A Conceptual Design Method of the Total Site Energy System in Process Industries

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Abstract

Although there are numerous works concerning the optimal synthesis of energy system including heat exchanger networks, utility systems and total site energy system (TSES), but there is lack of a decision support system for determining the TSES performance targets and their corresponding topological structure and main decision variables at the preliminary design stage of the whole plant or enterprise. To tackle this problem this paper proposed a conceptual design method of TSES based on the core decision model proposed earlier by Zhu(1989). According to this model, the TSES could be simplified as one consisted of a total heat exchanger network, boiler, turbine and steam pipelines at different pressures and other supplementary equipments. The main decision variables for the core decision model are the $\Delta T_{\min}$ of the total heat exchanger network, boiler pressure, the back pressures of the turbine, the amount of steam produced at pre-specified pressures. Here the conceptual design method is illustrated, but this paper concentrates on the essence not the detail. One case study is demonstrated to show the broad application perspective of the proposed method.

Key words: Process energy system; Optimal synthesis; Total site energy system; Pinch technology

INTRODUCTION

For the production system in the process industries (chemical, petro-chemical, metallurgy), the processing process from raw material to products is always accompanied with energy supply, use, recovery, loss etc. As known, the optimal synthesis technology has played an important role in making improvements in process energy system. So far there are numerous works concerning the optimal synthesis of energy system including heat exchanger networks, utility systems and total site energy system (TSES), but there is lack of a decision support system for determining the TSES performance targets and their corresponding topological structure and main decision variables at the preliminary design stage of the whole plant or enterprise. The

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TSES is a very complicated system consisted of heat exchanger networks, utility system and other supplementary equipments. There is no need of having a detailed design of the TSES at the preliminary design stage of the whole plant/enterprise because a lot of technological parameters, such as temperatures and pressures of the streams from reactors, separation columns etc., possess some uncertainty at this stage. As known, these technological parameters have great impact on the design of TSES. To obtain a TSES with minimum annual cost and satisfied operation performance, it is required to do some iteration between TSES and a set of technological parameters. If the detailed design method is used, it is very time-consuming. Zhu (1989) has proposed a core decision model of TSET. In this model a chemical plant's total energy system can be represented by using a simplified topological structure with several key variables, shown in figure 1. It has been shown that the relative error of the energy consumption calculated based on this core model with respect to the practical one is less than 5 to 10 percents. Based on this model, here we presented a conceptual design method of the TSES which is able to be used for determining the TSES performance targets and their corresponding topological structure as well as main decision variables quickly so that to conduct the iterative calculation effectively for selecting the appropriate technological parameters at the preliminary design stage of the whole plant or enterprise. The energy consumption of the chemical plant can be obtained through solving a NLP problem formulated according to this structure (Figure 1)..

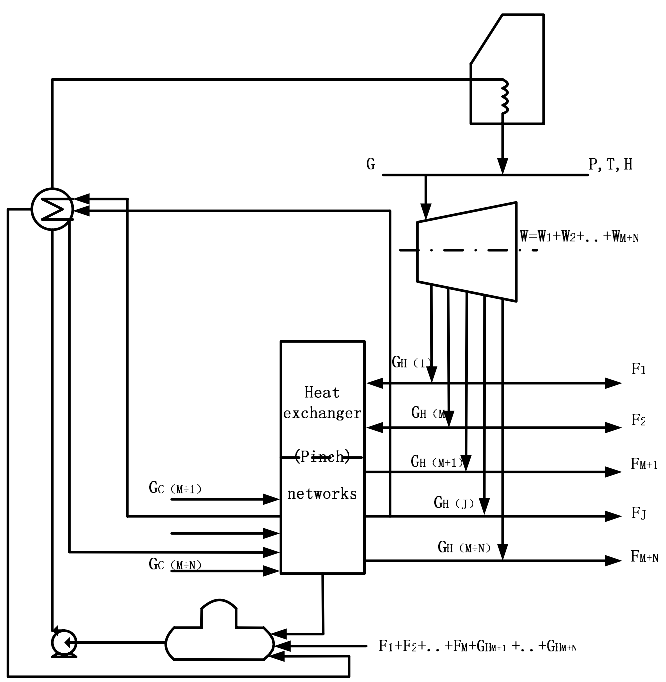

Figure 1 the core decision model

A CONCEPTUAL DESIGN METHOD

The conceptual design method for determining the performance targets and their corresponding topological structure as well as decision variables is illustrated as follows:

