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Abstract

System analysis is necessary to systematically evaluate site-wide efficiency of generation, distribution, utilization and discharge of energy. In order to capture overall characteristics of energy utilization for a site, graphical manipulation and interpretation of energy demands at different quality and quantities are carried out. This conceptual methodology will synthesize the entire total energy system, subject to structure and operation of site utility systems, energy recovery of individual processes, site-wide strategy for combined heat and power generation, and carbon footprint. New targeting method for total site analysis will holistically integrate overall heating and cooling requirements from individual processes, which will then produce realistic and practical targets for heat and power productions for the site, as well as provide design and operational guidelines for improving energy efficiency. The method will also systematically evaluate the recovery of any waste heat available from the site, and fully exploit their integration potentials in the context of total site.

This work developed a new graphical approach to extend pinch analysis for utility targeting and offered the effect of steam mains selection and process variation on the cogeneration improvement.

This graphical tool - the steam cascade curves - enables integration of process heating loads, process indirect heat recovery, and utility system targets, and can reveal the cogeneration improvement from both utility selection and process modification. The steam cascade can provide all the site utility targets such as VHP steam from fuel combustion, shaft power potential by steam expansion, etc. Besides that the new tool enables steam mains selection on the cogeneration and also enables processes modifications, the new tool can replace a sequence of graphical tools to obtain process and utility quantative targets and gives the insights of interaction between processes and utility systems. Additionally, the graphical method is helpful to explore the maximum driving force, and then work out the corresponding matching design parameters for energy-intensive process units.

This work also develops novel models for key components performance such as steam turbines and boilers in utility systems, able to provide more precise and reliable system optimization results.

New full load and part load steam turbine performance models considering turbine size, steam inlet pressure and temperature, and exhaust pressures, have been developed and are used in design and operational optimisation. The key feature of the new model is that it

allows for steam pressure varied directly which was not the case for previous models. The new model can be applied for design with consistent accuracy compared to existing models. It is especially beneficial for operational optimization and retrofit with complex turbines.

The previous boiler model used in total site integration does not capture such important factors as combustion conditions and fuel quality, which is not consistent with the real data. For boilers, a series of industrial standards (ASME, DIN, BS, etc) have been built and are well established. A boiler model complying with these well verified codes should be integrated with the total site design and optimisation in order to get more realistic and reliable results. However, these boiler performance test codes were not developed for the purpose of the total site integration and optimisation. A detailed boiler performance calculation following the codes exactly is impossible to implement in the total site methodology. Accordingly, a simplified boiler performance model has been developed that is characterised by the key factors involved in the standard complex model. This new model is suitable for the total site design and optimisation, and at the same time includes the key parameters from the industrial standard codes. An important feature of the new model is that it inherently characterises part-load performance through regression parameters that vary with the load.

Contents

1 Introduction

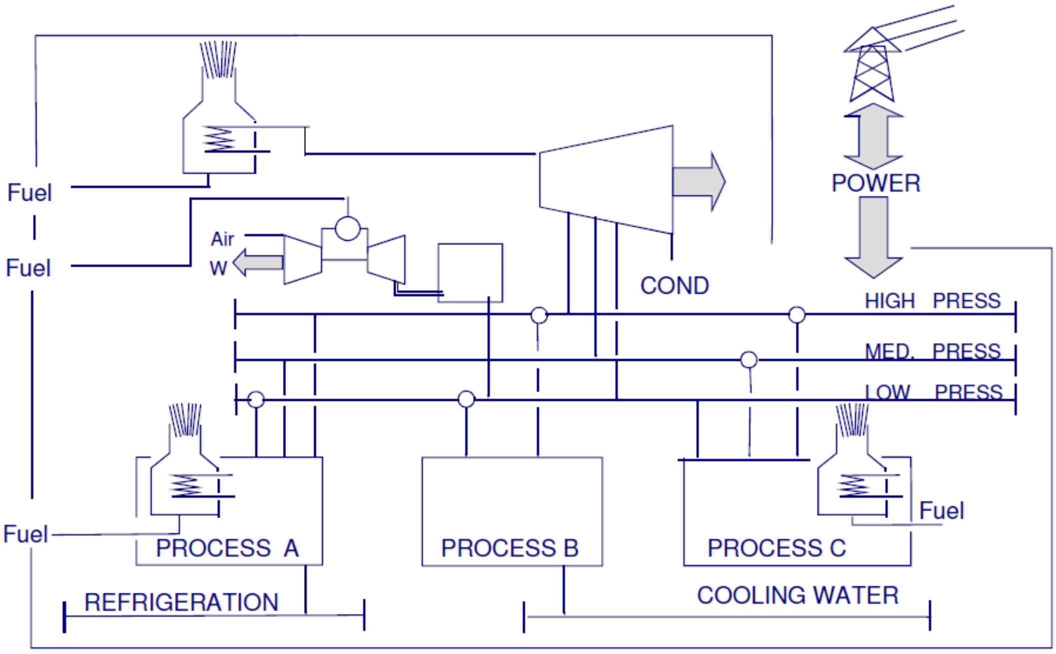


Figure 1 A Total Site Utility System

Various processes operate on the site and are connected to a common utility system. A typical site utility system is shown in Figure 1. The source of utility very high pressure (VHP) steam is fuel combustion in boilers and gas turbines heat recovery steam generators, and VHP steam distribute to lower pressure steam mains to satisfy process heating demand. Steam cascade in the utility system is determined by utility VHP steam from boilers, process heating and cooling demands, and process indirect heat recovery through the utility medium. Utility power is generated by fuel combustion in gas turbines and steam expansion or condensation in steam turbines. Cogeneration means both heat and power production simultaneously. The deficit or excess power is imported from or exported to the grid.

