Calculation of Cogeneration Potential of Total Site Utility Systems with Commercial Simulator

Xiao-Ying Ren[a], Xue-Xiu Jia[b], Petar S. Varbanov[b], Jiří J. Klemeš[b], Zhi-Yong Liu[c,*]

[a]School of Chemical Engineering, Hebei University of Technology, Tianjin 300130, China
[b]Sustainable Process Integration Laboratory - SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
[c]School of Marine Science and Engineering, Hebei University of Technology, Tianjin 300130, China
 liuzhiyong@hebut.edu.cn

Cogeneration potential of utility systems is one of the important indicators for the design of Total Site utility systems. In this paper, a new method is proposed to calculate cogeneration potential of Total Site utility systems. The temperatures of steam mains are calculated with Aspen Plus simulator first. Steam flow rates are calculated based on temperatures of steam mains and head loads of process, then. Based on the temperatures and steam flow rates obtained, shaft powers generated by the steam turbines in expansion zones can be obtained with the built-in block COMPR in Aspen Plus simulator. Compared to the existing methods, the method proposed needs not complex calculation procedure. For the illustrated case studies, the results obtained by this method are comparable to that obtained in the literature. It is shown that the calculation procedure proposed in this paper is simple, and the results are accurate.

1. Introduction

It is important to calculate cogeneration potential of utility systems before designing of Total Site utility systems (Klemeš et al., 1997).

Sorin and Hammache (2005) introduced a thermodynamic model for targeting fuel consumption, cooling water requirement and shaft power production based on a modified Site Utility Grand Composite Curve (SUGCC). In the model, the targets are represented as special segments on the modified SUGCC. El-Halwagi et al. (2009) presented a systematic method for targeting cogeneration potential in steam systems before designing of the power generation network. With the method, combustible wastes are used effectively, and the utilisation of fuel sources, heating and power generation are coordinated. Bandyopadhyay et al. (2010) proposed a graphical method to estimate the cogeneration potential at the total site level. Kapil et al. (2012) developed a method by combining bottom-up and top-down procedures. In their method, steam levels are systematically optimised in the design of site utility configurations. An Iterative Bottom-to-Top Model (IBTM) was developed by Ghannadzadeh et al. (2011). The method considers the degree of superheat and also employs the same thermodynamic equations as Kundra (2005). The IBTM uses an iterative procedure to calculate cogeneration potential with less required data compared to the method of Kundra (2005). Oluleye et al. (2014) presented a mathematical model to evaluate the potential of a processing site for waste heat recovery. Ng et al. (2017) developed an algebraic method to determine cogeneration potential.

The listed methods need complex calculation procedure or tedious steps for constructing of the curves. The calculation of the cogeneration potential with commercial simulators still desires more development. In this paper, a commercial simulator is used to calculate cogeneration potential of Total Site utility systems. In the calculation procedure, parameters are adopted from Ghannadzadeh et al. (2011). The results obtained by the proposed method are comparable to that obtained with the literature methods.

2. New Method

In the calculation procedure of targeting the cogeneration potential, many required data can be obtained from commercial simulator easily. In addition, many simulators have flexible and robust calculation framework in

which material and energy balances can be obtained easily. Simulators have many built-in model blocks which can be directly used in the simulation of utility systems. In this paper, Aspen Plus simulator is used to calculate the cogeneration potential. In the calculation, steam is the working fluid of turbine, the Property Method is STEAMNBS.

In this work, the targeting of cogeneration potential for the site utility system is divided into three steps as shown in Figure 1, Step 1: calculation of temperatures of steam mains, Step 2: calculation of the mass flow rates of steam mains, and Step 3: calculation of shaft powers of steam turbines. The detailed procedure will be discussed as follows.