1. The heat exchange between process streams was carried out at first within each process by using pinch technology.

2. The heat exchange between the process hot and cold streams remained after the heat exchange within different processes could be integrated to one total heat exchanger network by using the pinch technology.
3. A total turbine is integrated with the total heat exchanger network above the pinch, which satisfies the criterion of the appropriate placement of the heat engine to the process heat sink proposed by Linnhoff(1983).
4. A boiler is integrated to the total turbine.
5. A NLP or MINLP mathematical model was formulated and solved for minimizing the total cost of the total site energy system with the above mentioned decision variables.
6. A sensitivity analysis is carried out to find the key technological parameters that affect the performance targets of TSES greatly.
7. Changing the key technological parameters within their feasible regions, return to step 1. Iteration stops when no improvements in the performance targets could be found. The conceptual design of TSES is completed.

EXAMPLE

There are two processes, process A and process B. The data for the case are shown in Table 1- 5.

Table 1. Data for process A

Streams	T^s (℃)	T^t(℃)	FCp(*10^4kJ/Hr*℃)
C1(Cold)	50	200	6
C2(Cold)	160	280	24
H1(Heat)	220	60	10
H2(Heat)	260	150	15

Table 2. Data for process B

Streams	T^s (℃)	T^t(℃)	FCp(*10^4kJ/Hr*℃)
C1(Cold)	30	180	8
C2(Cold)	140	300	20
H1(Heat)	240	50	18
H2(Heat)	270	140	14

Table3. Equipment data

The efficiency of boiler	0.9
The efficiency of furnace	0.9
The efficiency of equivalent entropy	0.7
Turbine price	$10*W^{0.424}$
Boiler price	$4.8*G^{0.82}$
Furnace price	$36.549+4.902*Qf*10^{-6}$

Table 4. Operation data

The average heat transfer coefficient	600 kJ/m^2℃Hr
Annual Operation	8000Hr
The payback time of electricity plant investment	4 Yr
The payback time of heat exchange network investment	2 Yr
The minimum transfer temperature of process A	20℃
The minimum transfer temperature of process B	20℃
The maximum increment of cooling water temperature	15℃

Table 5. The utility data

Heat of fuel	4.186*10^{4}kJ/kg
Electricity price	0.4*10^{-4} /kW*Hr
Fuel price	0.6*10^{-4} /kg
Cooling water price	0.2*10^{-7} /kg
1.0MPa stream price	3*10^{-4} /t
0.3MPa stream price	1.5*10^{-4} /t
Supply temperature of cooling water	20 ℃

Table 6. The demand task

Electricity	10000kW
1.0MPa stream	30 t/Hr
0.3MPa stream	30 t/Hr

Now we study the case with the conceptual design method step by step.

Step1 The heat exchange within the process A and B, respectively, is conducted by using pinch technology. The results are shown in table 7.

Table 7. Process heat exchange data

	ΔT_{min}(℃)	Pinch Temperature(℃)	Q_{Hmin}(kJ/Hr)	Q_{Cmin}(kJ/Hr)
Process A	20	170	15.20*10^6	9.90*10^6
Process B	20	230	20.20*10^6	11.8*10^6

Step 2 The remainder of the hot and cold streams of processes after the heat exchange within the process A and B change heat with each other. The Grand composite curve is shown in figure 2:

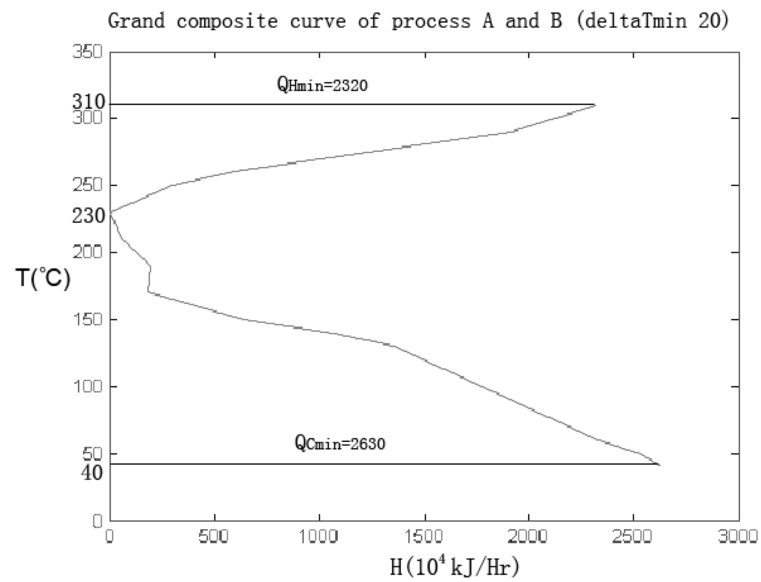

Figure 2. Grand Composite curve

We can see from Figure 2 that the minimum heating utility required is 2.32*10^7 kJ/Hr, the minimum cooling utility required is 2.63*10^7 kJ/Hr.

Step 3, 4, 5. A total turbine is integrated with the total heat exchanger network, a boiler integrated with the total turbine. The results are shown in figure 3. For the case studied, a NLP mathematical model was formulated with 37 variables, 62 rows (See Appendix).

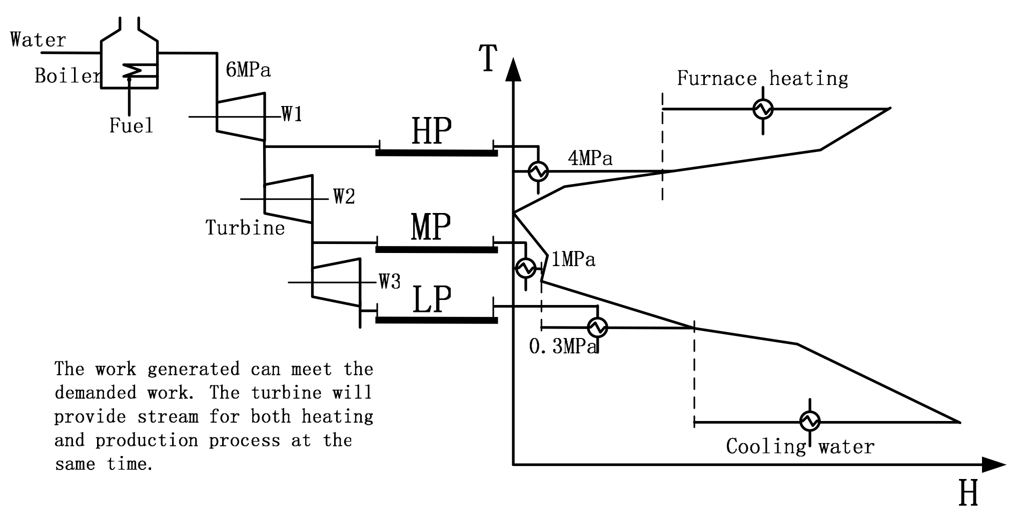

Figure 3. Total turbine and boiler integrated with heat exchange network

Step 6 The sensitivity analysis of the technological parameters to the annual cost has been carried out. The sensitivity coefficient of process data are shown in table 7.