The heating and cooling duties generated or required by the processes, the power demand on the total site are determined by the process characteristics. The selection of the utility system configuration, steam loads along steam mains, and steam/ power generation equipments like gas turbines, steam turbines, etc, determine utility system performance.

The research of the integration of utility system with processes focus on the utility system analysis and the interaction between utility systems and processes. The conceptual methodology would be developed for the entire total energy system synthesis firstly, subject to structure and operation of site utility systems, energy recovery of individual processes, site-wide strategy for combined heat and power generation. More precise model development for key components performance such as steam turbines and boilers in utility system is able to provide reliable system optimization results.

2 Previous conceptual design methodology for the total site energy analysis

To finish the thermodynamic analysis and targeting for the utility system, both graphical approaches and mathematical programming methodologies are developed for the site targeting and power analysis to improve the integration of utility systems and processes.

The the utility system design mainly works on the steam system configuration and the steam and power generation.

2.1 Process heat recovery and utility demands

The hot and cold utility demands are obtained after the process heat integration.

Based on the pinch analysis approach (Linnhoff,1982), the Composite Curves can be used to set energy targets for an individual process and are useful in providing conceptual understanding of the process, but they are not a suitable tool for the selection of utilities. The Grand Composite Curve (Linnhoff et al. 1994) is a more appropriate tool for understanding the interface between the process and the utility system, and presents the heat recovery within individual process, and the utility demands by the process.

The process hot and cold utility demands and power demand are the basis of utility system design. What is more, the process heat recovery for steam generation would affect the utility targets of steam cascade and power generation. There is an interaction between utility systems and processes.

2.2 Site targeting by graphical methods

Targeting method for total site analysis will integrate overall heating and cooling requirements from individual processes, which will produce realistic and practical targets for heat and power productions for the site, as well as provide design and operational guidelines for energy efficiency improvement.

Graphical approach has been developed for process and utility system integration. A temperature - enthalpy picture for the whole site is needed.

2.2.1 Steam systems and power generation

The site source-sink profiles (Dhole and Linnhoff ,1993) of the overall site utility system is obtained by the combination of the Grand Composite Curve of each of processes on the site. As shown in Figure 2, these profiles implement processes and utility system integration and provide the process quantified heating and cooling targets graphically. The heating requirements normally are satisfied by the steam system generated from the boilers and gas turbines with fuel consumption. The cooling requirements should be met by air cooling, cooling water, refrigerants, etc due to the cooling temperature and heat load. However, the site steam saving due to process indirect heat recovery cannot be obtained from the profiles.

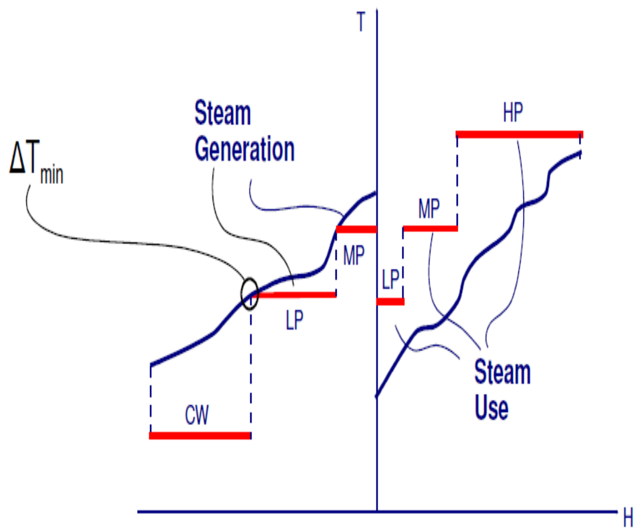


Figure 2 Site Source-Sink Profiles and Targets for Process Steam Usage and Generation

To address the heat recovery between the processes through the steam system, Site Composite Curves (Linnhoff et al. 1993, 1994; Klemes et al., 1997) are constructed following the zero approach between the utility loads, and provides the targets for indirect process heat recovery. As shown in Figure 3, the minimum site VHP steam demand and cooling demand for the utility system are obtained as well. Steam generation from available heat by the process reduces the VHP steam demand generated from fuel burning in steam generators such boilers and gas turbines with HRSG. The maximum heat recovery means the minimum VHP steam demand in utility systems. Fuel consumption in boilers and gas turbines through

HRSG for VHP steam generation can also be calculated from the site composite curves (Raissi, 1994; Perry 2008).

