures, present analytical methodology avoids the iteration. The results show the importance of fixing the excess air and dew point temperature to the minimum for better energy efficiency. The results also show that the minimum fuel requirement remains same for air preheat temperature lies between the minimum and the practical maximum limits.

Stirred Reactor Model

This simple furnace model is found to make substantially correct predictions of the overall heat transfer performance for a wide range of furnace types [5]. 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. The hot gas is assigned a mean effective radiating temperature T_g, and the refractory surfaces is radiating adiabatically. Radiation losses through the openings and surfaces are neglected. 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 gives,

$$Q_1 = g_{g-1,r}\sigma(T_g^4 - T_1^4) + hA_c(T_g - T_1) \tag{1}$$

where σ is the Stefan-Boltzmann constant, h is the convection heat transfer coefficient between the gas and heat sink, A_c is the area of the sink receiving the heat by convection and $g_{g-1,r}$ is the total radiation transfer factor from gas to the heat sink. The Eq. (1) can be rearranged as

$$q_r = \frac{Q_1}{A_c} = \frac{g_{g-1,r}\sigma(T_g^4 - T_1^4)}{A_c} + h(T_g - T_1) \tag{2}$$

where q_r is the average radiation section heat flux, this value is generally selected depending on the fired heater application. For most practical furnaces the total transfer factor $g_{g-1,r}$ may be calculated with reasonable precision from the speckeled wall condition [5].

$$g_{g-1,r} = \frac{A_T}{\dfrac{1}{C_1\varepsilon_1} + \dfrac{1}{\varepsilon_g} - 1} \tag{3}$$

where A_T is the total surface area of the furnace chamber and C_1 is the fraction of the total area covered by the heat sink, ε_1 and ε_g are the emissivity of sink surface and gas respectively. The Eq. (2) can be expressed in the general form

$$q_r = C_r\sigma(T_g^4 - T_1^4) + C_c(T_g - T_1) \tag{4}$$

where C_r combines the overall radiation transfer factor and the geometrical arrangement, and C_c combines the overall convection heat transfer factor between the sink and hot flue gas in the radiation chamber. From the above equation the mean radiating temperature T_g can be estimated now with known coefficients C_r and C_c. Flue gas leaves the radiation section at the bridge-wall temperature T_{bw}, with a drop from T_g and is given by

$$T_{bw} = dT_g - (d-1)T_{FT} \tag{5}$$

where d account for the degree of stirring with $d \geq 1$, the value of d is unity for perfect stirring [5]. The flame temperature T_{FT}, considering the setting losses in the combustion chamber as 2% of the fuel input can be found from the energy balance

$$T_{TFT} = T_0 + \left[\frac{Sc_{pa}(1+E)(T_a - T_0) + 0.98C_v}{c_{pg}[S(1+E)+1]}\right] \tag{6}$$

where E is the excess air, S is the stoichiometric air fuel ratio, C_v is the net calorific value of the fuel and T_a is the air preheat temperature. The model as described above is shown balanced against the process GCC in the Fig. 4. The radiation duty fraction of the total heat duty required can be found as

$$Q_{rfr} = \frac{T_{FT} - T_{bw}}{T_{FT} - T_{gout}} \tag{7}$$

Thus the duty split between the radiation and convection chamber can be established. This will be useful to target multiple streams in the convection section.

The model described above is used to fit the data relating the bridge-wall temperature, radiation flux and tube metal temperature as given by Berman [6]. The imperfect mixing factor *d* is also kept as a variable and the regression analysis of the data performed assigned the following value for C_r, C_c and *d* as in the Eq. (4) and (5).The radiation coefficient, C_r = 0.201, the convection coefficient, C_c = 0.02197 and the imperfect mixing factor, *d* = 1.07. The regression gave a good fit with the data. The data for the vertical cylindrical and horizontal tube heater are combined in the analysis. The coefficient of determination (R^2) value of the regression fit is found to be 91.5%. These coefficients can now be used to predict the bridge-wall temperature and to get the radiation convection duty split at the targeting stage.

Parametric Effect On Fired Heater Performance

The fuel quantity, air preheat and average radiation flux are identified as the variables at the design stage and the variation of these parameters on the flue gas profile can be made use for the integration of the fired heater with the process.

1. Fuel Fuantity

The most important parameter in the furnace integration to match the process GCC is the fuel fired. The effect of variation of fuel fired on the flue gas profile is shown in Fig.5. As the fuel quantity is reduced the air preheat loop closes in and the minimum will be when the loop get pinch.

2. Air Preheat

The effect of air preheat will be on the convection zone. The bridgewall temperature come down as we decrease the air preheat, also the temperature of gases leaving the convection zone come down. Thus the air preheat temperature can be fixed when the flue gas line pinch against the process GCC. The variation is shown in Fig.6. The duty split between the radiation and convection zone changes with the air preheat temperature change.

3. Radiation Flux

When the furnace design radiation flux changes, the mean radiating temperature and thus the bridgewall temperature also changes. For a lower radiation flux design the bridgewall temperature would be low. The effect of flux variation on the flue gas profile is shown in the Fig.7.

Analytical Methodology For The Integration Of Fired Heater System

An analytical methodology for the integration of the Fired Heater is presented here. The Fig. 8 shows a general case of the flue gas profile matched against the process GCC. The hot utility required is obtained from the problem table algorithm (PTA) and the flue gas supply the required hot utility. Flue gas leaves the fired heater convection section after supplying the required heat at T_{gout}. The combustion air is preheated by the flue gas after this in the air preheater and leaves to the stack at temperature T_{stack}. The heat balance between the hot utility load requirement and the flue gas heat gives

$$Q = (T_{FT} - T_{gout})[(1+E)S+1]m_f c_{pg} \tag{8}$$

Also we have the air preheat energy balance

$$c_{pg}[(1+E)S+1](T_{gout} - T_{stack}) = Sc_{pa}(1+E)(T_a - T_0) \tag{9}$$

Now substituting for the flame temperature from Eq. (6), and solving for m_f from the above two equations results

$$m_f = \frac{Q}{\{0.98C_v - c_{pg}(T_{stack} - T_0)[S(1+E)+1]\}} \tag{10}$$

Thus with known fuel characteristics and stack temperature T_{stack} the fuel required to meet the heat duty Q can be found from the above relation. The stack temperature needs to be fixed at the first step of a fired heater design. From the above result it is clear that the fuel fired depends on the excess air and on the stack temperature. A low excess air and low design stack temperature (the stack temperature may be limited by the dew point temperature) is recommended to reduce the fuel requirement, and thus a higher fired heater efficiency.