Table 8. sensitivity coefficients of process data to annual cost

Process	Stream	F*Cp	T^s	T^t
	C1	-2.3180	0.1010	-0.0680
A	C2	**5.6480**	0.3780	**2.5310**
	H1	3.3810	0.1800	-0.2260
	H2	-0.3040	**-1.4980**	-0.3390
	C1	-2.5430	0.1350	-0.1360
B	C2	**7.0800**	0.3390	**3.5320**
	H1	**4.2790**	0.2430	-0.3160
	H2	-0.7410	**-1.3980**	-0.3160

According to the table, we can see that the CP and T^t of stream C2 in process B and CP and T^t of stream C2 in process are the sensitive variables. Consequently, more attention should be paid to these data in order to get a satisfied design of TSES.

Besides, the process data, the coefficient of device's cost regression can affect the optimized result also. Take the area cost coefficient as an example. The annual cost is increased by 0.9900 and 7.7080 when the coefficient *a* and b is increased by 1 percent, respectively. The power *b* is more sensitive than the coefficient *a*. a

Step 7 Adjust the sensitive data within their feasible region iteratively until find the satisfied design.

The optimization results of the case studied are:

Annual cost is 2441.976 (*10^4yuan)

$\Delta T_{\min}$ = 20 ℃

Boiler pressure: 6.1 MPa

Back pressure of turbine: 4.0MPa

The amount of streams generated by the heat exchanger network:

1.0MPa: 5.9 t/Hr.

0.3MPa: 0 t/Hr.

CONCLUSION

As it has been demonstrated with the example problem that a conceptual design of the TSES could be obtained easily by using the proposed method .when the process data and regression coefficients are given. Thus, a design alternative could be analyzed quickly based on their performance targets and corresponding topological structure as well as decision variables to show whether it is satisfied with the energy saving requirement or not. If not, the conceptual design could be improved by changing the sensitive technological parameters within their feasible region iteratively. This would help engineers to improve the TSET step by step. or to select a best alternative among a number of design alternatives, which shows the broad application perspective of the proposed method.

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References

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D.W. Townsend and B. Linnhoff. Heat and process networks in Process Design (I), AIChE J., 29, pp742-747, 1983