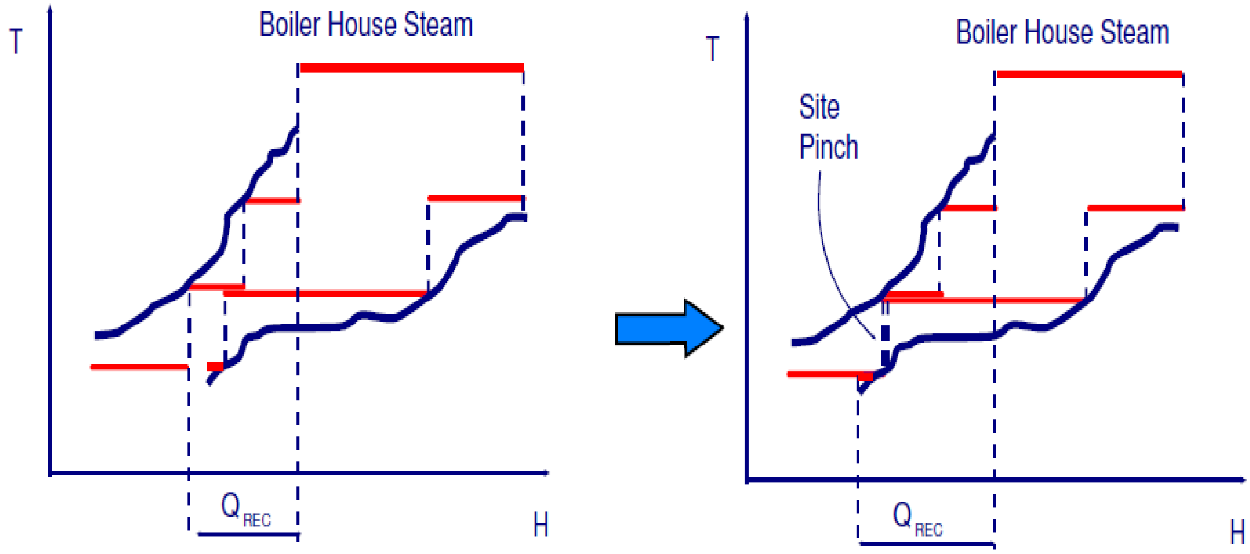


Figure 3 Site Composite Curves and Site Steam Saving by Process Heat Recovery

Site Utility Grand Composite Curves (Raissi, 1994) are constructed from the steam cascade extracted from the Site Composite Curves, and allow the visualization of the steam cascade in the utility system. Based on the temperature enthalpy (T–H) model (Raissi, 1994), the shaft power potential by steam expansion in steam turbines is a function of the steam load and the saturation temperature drop between the inlet and outlet steam of the steam turbine. So, as shown in Figure 4, the area in the site utility grand composite curves is approximately proportional to the potential shaft power generation by steam expansion.

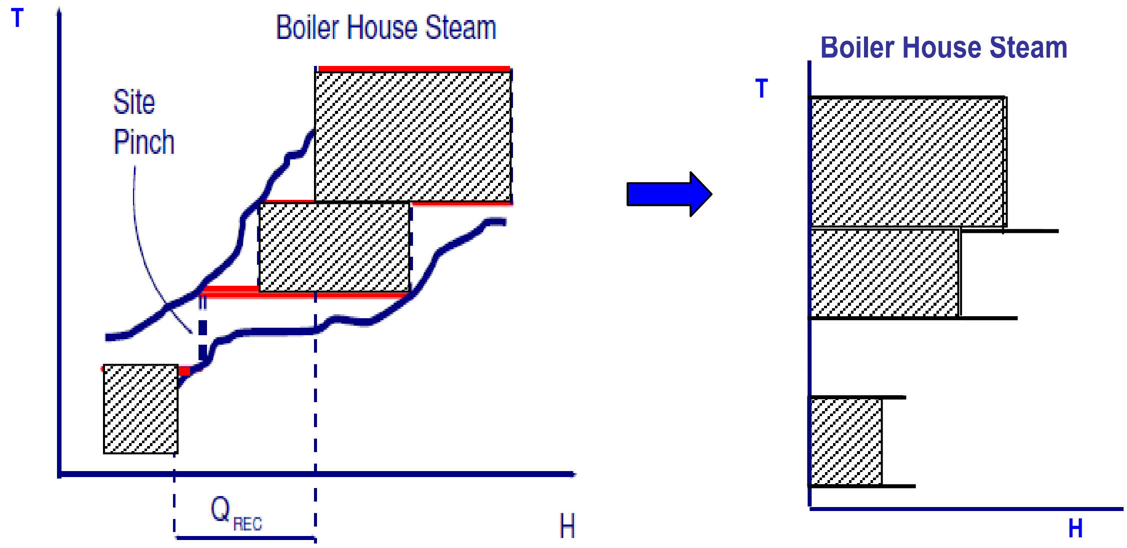


Figure 4 Site Utility Composite Curves and Shaft Power Potential

Based on above analysis, steam system targets can be obtained only when all these three curves are available simultaneously.

Other graphical methods have extended pinch analysis for site-wide heat and power integration. Klemes et al.(1997) plotted Carnot factor versus enthalpy. Makwana et al. (1998) extended the application of total site targeting methodology. Wan Alwi et al. (2012) adopted pinch graphical tools to achieve minimum electricity targets in hybrid renewable energy system. Hackl et al. [10] used such tools for energy efficiency targeting. Bandyopadhyay et al. (2011) estimated the cogeneration potential at the total site level by the site level grand composite curve. Botros and Brisson (2011) improved the targeting by including sensible heating of steam in composite curves. Varbanov and Klemes (2010) set time slices into site profiles and site composite curves to integrate renewables into the corresponding total site CHP energy systems. Wan Alwi and Manan (2010) introduced a stream temperature and enthalpy plot technique to represent continuous individual hot and cold streams. Varbanov et al. (2012) specified process specific minimum temperature difference to obtain more realistic utility and heat recovery targets. Hackl et al.(2011) investigated the opportunities to deliver waste heat from one process to another using total site analysis. Abbood et al.(2011) utilized a grid diagram table and chemical pinch analysis for the synthesis of chemical reactors or separation trains for a whole plant. Tan and Foo.(2008) also extended pinch analysis to consider carbon emissions.

2.2.2 The cooling system and low temperature waste heat recovery

For the cooling system, priority should be given to recover waste heat in the first instance within the process. Hot oil can be used to transfer heat around at high temperatures. Below steam temperature, heat can be passed around a site using hot water, or boiler feed water preheating or combustion air preheating.