To find the minimum air preheat temperature consider the air preheating, where combustion air is heated from T_0 to T_a using flue gas heat which is cooled from T_{gout} to the stack temperature T_{stack}. Consider a general case wherein the flue gas is matched against the process GCC and the flue gas and process GCC pinch at point (H_n, T_n) forming a utility pinch. To find the pinch point holding the utility pinch which controls the air preheat level required, consider the vertices of the GCC enthalpy temperature interval as (H_n, T_n) where n varies from 1 to k, k is the total number of temperature intervals above and including the pinch point. The point (H_1, T_1) is the pinch point, with $H_1 = 0$. From Fig.8 we can see the energy balance of the flue gas and process heat requirement as

$$H_n = m_f[S(1+E)+1](T_n + 0.5\Delta T_{p\min} - T_{gout}) \tag{11}$$

The process minimum temperature difference factor $0.5.\Delta T_{pmin}$ is added to transform the pinch point temperature T_n of the flue gas to actual temperature. The energy balance of the air preheater gives

$$S(1+E)(T_a - T_0) = [S(1+E)+1](T_{gout} - T_{stack}) \tag{12}$$

Substituting for T_{gout} from the above equation, m_f from Eq. (10) and solving for T_{air}

$$T_a = T_0 + \left[\frac{c_{pg}Q(T_n + 0.5\Delta T_{p\min} - T_{stack})[S(1+E)+1] - H_n[0.98C_v - c_{pg}(T_{stack} - T_0)\{S(1+E)+1\}]}{[Sc_{pa}Q(1+E)]}\right] \tag{13}$$

This gives the air preheat temperature required, at this condition the flue gas will be pinched against the process GCC at (H_n, T_n). Repeat this procedure for n=1 to k, and find the largest value of T_a, this will be the minimum air preheat temperature $T_{a,min}$ required. If all the T_a calculated are less than the ambient temperature T_0, $T_{a,min}$ is to be chosen as T_0. The practical maximum for the air preheat temperature corresponds to, the air preheat temperature approaching the flue gas exit temperature of the convection section. The air preheating energy balance gives

$$Sc_{pa}(1+E)(T_a - T_0) = c_{pg}[S(1+E)+1](T_{gout} - T_{stack}) \tag{14}$$

As T_a approaches the flue gas outlet temperature T_{gout}, the above equation can be simplified as

$$T_{a,\max} = \left[\frac{c_{pg} T_{stack} [S(1+E)+1] - Sc_{pa} T_0 (1+E)}{c_{pg}[S(1+E)+1] - Sc_{pa}(1+E)} \right] \tag{15}$$

The Eq. (10) shows that the air preheat temperature do not influence the fuel requirement provided the air preheat temperature is above the minimum value $T_{a,min}$. The fuel consumption would remain the same for any air preheat temperature between $T_{a,min}$ and $T_{a,max}$. The above result shows that if the air preheat temperature is fixed below the $T_{a,min}$ the total available heat from the flue gas would not be recovered fully leading to energy loss. It emphasize that the air preheat should be fixed between the maximum and minimum limits. Thus using the above relations we can fix the fuel requirement and air preheat temperature of the fired heater, in a non iterative and analytical way.

Illustrative Example

An example is illustrated here to make use of the methodology. The stream data is as given in the Table-1 [7]. The fuel used is having net heating value of 41000kJ/kg. The stoichiometric air fuel ratio is 15 and minimum excess air recommended is 10%. The limiting dew point temperature of the flue gas is 433 K. The ambient is at 303K, average specific heat of air and flue gas can be assumed as 1.1kJ/kgK and 1.3kJ/kgK respectively. The design average radiant tube flux can be taken as 29kW/m^2 and average tube skin temperature as 729 K (assuming 0.65 radiation duty and average tube skin temperature is 42K above the mean bulk fluid temperature [6]).

The problem table algorithm is constructed as per the Table 2. The pinch point is identified as 673K on the hot stream side and 623K on the cold stream side. The results of the fired heater integration are shown in Table 3. The minimum fuel required is found to be 0.018 kg/s, to meet the hot utility requirement of 670 kW corresponding to a ΔT_{pmin} of 50 K. The fired heater efficiency is calculated as 90.8 %. The ambient air need to be preheated to 603.8 K. The Fig.9 shows the process GCC matched against the flue gas and air GCC. The detailed heat exchanger network synthesized below pinch is shown in Fig.10 and above the pinch is shown in Fig. 11. In the above network stream enters twice in the fired heater and this is not the usual practice in the industry, hence a simplified network synthesized is shown in Fig. 12. In this the stream enters the fired heater only once. In this network the fuel fired remains the same and hence the fired heater efficiency remains unchanged. The stream enters at 678.6K and the shifted temperature T_n = 703.6K, corresponding to this the minimum air preheat temperature can be found by using the Eq. 13.and the new $T_{a,min}$ = 673.5K. Thus the fired heater got integrated with the process effectively.

Conclusions

Integration of fired heater with the process considering the effects of the fired heater variables on its performance improves the energy efficiency of the overall process. The simple fired heater model established can be used to target the duty split at the targeting stage and this will be useful to target multiple streams in the convection section during the network development. The parametric study of the variables identified can be used to integrate the fired heater with the process.