Appendix

A NLP mathematical model of the case studied:

```
MIN = C1/N1+(C4+C8+C9)/N2+C2+C3+C5-C61-C62-C63+C7;
!-----------------------conditions-----------------------------------;
[Year_working_hours]
HR=8000;
[Heatexchager_device_payback_year]
N1=4;
[Electrisity_plant_payback_year]
N2=2;
!----------------------- thermodynamics------------------------------;
  [T0_Expression]
T0=122.066+75.406*P0-20.447*P0^2+2.616*P0^3;
[T1_Expression]
T1=122.066+75.406*P1-20.447*P1^2+2.616*P1^3;
[T2_Expression]
T2=122.066+75.406*P2-20.447*P2^2+2.616*P2^3;
[T3_Expression]
T3=122.066+75.406*P3-20.447*P3^2+2.616*P3^3;
[H0_Expression]
H0_p0t0=2018.24+1.6974*(T0+273.15)+0.0002721*(T0+273.15)^2+(3.634-5945*P0)/((T0+273.15)/100)^3.1+(0.6156-2.696*10^9*P0^3)/(
(T0+273.15)/100)^13.5;
[H1_Expression]
H1_p1t1=2018.24+1.6974*(T1+273.15)+0.0002721*(T1+273.15)^2+(3.634-5945*P1)/((T1+273.15)/100)^3.1+(0.6156-2.696*10^9*P1^3)/(
(T1+273.15)/100)^13.5;
[H2_Expression]
H2_p2t2=2018.24+1.6974*(T2+273.15)+0.0002721*(T2+273.15)^2+(3.634-5945*P2)/((T2+273.15)/100)^3.1+(0.6156-2.696*10^9*P2^3)/(
(T2+273.15)/100)^13.5;
[H3_Expression]
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```
H3_p3t3=2018.24+1.6974*(T3+273.15)+0.0002721*(T3+273.15)^2+(3.634-5945*P3)/((T3+273.15)/100)^3.1+(0.6156-2.696*10^9*P3^3)/(
(T3+273.15)/100)^13.5;
[S0_Expression]
S0_p0t0=1.693*@log(T0+273.15)-0.4795*@log(10*P0)-2.9347+0.0005442*(T0+273.15)+(0.02747-44.95*P0)/((T0+273.15)/100)^4.1+(0.
005731-2.51*10^7*P0^3)/((T0+273.15)/100)^14.5;
[S1_Expression]
S1_p1t1=1.693*@log(T1+273.15)-0.4795*@log(10*P1)-2.9347+0.0005442*(T1+273.15)+(0.02747-44.95*P1)/((T1+273.15)/100)^4.1+(0.
005731-2.51*10^7*P1^3)/((T1+273.15)/100)^14.5;
[S2_Expression]
S2_p2t2=1.693*@log(T2+273.15)-0.4795*@log(10*P2)-2.9347+0.0005442*(T2+273.15)+(0.02747-44.95*P2)/((T2+273.15)/100)^4.1+(0.
005731-2.51*10^7*P2^3)/((T2+273.15)/100)^14.5;
[S3_Expression]
S3_p3t3=1.693*@log(T3+273.15)-0.4795*@log(10*P3)-2.9347+0.0005442*(T3+273.15)+(0.02747-44.95*P3)/((T3+273.15)/100)^4.1+(0.
005731-2.51*10^7*P3^3)/((T3+273.15)/100)^14.5;
[R0_Expression]
R0_p0t0=(688.45722-2.00135*T0+7.8851*10^-3*T0^2-1.7031*10^-5*T0^3)*4.186;
[R1_Expression]
R1_p1t1=(688.45722-2.00135*T1+7.8851*10^-3*T1^2-1.7031*10^-5*T1^3)*4.186;
[R2_Expression]
R2_p2t2=(688.45722-2.00135*T2+7.8851*10^-3*T2^2-1.7031*10^-5*T2^3)*4.186;
[R3_Expression]
R3_p3t3=(688.45722-2.00135*T3+7.8851*10^-3*T3^2-1.7031*10^-5*T3^3)*4.186;
!-----------------------device---------------------------------------;
!!-----------------------turbine------------------------------------;
[Turbine_Mass_Conservation]
G=GH1+GH2+GH3;
[Turbine_efficient]
Efficient_w=0.7;
[Turbine_Energy_Conservation_3]
W1=Efficient_w*G*(H0_p0t0-H1_p1t1)*10^3/3600;
W2=Efficient_w*(G-GH1)*(H1_p1t1-H2_p2t2)*10^3/3600;
W3=Efficient_w*(G-GH2-GH1)*(H2_p2t2-H3_p3t3)*10^3/3600;
[Turbine_produced_total_power]
W=W1+W2+W3;
[Turbine_coe_a2]
a2=10;
[Turbine_coe_b2]
b2=0.424;
[Turbine_device_cost]