The most direct way to reject heat above ambient temperature to the environment is by air cooling. Another way is through the use of water in once-through cooling systems, like river water. If heat rejection is required below ambient, the refrigeration is required.

Normally, there are two broad classes of refrigeration system: compression refrigeration which is by far the most common in industry, and absorption refrigeration which is only applied in special circumstances. Generally, the lower the temperature of the cooling required to be serviced by the refrigeration system and the larger its duty, the more complex the refrigeration system.

Figure 5 performs the practical refrigeration cycles. Figure 6 shows the operating ranges of a number of refrigerants (Smith, 2005).

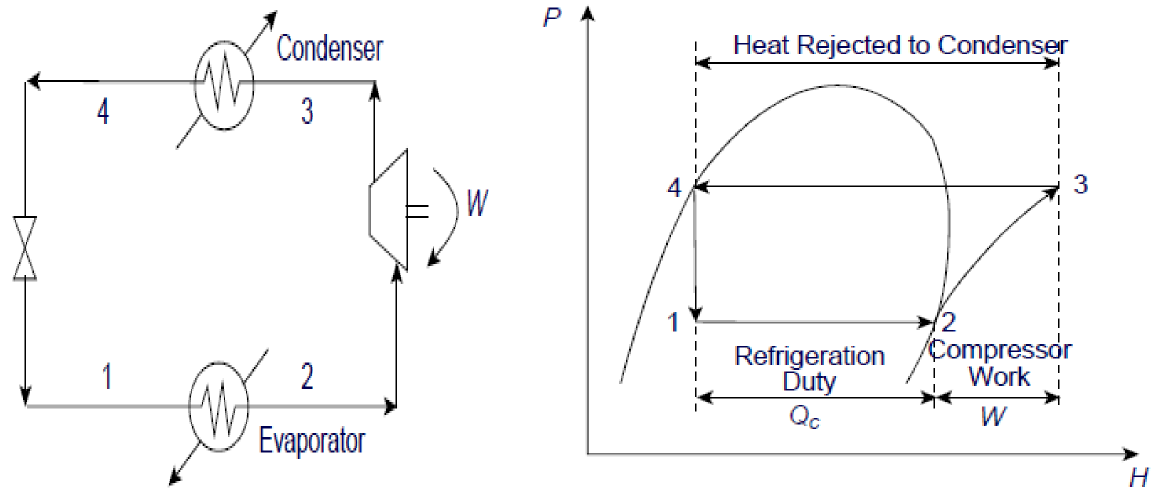


Figure 5 Performance of Practical Refrigeration Cycles

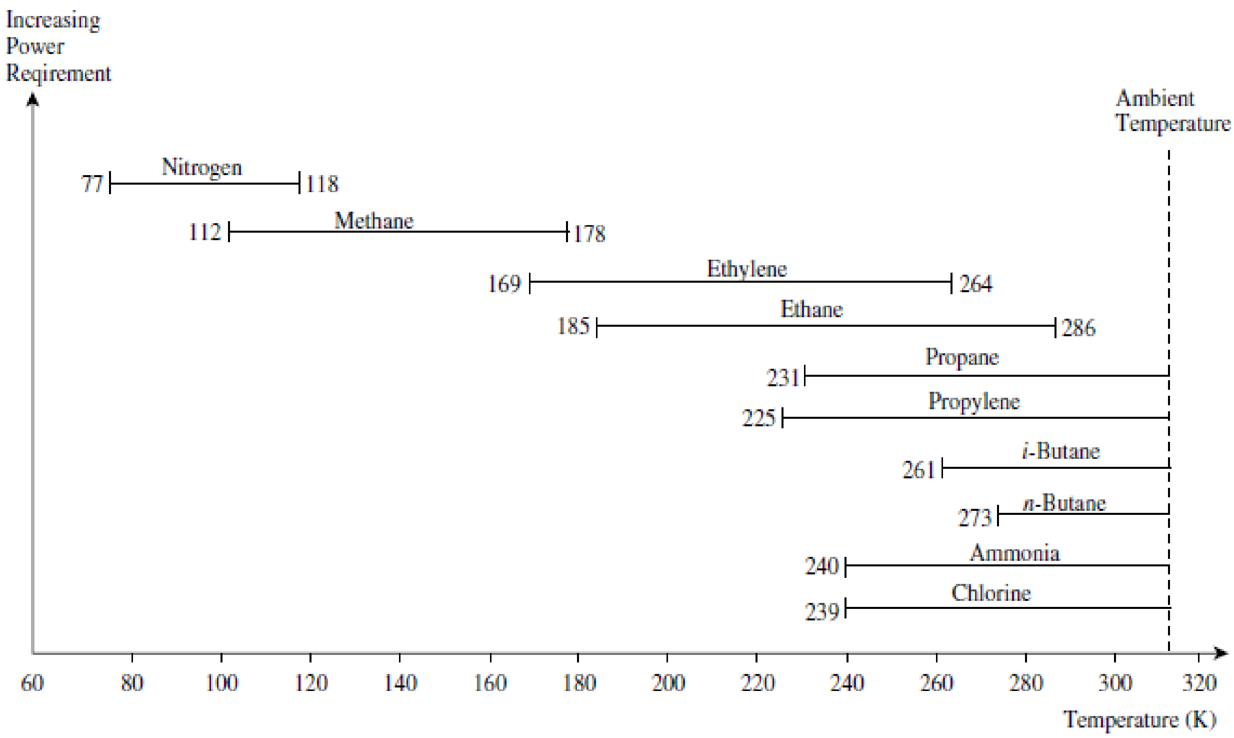


Figure 6 Operating Ranges of Refrigerants

Low temperature waste heat recovery attracts more attention in practice. The site composite curves identify opportunities for low temperature waste heat recovery, shown in Figure 7. Low temperature waste heat recovery can either be transferred out of the site for district heating, or recovered and integrated with the total site by the heat upgrade and recovery options such as heat pump, absorption refrigeration, Organic Rankine Cycle (ORC), boiler feed water (BFW) heating, etc.