Analytical solution for the fuel fired directly shows the need for low excess air and limiting the stack temperature to the minimum for better efficiency. The importances of these parameters are not recognized in earlier methods. The results obtained can be used to find the minimum fuel required and minimum air preheat temperature avoiding any iteration. The analytical procedure developed is with air preheat using the flue gas heat only and is capable to handle cases of pinch above or below dew point and the utility pinch between the flue gas GCC and process GCC. Also it shows that the fuel requirement remain same for any air preheat between the minimum and practical maximum limits. The fired heater parameters can differ from the preliminary integration results during the network development and the analytical results obtained becomes an essential tool to refine it. The variables identified influence the capital of the fired heater system and optimization of the total plant involves capital considerations of fired heater system along with the process.

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Table 1. Case study stream data

Stream	MCp (kW/K)	Temperature in (K)	Temperature out (K)
Hot1	10	773	623
Hot2	12	723	623
Hot 3	8	673	593
Cold 4	9	573	753
Cold 5	10	613	693
Cold 6	8	613	673

Table 2. Problem table algorithm (PTA) corresponding to process ΔT_{pmin} 50 K

Temperature interval (K)	$MC_{p,\ int}$ (kW/K)	Q_{int} (kW)	Q_{cas} (kW)	R_{cas} (kW)
778	0	0	0	**670**
748	9	270	-270	400
718	-1	-30	-240	430
698	9	180	-420	250
648	**5**	**250**	**-670**	**0**
638	-3	-30	-640	30
598	-21	-840	200	870
568	-8	-240	440	**1110**

Table 3. Fired heater integration results.

Parameter	Result		Remarks
Pinch temperature	648 K		PTA
Hot utility required	670 kW		PTA
Cold utility required	1110 kW		PTA
Minimum fuel	**0.018 kg/s**		Equation -10
Minimum air preheat temperature	(H_n, T_n)	T_{air} K	Equation - 13 The maximum value is chosen as the minimum air preheat required. **$T_{air,min}$ = 603.8 K.**
	(670,778)	-1329	
	(400,748)	-522	
	(430,718)	-653	
	(250,698)	-115	
	(0,648)	**603.8**	
The flame temperature	2309 K		Equation 6
Mean radiating temperature	1182 K		Equation 4
The bridge-wall temperature	1103 K		Equation 5
Radiation fraction	0.74		Equation 7

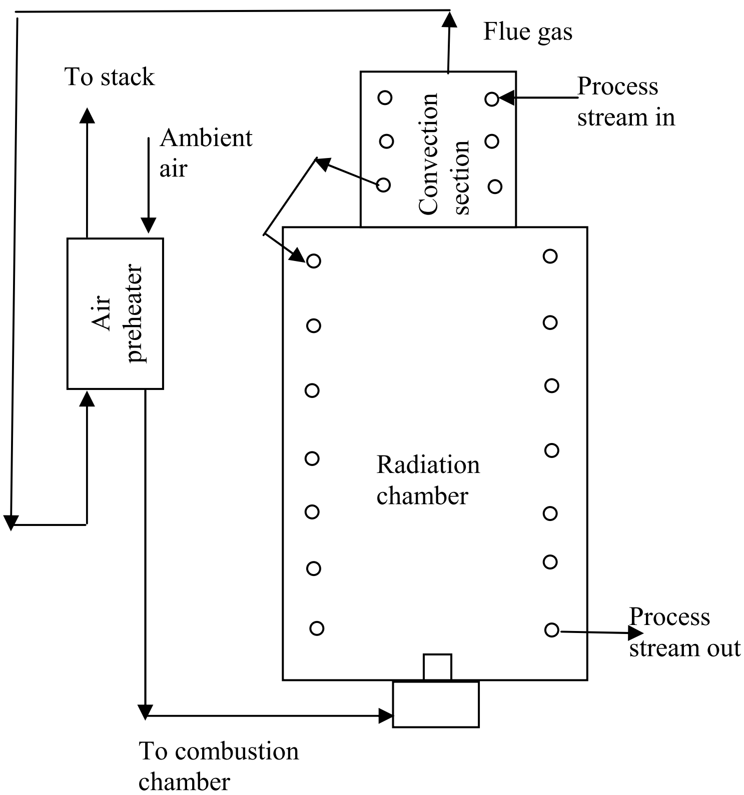

Figure 1. Schematic of a fired heater.