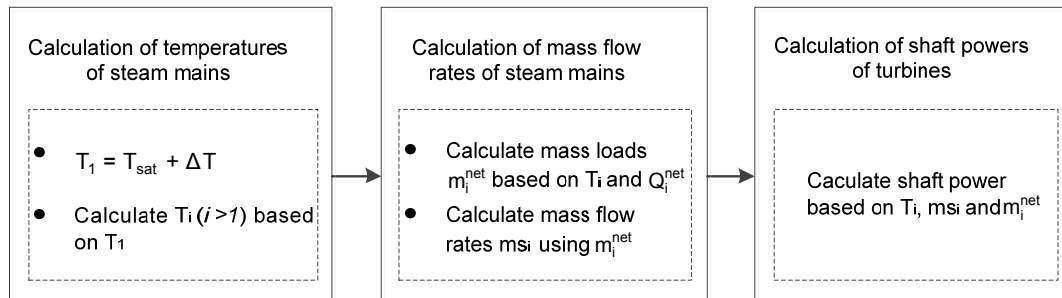| Calculation of temperatures of steam mains	Calculation of mass flow rates of steam mains	Calculation of shaft powers of turbines
• $T_1 = T_{sat} + \Delta T$ • Calculate T_i ($i > 1$) based on T_1	• Calculate mass loads m_i^{net} based on T_i and Q_i^{net} • Calculate mass flow rates ms_i using m_i^{net}	Caculate shaft power based on T_i, ms_i and m_i^{net}

Figure 1: Overview of the new method for calculating cogeneration potential

Step 1: Calculation of temperatures of steam mains

The procedure for manipulating stream data to generate the Site Utility Grand Composite Curve (SUGCC) can be found in Klemeš et al. (1997). Figure 2 shows the diagram of steam turbines configuration with a set of steam mains in SUGCC. It can be seen that different level steams are required or generated by the process. To meet the process steam demands and utilise the energy effectively, higher-pressure steam can be used to generate shaft power via steam turbines and reduced to lower-pressure steam. In SUGCC, pressure and heat load of every steam level are shown. Net heat load Q_i^{net} is the difference between the process demand steam and the process generated steam in the same steam level.
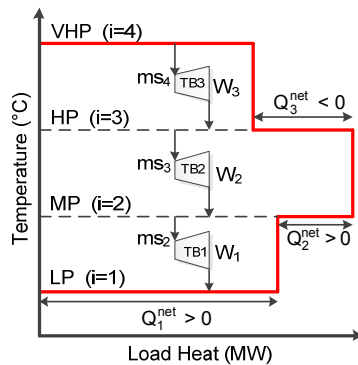

Figure 2: An illustration of SUGCC with steam turbines

Using Aspen Plus simulator, temperatures of all steam mains can be calculated based on the lowest-pressure steam main T_1. The temperature of the lowest-pressure steam main T_1 is specified by adding a degree of superheat (ΔT) to its saturation temperature because the lowest-pressure steam main would be used for steam heating. When steam is used for steam heating, it is desirable to have at least 10 °C superheat in steam mains to avoid excessive condensation in the transport. As shown in Figure 2, the very high pressure (VHP) steam expands through turbines to the low-pressure (LP) steam. When the isentropic efficiency of steam turbines is constant, the temperature of the VHP steam main determines temperatures of the lower-pressure steam mains. When the temperature of the LP steam main is specified, the temperatures of VHP, HP and MP steam mains can be calculated based on the temperature of LP steam main. The simulation flowsheeting for calculating temperatures of steam mains is shown in Figure 3. The built-in block COMPR is used to model steam turbines with isentropic efficiency. In the simulation, the flow rate of VHP can be taken as 1 t/h. In the "Design Spec" of Aspen Plus simulator, the temperature of LP steam main is set to the target

value and the temperature of the VHP steam main is the manipulated variable. By running simulator, temperatures of all steam mains can be obtained.
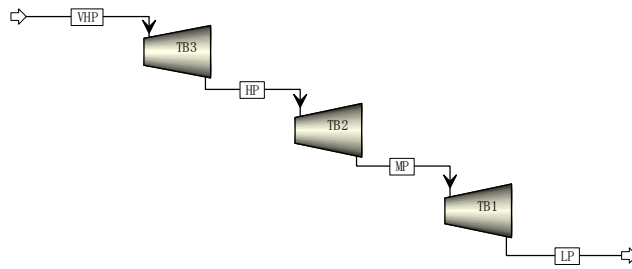

Figure 3: The simulation flowsheeting for calculating temperatures of steam mains