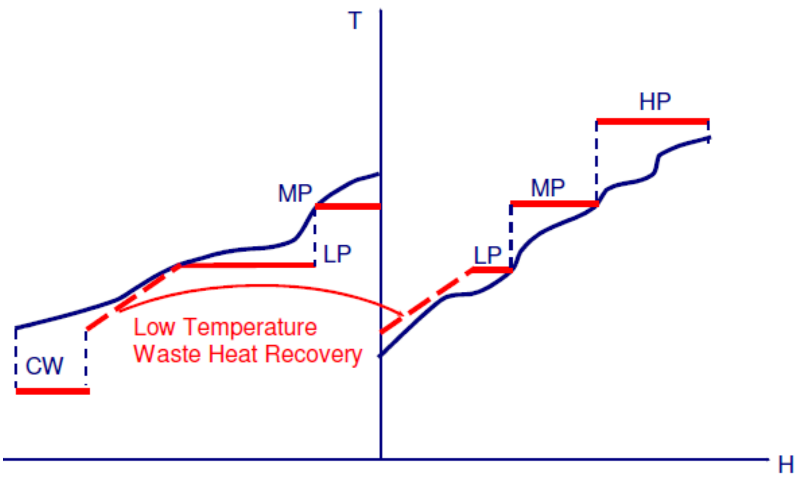


Figure 7 Low Temperature Waste Heat Recovery

3 A new graphical methodology development for processes integration with utility systems

A new graphical methodology has been developed as a visual tool for utility targeting. It can replace a sequence of graphical tools to obtain process and utility quantitative targets and gives the insights of interaction between processes and utility system.

This graphical tool - the steam cascade curves - enables integration of process heating loads, process indirect heat recovery, and utility system targets, and can reveal the cogeneration improvement from both utility selection and process modification.

3.1 Steam cascade curves and utility system targets

The steam cascade curves are constructed analogous to the Site Utility Grand Composite Curves. As shown in Figure 8, they are extracted from the Site Source-Sink Profiles directly instead of Site Composite Curves in the previous approach.

The steam cascade is obtained under the total process steam demand, instead of utility VHP steam target, and can provide all the site targets.

The steam cascade curves shows the steam cascade along steam mains. They are different from the Site Utility Composite Curves. because they are obtained under the total process steam demand, instead of utility VHP steam target in the Site Utility Composite Curves.

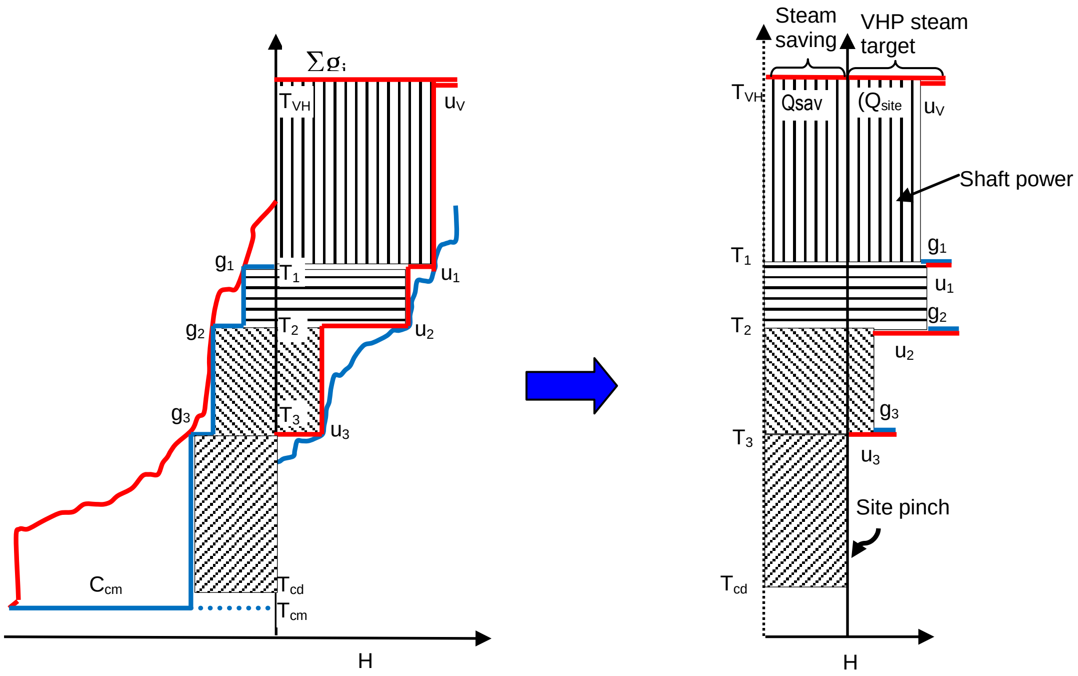
The steam cascade curves can provide all the site targets.