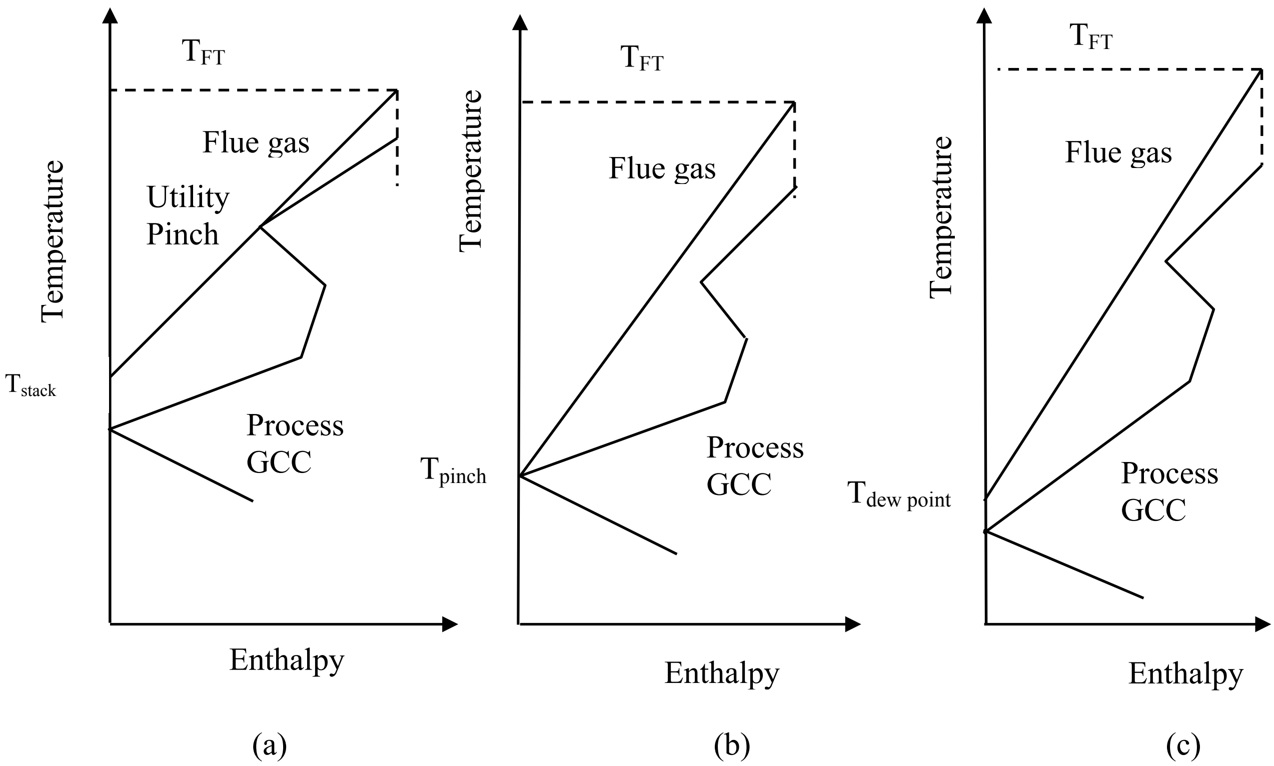

Figure 2. Limitations of stack temperature: (a) by the utility pinch, (b) by the process pinch (c) by flue gas acid dew point

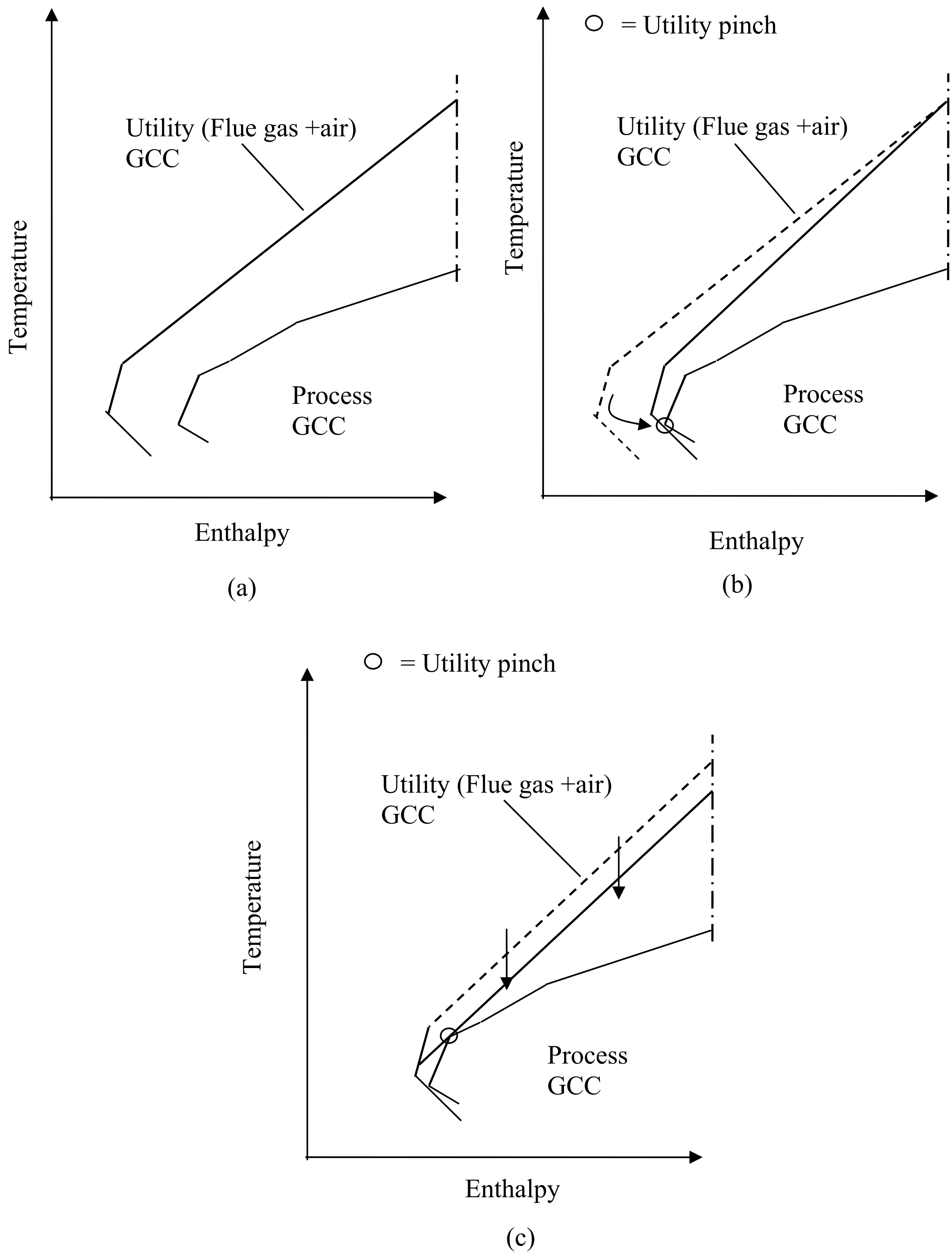

Figure 3 Furnace integration into process :(a).Process GCC matched against Utility GCC with high fuel and air preheat; (b)Varying fuel to set the minimum fuel;(c) Varying the air preheat at minimum fuel to set minimum air preheat.