Step 2: Calculation of the mass flow rates of steam mains
For a given Total Site, the net heat loads (Q_i^{net}) at different pressure levels are often known except for the highest-pressure level that is aimed to be determined at the end of targeting stage. The process required steam is assumed to be turned into condensate water after being used. The steam generated by the process is assumed to be superheated steam that is obtained by heating condensate water. The net mass load (m_i^{net}) at every pressure level will be calculated using the net heat load by Eq(1).

$$m_i^{net} = \frac{Q_i^{net}}{h_i - h^{Ref}}$$ (1)

where h_i is the enthalpy at the temperature and pressure of steam main i, and h^{Ref} is the enthalpy of the condensate water at the pressure of the steam main and temperature of boiler feed water.
The net mass loads are mass flow rates of net process generation steam or net process demand steam at different pressure levels. The mass flow rates (ms_i) of steam i expanding through the *(i-1)* steam turbine to generate shaft powers can be calculated using net mass loads by Eq(2), as shown in Figure 2. It should be noted that flow rate of steam expanding through the top turbine is equal to the flow rate of VHP steam main.

$$ms_i = \sum_{i=1}^{i-1} m_i^{net}$$ (2)

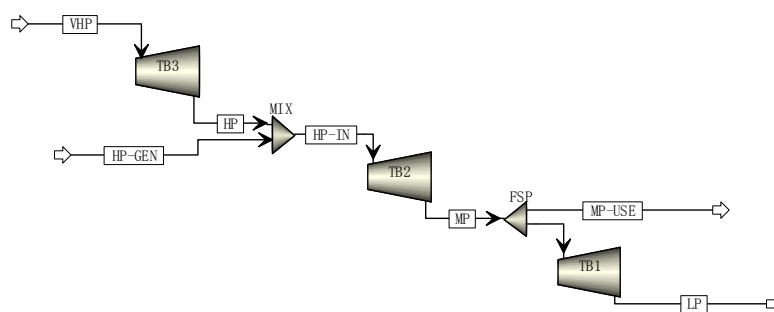Step 3: Calculation of shaft powers of steam turbines

Figure 4: The simulation flowsheeting for calculating shaft powers

In Figure 4, the simulation flowsheeting for calculating shaft powers is established based on the SUGCC shown in Figure 2. The temperatures and flow rates of VHP, HP-GEN and MP-USE steam mains should be inputted. Temperatures have been obtained in step 1. The flow rates of HP-GEN and MP-USE steam mains can be calculated by Eq(1), and flow rate of VHP steam main is calculated by Eq(2) in step 2. Inputting these parameters, running the simulator, the shaft powers can be determined.

3. Case study

In this section, the new method proposed will be demonstrated by three case studies presented by Ghannadzadeh et al. (2011). Figure 5 shows the required input parameters for cogeneration targeting of the site utility systems. In these cases, the temperature of condensate water is assumed to 105 °C. The condensate water is supplied to the boiler house or steam generated in the process. The isentropic efficiency of all turbines is taken as 0.7 and mechanical efficiency is assumed as 100 %. In Example 1, the degree of superheat (ΔT) in LP steam main is assumed to be 30 °C. In Examples 2 and 3, the degree of superheat (ΔT) in LP steam main is assumed to be 40 °C.
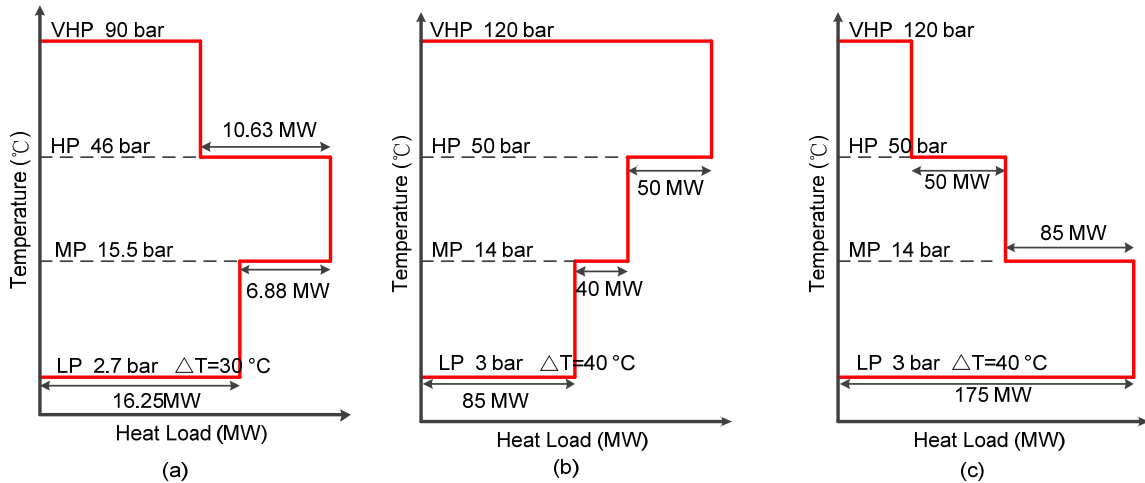