C8=a2*W^b2;
[Turbine_Elec_price]
cw=4e-005;
[Turbine_Elec_cost]
C7=(Wo-W)*cw*HR;
!!---------------------steam network--------------------------------;
[Stream_Produce_stream_equation_3]
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Gcr1=0;
Gcr2>0;
Gcr3>0;
[Stream_Rank_Stream_Needed_eq_3]
G1>0;
G2=0;
G3=0;
[Stream_mass_Conservation_equ_3]
GH1+Gcr1=G1+F1;
GH2+Gcr2=G2+F2;
GH3+Gcr3=G3+F3;
!!---------------------------boiler---------------------------------;
[Boiler_efficient]
Efficient_g=0.9;
[Boiler_energy_conservation]
R0_p0t0*G*1000=Qg*Efficient_g;
[Boiler_coe_a1]
a1=4.8;
[Boiler_coe_b1]
b1=0.82;
[Boiler_device_cost]
C4=a1*G^b1;
[Boiler_fuel_price]
cf=6e-005;
[Boiler_Fuel_cost]
C5=cf*Qg*HR/(4.186*10^4);
!!-------------------------furnace----------------------------------;
[Furnace_efficient]
Efficient_f=0.9;
[Furnace_energy_conservation]
Q_F=Qf*Efficient_f;
[Furnace_energy_usage]
Q_F=Q_H0+G*1000*(T0-(T2-DeltaT))*4.18;
[Furnace_device_cost]
C9=36.549+4.9020*10^-6*Qf;
[Furnace_Fuel_cost]
C2=cf*Qf*HR/(4.186*10^4);
!!----------------------total exchanger ---------------------------;
[HeatExchanger_mass_conservation]
G1+G2+G3+Gc2+Gc3=Gcr1+Gcr2+Gcr3+Gcondensation;
[HeatExchanger_Hneeded]
Q_HNeeded=2.32e+007;
[HeatExchanger_Houtput]
Q_COutput=2.63e+007;
[HeatExchanger_HeatDemanded]
Q_HNeeded=Q_H0+Q_H1;
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```
[HeatExchanger_stnetwork_1]
G1*1000*R1_p1t1=Q_H1;
[HtExchanger_Cooling_Water_TRise]
T_Rise=15;
[HeatExchanger_stnetwork_2]
Q_C1=Gcr2*1000*R2_p2t2;
[HeatExchanger_stnetwork_3]
Q_C2=Gcr3*1000*R3_p3t3;
[HeatExchanger_water_cooling_Q]
Q_C0=(Gc2-Gcr2+Gc3-Gcr3)*1000*4.18*T_Rise;
[Heat_output_limit]
Q_Coutput=Q_c0+Q_c1+Q_c2;
[HeatExchanger_T_max]
T_max=310;
[HeatExchanger_T_min]
T_min=40;
[HeatExchanger_TPinch]
TPinch=230;
[HeatExchanger_Area_Fixed]
A_Fixed=5200;
[HeatExchanger_coe_K]
coe_K=600;
[HeatExchanger_Furnace_Area]
A_H0=Q_H0/(1800-T_max)/coe_K;
[HeatExchanger_Heating_Area_1]
A_H1=Q_H1/((T1-TPinch)/2)/coe_K;
A_H=A_H0+A_H1;
[HeatExchanger_Cooling_Stream_A]
A_C1=Q_C1/((TPinch-T2)/2)/coe_K;
A_C2=Q_C2/((T2-T3)/2)/coe_K;
[HeatExchanger_Cooling_Water_A]
A_C0=Q_C0/(T_Min-35)/coe_K;
[HeatExchanger_Total_C_Area]
A_C=A_C1+A_C2+A_C0;
[HeatExchanger_Total_Area]
A=A_Fixed+A_H+A_C;
[HeatExchanger_Area_coe_a]
a0=0.22;
[HeatExchanger_Area_coe_b]
b0=0.8;
[HeatExchanger_Area_cost]
C1=a0*A^b0;
[HeatExchanger_cooling_watr_price]
Cc=2e-008;
[HeatExchanger_Cooling_Water_Cost]
Qc=Q_C0;
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```
C3=Cc*HR*(Qc/T_Rise/4.186+1000*F1+1000*F2+1000*F3);
cv1=0.0005;
C61=F1*cv1*Hr;
cv2=0.0003;
C62=F2*cv2*Hr;
cv3=0.00015;
C63=F3*cv3*Hr;
Qc>Q_coutput/(Tpinch-T_min)*(T3-T_min);
Q_H0>Q_HNeeded/(T_max-Tpinch)*(T_max-T1);
DeltaT = 20;
F2*1000*R2_p2t2=G*1000*4.18*(T2-DeltaT-35);
!!-------------------------------init--------------------------------;
P0>6;
P1=4;
P2=1;
P3=0.3;
GH1>G1;
Wo=10000;
W>0.5*Wo;
F2>30;
F3>30;
```