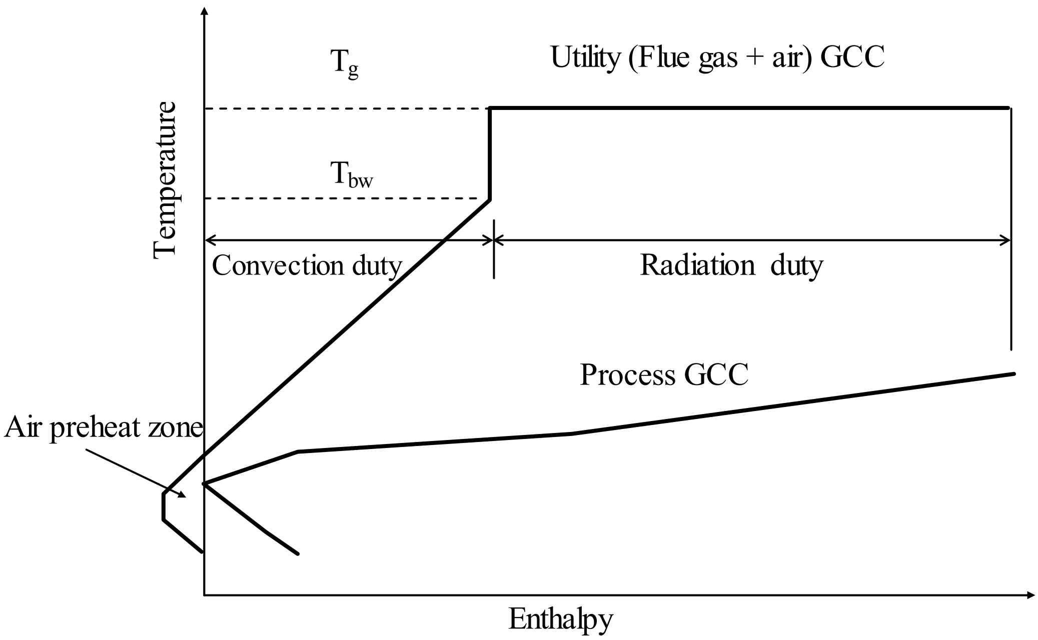

Figure 4. Placement of the fired heater against process GCC

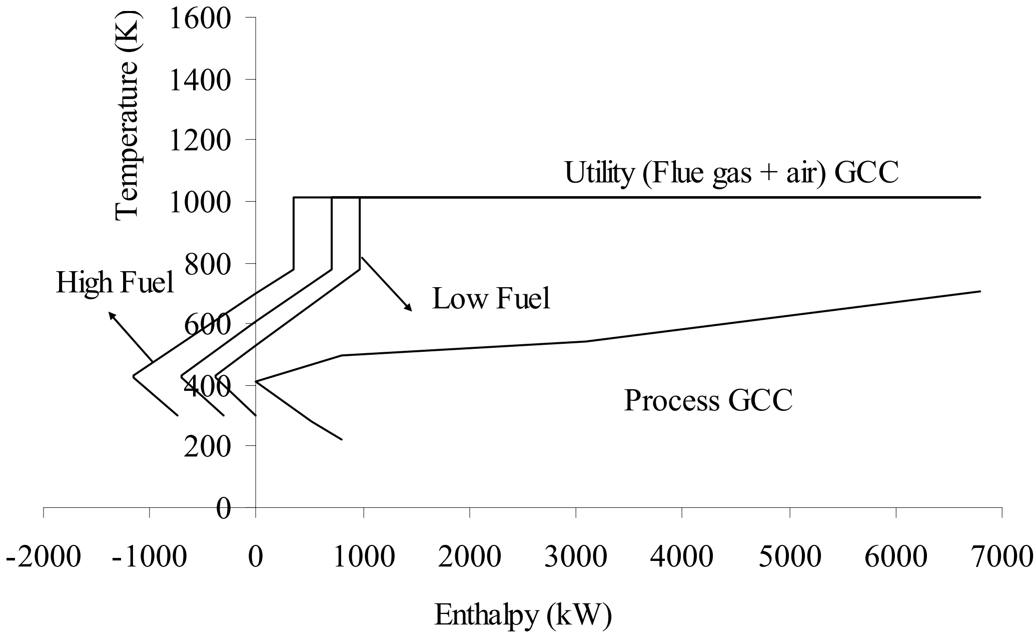

Figure 5. Effect of variation of fuel fired on the flue gas profile.