Figure 5: Input data: (a) Example 1, (b) Example 2 and (c) Example 3.

Step 1: Calculation of the temperatures of steam mains.
In Example 1, the saturation temperature of LP steam main is 130 °C. The degree of superheat in LP steam main is 30 °C. Then, the temperature of LP steam main is 160 °C. In the "Design Spec", specify the target temperature of LP steam main T_{LP} as 160 °C, and T_{VHP} is specified as the manipulated variable. After running simulator, the following results are obtained: T_{VHP}, T_{HP} and T_{MP} are 501, 417 and 302 °C, when T_{LP} achieve the goal 160 °C, as shown in Figure 6.
Step 2: Calculation of the mass flow rates of steam mains.
Figure 5 shows the net heat loads at the HP, MP and LP through the SUGCC. In Example 1, the net mass loads for LP, MP and HP levels calculated are 24.96, 9.53 and 13.69 t/h, with Eq(1). The mass flow rates of steams expanding through the steam turbines of MP-LP, HP-MP and VHP-HP intervals calculated by Eq(2) are 24.96, 34.49 and 20.80 t/h.
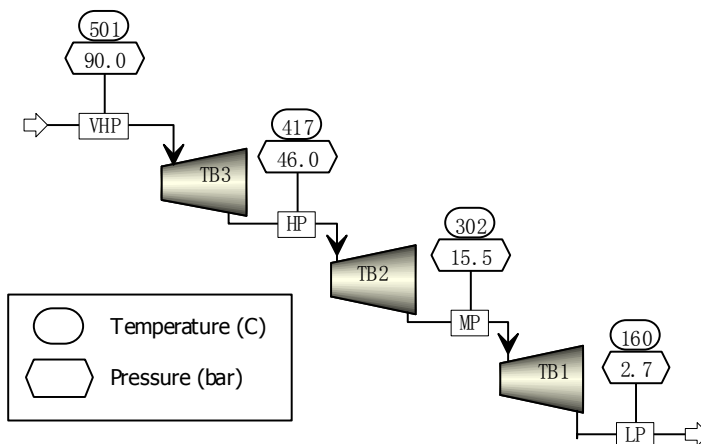

Figure 6: The simulation for calculating temperatures of steam mains of Example 1
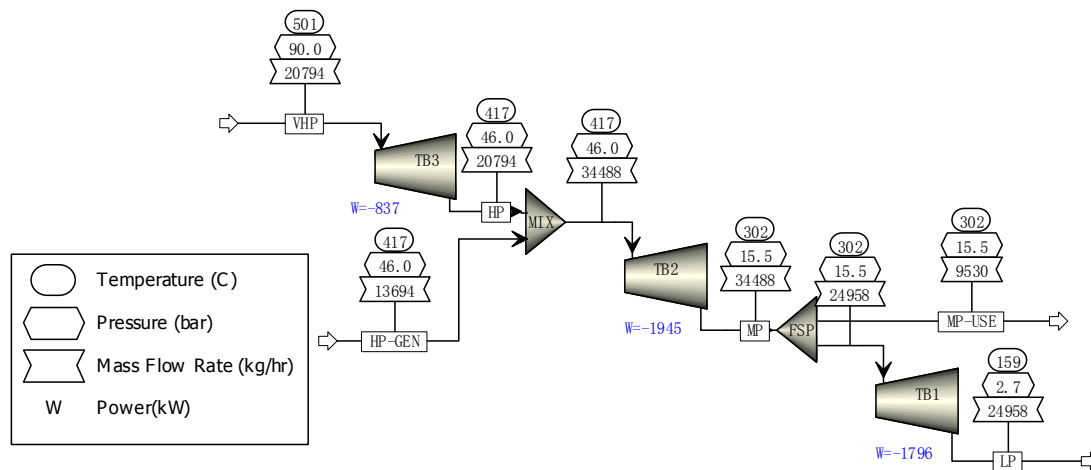
Figure 7: The simulation flowsheeting for calculating shaft powers of Example 1