The process heating target is u_i (kW) at each steam main, and the cooling target is Cm (MW). Subscript i=1, 2, 3, 4, represents the VHP, HP (high pressure), MP (medium pressure), and LP (lower pressure) steam main, respectively. m is cooling medium. Steam generation from the process heat recovery is g_i (MW) at each steam main, and contributes to process heating loads and increases power generation by steam expansion.

Total steam demand=Σu_i (1)

Steam generation from process heat recovery =Σg_i (2)

Process heating requirement is satisfied by the utility steam at different pressures. Process heat recovery can supply heat to processes, implementing both utility VHP steam and fuel combustion saving. The steam generation by process heat recovery also might allow more power generation. Obviously, the utility VHP target is the total process steam demand minus the utility steam saving. Normally, the site steam saving is lower than the whole process indirect heat recovery. Its identification in the profiles contributes to both utility VHP steam target as well as system cogeneration.



(a) Site Source-Sink Profiles (b) Steam cascade curves and site targets

Figure 8 Steam Cascade Curves

Utility VHP target= Total process steam demand – utility steam saving (3)

It is not possible to cascade steam from lower to higher pressure. Therefore, the minimum steam cascade would be empty. The maximum utility VHP steam saving is the minimum steam cascade in the steam expansion zone and condensing zone in Figure 8(b). The utility VHP steam target is achieved by removing the utility VHP steam saving from the total process steam demand. Thus, both the steam saving and utility VHP steam target can be identified in the steam cascade curves.

The steam zone with an empty steam cascade is defined as the site pinch. There is no potential shaft power at the site pinch.

The available shaft power targeting methods are exergy model, TH model, Turbine hardware model and Sorin model. Based on the temperature enthalpy (T–H) model (Raissi, 1994), the potential power generation is proportional to the sum of rectangular area.

$$W=c*Q*(T_{in}- T_{out}) \quad (4)$$

Where

W = the shaft power generation by the steam expansion, kW

c = the power conversion coefficient based on concept of T-H model, $°C^{-1}$

Q = the heat duty of the inlet steam of the steam turbine, kW

T_{in} = saturation temperature of inlet steam of the steam turbine, °C

T_{out} = saturation temperature of outlet steam of the steam turbine, °C

Applying a constant isentropic efficiency model, it should be noted that the larger the flow through a steam turbine, the greater the amount of power that will be generated. Also, the larger the pressure difference across the steam turbine, the more the power generation potential.

Thus, the steam cascade curves embody targets of process heating and cooling demands, steam generation by process indirect heat recovery, the minimum utility VHP steam target, the potential shaft power generation, as well as the site pinch. The fuel combustion in boilers can be calculated from the site VHP steam target.

3.2 Cogeneration improvement

In the utility system, one of methods to implement high efficiency of fuel combustion is cogeneration. Cogeneration interacts with utility VHP steam target and the steam cascade.

To improve heat and power targets, measures need to be taken both from processes and the utility system.

There are two approaches for cogeneration improvement:

1) Steam cascade adjustment. Steam mains selection is an important decision to affect steam cascade and the site pinch.

2) Modification of processes. This will cause variation of the site grand composite curve. In practice, it must be done with caution to maintain realistic operation.

Steam cascade curves integrate process heating loads, process indirect heat indirect recovery, and utility system targets, and can reveal the cogeneration improvement from both utility selection and process modification. Additionally, the graphical method is helpful to explore the maximum driving force, and then work out the corresponding matching design parameters for energy-intensive process units.

3.2.1 Impact of steam mains selection on the cogeneration

Steam mains selection is the important factors for the steam cascade adjustment. Steam mains variation changes the process heating and cooling loads, process indirect heat recovery, and utility VHP steam target. The variation of the steam cascade induces the fluctuation of shaft power potential by steam expansion and the site pinch relocation as well. More site VHP steam saving implies lower site VHP steam target and less fuel consumption.

Except the steam mains selection for the improvements in the cogeneration, a new steam mains introduction is beneficial for process heat recovery. Its effect on the boiler steam saving, utility VHP steam target and the shaft power generation potential depends on new steam mains introduction within or without the site pinch.

A new steam main added at the site pinch implies utility VHP steam target reduction and fuel saving. It means attractive system economy with less waste emission. At the fixed fuel consumption in the utility system, more shaft power would be produced for cogeneration improvement.

A new steam main added away from the site pinch does not change the site pinch. Extra power is generated on account of extra higher pressure steam generation from process heat recovery and lower pressure steam load to heat the processes. There is no variation on the boiler steam saving, site VHP target, and fuel combustion.

3.2.2 Processes modification

Processes can in principle be modified from two aspects: operating conditions or equipment adjustment. This could include variation on stream flow rates and temperatures, number of distillation column trays, heat exchanger area, and so on.

The process variation in heating and cooling demands can be classified into four cases: 1) More process heat recovery for more steam generation. 2) Less process heating and cooling demands. 3) Lower process stream heating target temperature. 4) Higher pressure instead of lower pressure steam generation from process heat recovery. The first three cases are obviously beneficial for more steam cascade and more potential power generation. The fourth process variation would achieve the same result while more heat is recovered for higher pressure steam generation, but the lower heat recovery for higher pressure steam generation is uncertain for cogeneration improvement.