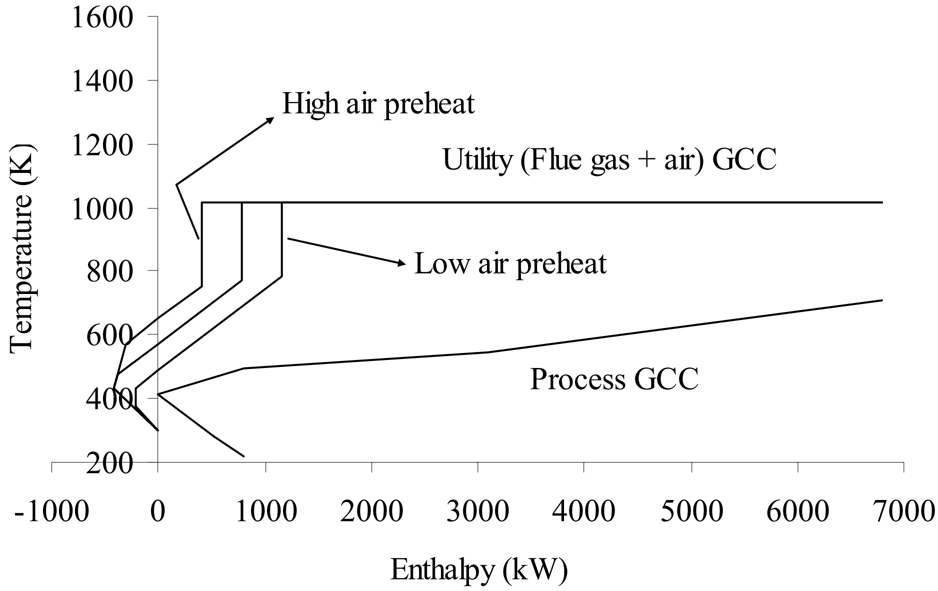

Figure 6. Effect of variation of air preheat temperature on flue gas profile

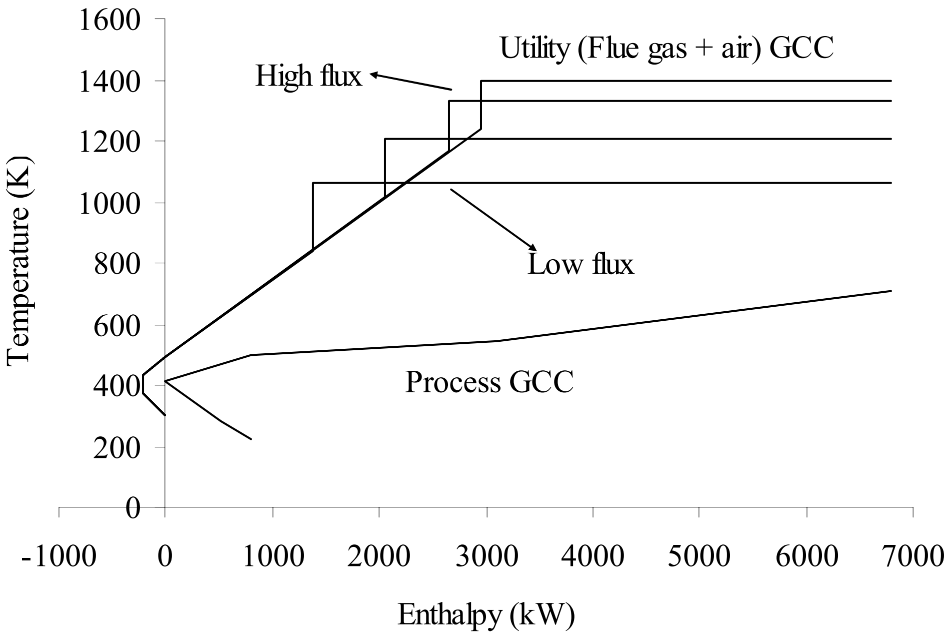

Figure 7. Effect of variation of average radiation flux on the flue gas profile

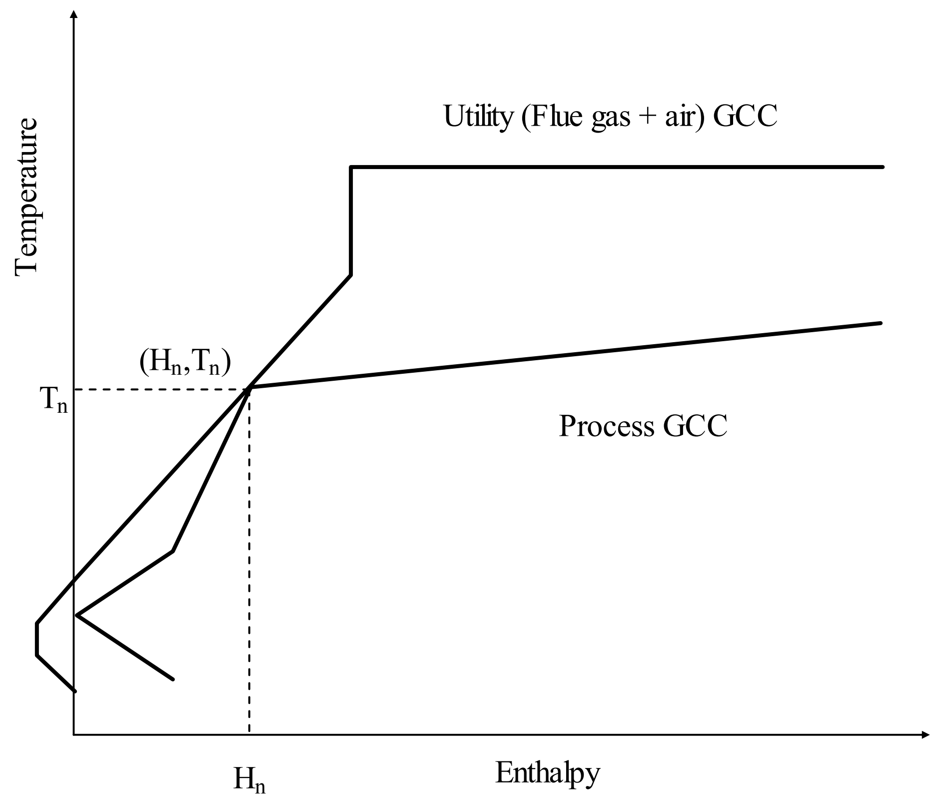

Figure 8. General case of the flue gas pinched against process GCC forming utility pinch.