Step3: Calculation of the shaft powers of the turbines.

In Example 1, the temperature of VHP steam main is 501 °C, and the steam flow rate of VHP steam main is 20.80 t/h. Net HP steam generated in the process is 13.69 t/h, and net steam demand in MP is 9.53 t/h. Inputting these constraint conditions into Aspen Plus simulator, shaft powers of steam turbines obtained are 0.84, 1.95 and 1.80 MW, and are shown in Figure 7.

Similarly, the temperatures of steam mains, steam flow rates and shaft powers generated by the steam turbines for Example 2 and Example 3 can be obtained. The results of three examples are listed in Tables 1, 2, 3 and 4.

Table 1: Temperatures of steam mains (°C)

Example	LP	MP	HP	VHP
Example 1	160	302	417	501
Example 2	174	301	436	549
Example 3	174	301	436	549

Table 2: Net mass flow loads (t/h) of process generation or process demand steam

Example	LP	MP	HP
Example 1	24.96	9.53	13.69
Example 2	129.10	55.36	63.42
Example 3	265.79	117.63	63.42

Table 3: Mass flow rates (t/h) of steam expanding through the steam turbines

Example	MP-LP	HP-MP	VHP-HP
Example 1	24.96	34.49	20.80
Example 2	129.10	184.46	247.88
Example 3	265.79	148.16	84.74

Table 4: Shaft powers (MW) of steam turbines

Example	VHP-HP	HP-MP	MP-LP
Example 1	0.84	1.95	1.80
Example 2	13.47	12.28	8.32
Example 3	4.61	9.86	17.13

Table 5: The shaft powers generated by turbines and the temperature of VHP steam main

Example	Method	VHP-HP (MW)	HP-MP (MW)	MP-LP (MW)	Temperature of VHP (°C)
Example 1	New method	0.84	1.95	1.80	501
	IBTM	0.8	1.9	1.7	500
Example 2	New method	13.47	12.28	8.32	549
	IBTM	13.49	12.28	8.33	550
Example 3	New method	4.61	9.86	17.13	549
	IBTM	4.6	9.8	17.1	550

The comparison of the results of the IBTM method and that of the new method are presented in Table 5. From Table 5, it can be seen that the results of the two methods are almost the same. However, the calculation procedure of the new method is simpler than that of IBTM method (Ghannadzadeh et al., 2011). The parameters required in the new method are less than the targeting approach of Kundra (2005).

4. Conclusions

In this paper, a new method is presented for calculating cogeneration potential of site utility systems by Aspen Plus simulator. In the new method, the temperatures of steam mains are calculated with the built-in block COMPR of the simulator. Then, steam flow rates are determined based on the temperatures of steam mains and heat loads. Shaft powers generated by the steam turbines are obtained with the temperatures of steam mains and steam flow rates obtained. By using the simulator, it is not necessary to develop mathematical programs or set up thermodynamics models, this makes the calculation procedure much easier. For the illustrated case studies, the results obtained by this method are comparable to that obtained in the literature.

As a future work, the evaluation of the steam turbine capital cost and environmental footprints should be further added to the targeting procedure, to provide decision makers with more complete picture of the designed sites. This should allow them to efficiently screen and compare the major design options on the basis of economic and environmental performance.

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