4 New model developments for component performance in utility systems

Mathematical programming methodology has been developed for utility system optimization (Papoulias and Grossmann,1983; Petroulas and Reklaitis,1984; Colmenares and Seide,1989). Linear models (Raissi,1994; Bandyopadhyay et al. 2010) and non-linear models (Mavromatis and Kokossis,1998) have been used in the optimization. Rigorous mixed integer non-linear programming model (Bruno et al. 1998) would obtain more accurate results. There were also models developed in the optimization based on thermodynamic models (Medina-Flores and Picon-Nunez, 2010; Sorin and Hammache, 2005), and Iterative Bottom-to-Top Model (Ghannadzadeh, et al. 2012). Manesh et al. (2012) developed a new cogeneration targeting model based on entropy, enthalpy and the isentropic efficiencies of the turbines. Prashant and Perry (2012) used mixed integer linear programming techniques to examine the optimal location and the number of steam levels to meet the process heating and cooling demands.

The performance of the utility system mainly depends on its components and their configuration. The components contain gas turbines, boilers, HRSG, steam turbines, etc. The components properties are determined by the equipment technological development. Applications experience has shown previous system component models have shortcomings. Accurate modelling for component performance would beneficial for more reliable system optimization result.

4.1 Steam turbines

Steam turbines mainly work in three functions: lower pressure steam distribution to balance process steam requirements at different temperature; shaft power generation during the steam expansion in steam turbines, especially in the heat and power (CHP) production design; and running rotary mechanical equipments directly as drivers.

Steam turbines can be divided into two basic classes: Back-pressure turbines and condensing turbines. Steam turbine sizes range from small 0.75 kW units as mechanical drivers to 1,500 MW turbines for electricity generation.

The ideal performance of steam turbine follows Rankine cycle as shown in Figure 9. However, it cannot be realized in practice. As shown in the T-s diagram for steam in Figure 9, the starting pressure and temperature is the same for both the actual and the ideal turbines, but at turbine exit the energy content ('specific enthalpy') for the actual turbine is greater than that for the ideal turbine because of irreversibility in the actual turbine.

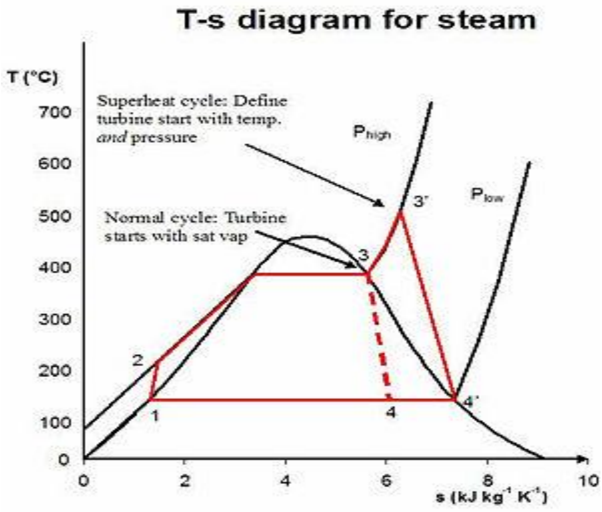


Figure 9 Rankine Cycle in T-s Diagram

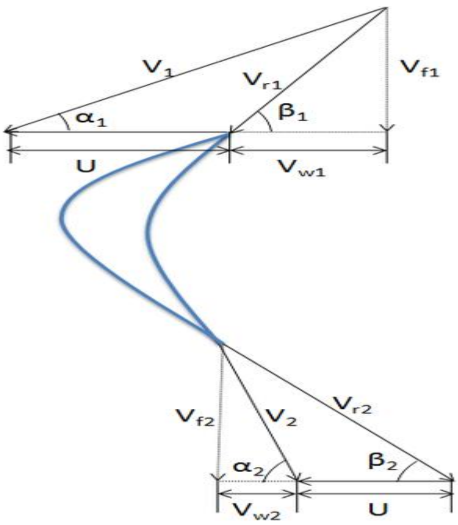


Figure 10 Velocity Triangle

Isentropic efficiency also can be used to measure how well a turbine is performing. The isentropic efficiency η_{iso} is the ratio of the actual work by the ideal work. Normally, there are different efficiencies for different expansion zones.

The Isentropic turbine efficiency is expressed by following equation, and the location of point 4 in Figure 10 is also determined by the operation load and the equipment structure. There is no rigorous model for the function.

$$\eta_{iso}=(h_3-h_4)/(h_3-h_{4s}) \quad (5)$$

Where

h_3 = the specific enthalpy at state three

h_4 = the specific enthalpy at state four for the actual turbine

h_{4s} = the specific enthalpy at state four for the isentropic turbine

The steam turbine efficiency also can be obtained by velocity triangle analysis as shown in Figure 10 and thermodynamic analysis. Take the impulse turbine efficiency analysis as example, the stage efficiency (η_{stage}) is contributed by blade efficiency (η_b) and nozzle efficiency (η_N) based on the law of Moment of Momentum, the first law of thermodynamics, and the velocity triangle analysis shown in Figure 10.

$\eta_{stage} = \eta_b * \eta_N$ (6)

$\eta_N = V_2^2/(2\ (h_1-h_2))$

η_b= work done/kinetic energy supplied= $2UV_w/V_1^2$

η_{stage}=work done on blade/energy supplied per stage= $U*\Delta V_w/V_1^2$

Where

η_b = blade efficiency

η_{stage} = stage efficiency

η_N = nozzle efficiency

(h_2-h_1) = the specific enthalpy drop of steam in the nozzle

All above conclusions are obtained following strict velocity triangle which is determined by the equipment structure. But in practice, the velocity triangle deviates due to the function of operation load and the equipment structure, and there is no rigorous model for the deviation.

Instead a model based on a thermodynamic approach has been developed, Willans' line is important to show the relationship between shaft power generation and steam mass flow.