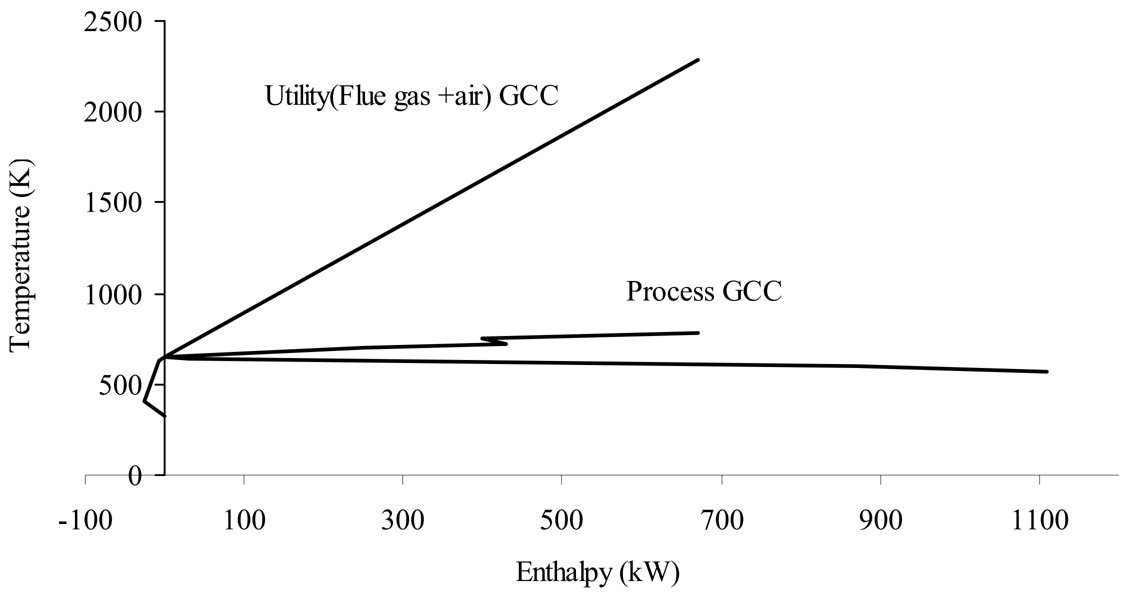

Figure 9. Utility (Flue gas+air) GCC matched against the process GCC for the example

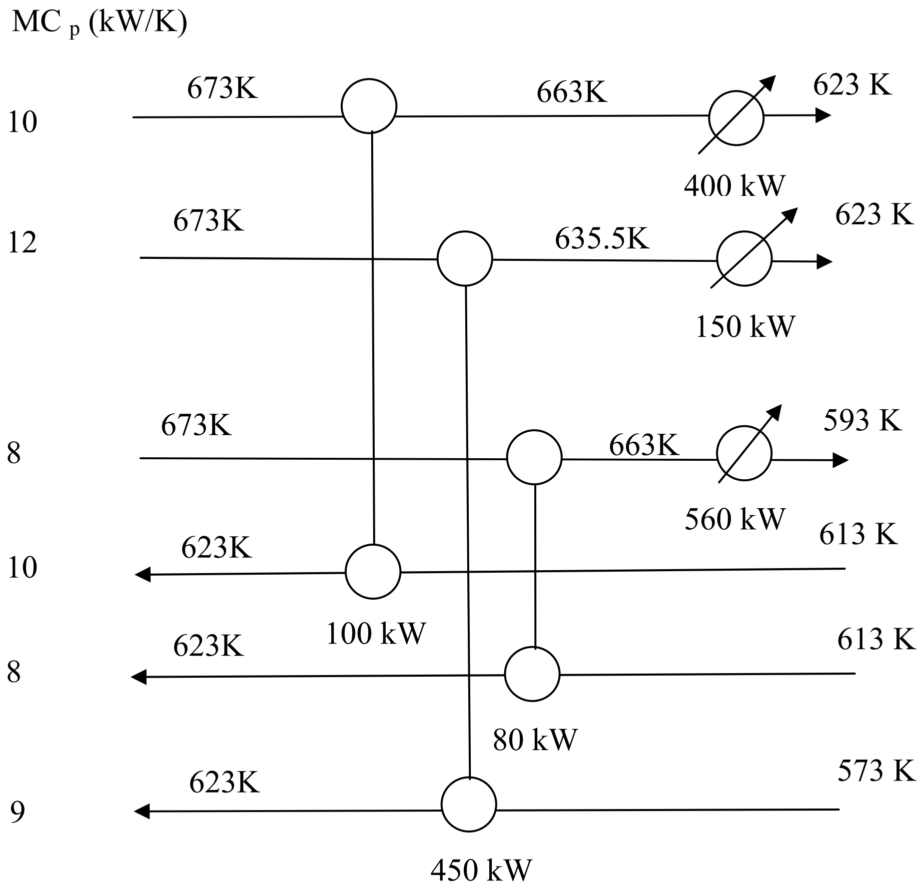

Figure 10. Synthesized heat exchanger network of the example below pinch.

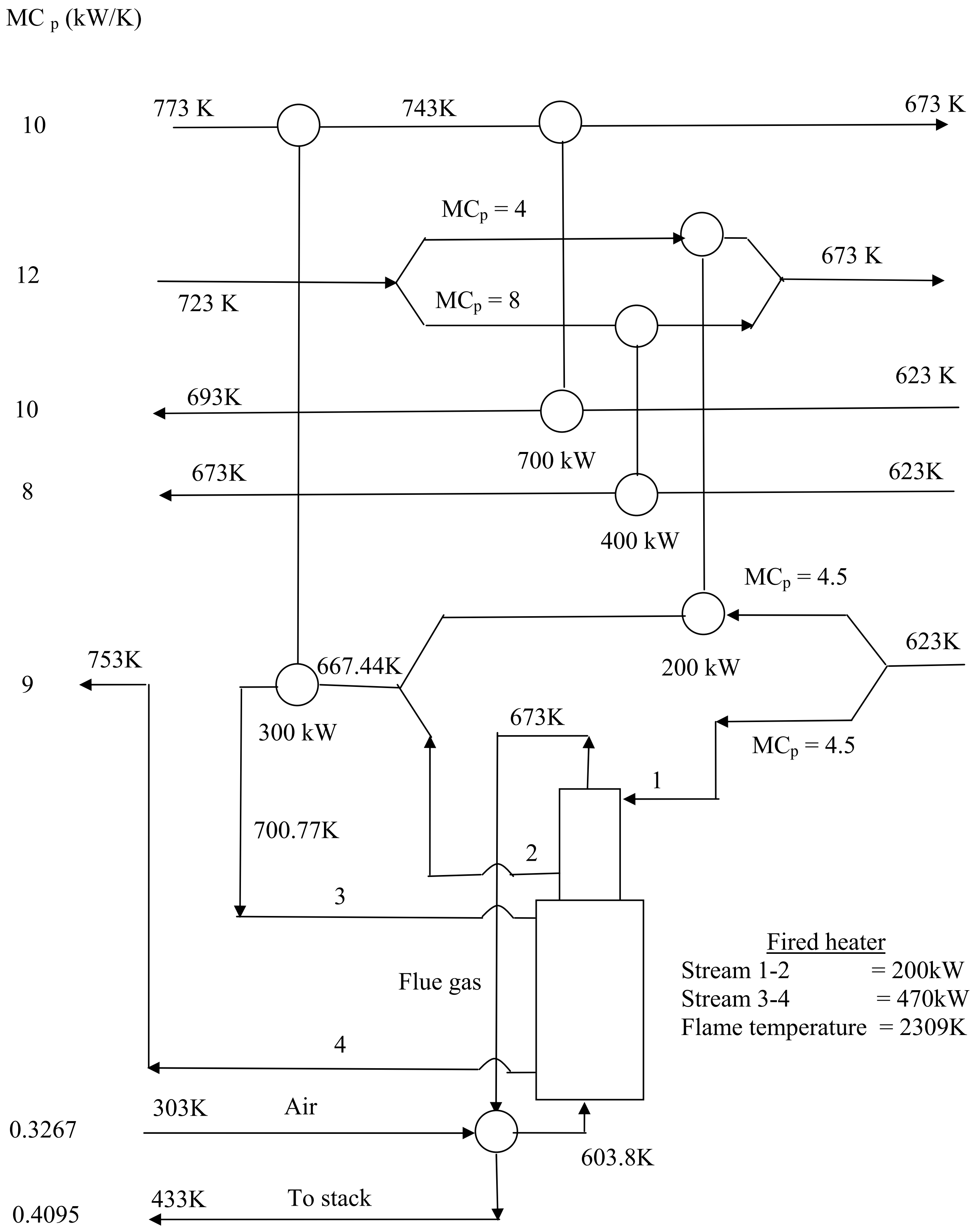

Figure 11. Synthesized heat exchanger network of the example above pinch.

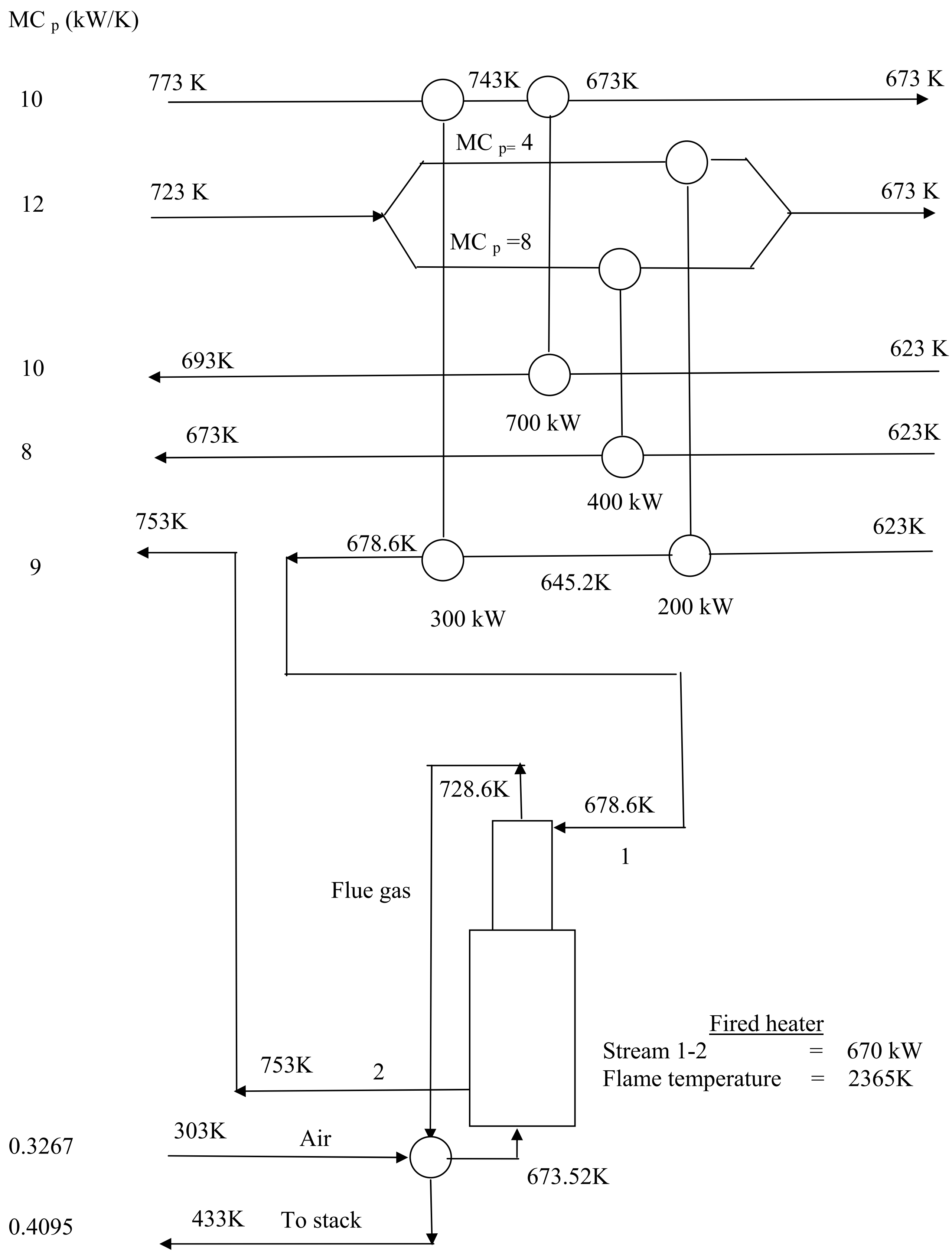

Figure 12. Synthesized heat exchanger network modified of the example above pinch.