$W= nm- W_{INT}$ (7)

$W_{max}= nm_{max}- W_{INT}$ (8)

Where

W = the shaft power generation by the steam expansion in steam turbine at part load, kW

n = the slope of Willian's line

m = the steam extraction from steam turbine at part load, kg/s

W_{INT} = the intercept of Willian's line, kW

The previous work focused mainly on the derivation of parameters n and W_{INT} [Mavromatis et al. 1998; Shang, 2000; Varbanov et al. 2004].

$n=((L+1)/b) *(\Delta H_{is}- a/m_{max})$ (9)

$W_{INT} = (L/b) *(\Delta H_{is} *m_{max}- a)$ (10)

$a= a_0+a_1* \Delta T_{SAT}$ $b= a_2+a_3* \Delta T_{SAT}$ (11)

Where

m_{max}- the steam extraction from steam turbine at maximum load, kg/s
ΔT_{SAT} = the saturation temperature drop of input/output steam in steam turbine, °C

However, important operating parameters like inlet steam pressure /superheating temperature and exhaust pressure are not included directly in previous models.

Our work develops a new full load and part load performance models considering turbine size, steam inlet pressure and temperature, and extraction steam pressures. Furthermore, the model developed can quantify accurately the performance of a wide range of commercial machines and can be adapted to model the performance of a specific existing machine.

General steam turbine performance estimation is obtained by thermodynamic principles and semi-empirical equations. The power estimation at full load and part load operation is expressed in Equ(12) and Equ(13).

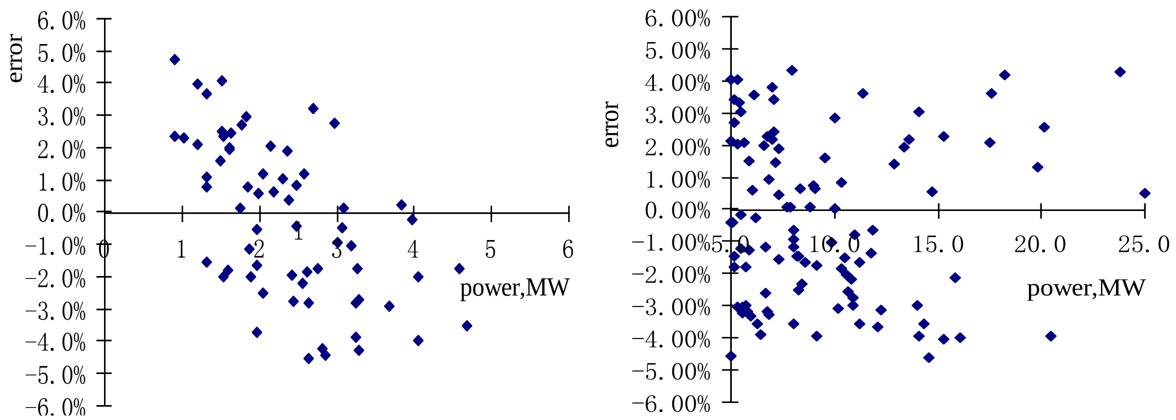
$W_{max}= ab\Delta H_{is}\, m_{max}$ (12)
$W= b(1+a)\, \Delta H_{is} \cdot m - ab\cdot\Delta H_{is}\cdot m_{max}$ (13)

Where

m_{max}= the steam extraction from steam turbine at maximum load, kg/s
W_{max} = the shaft power generation in steam turbine at maximum load, kW

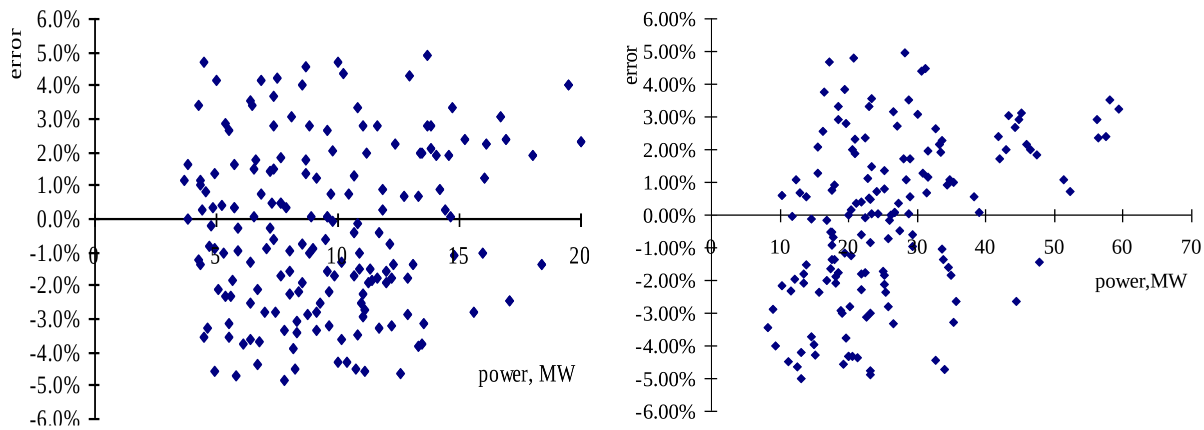
These new models containing turbine size, steam inlet pressure and temperature, and extraction steam pressures, have been verified to have good accuracy for a wide range of steam turbines. Figure 11 illustrates the model accuracy based on 70 back-pressure commercial turbines with sizes from 1 to 35 MW. There are 214 operating states at the range of 40–100% load. The mean error is about 2.2% for back pressure turbine model. Figure 12 gives the model accuracy based on 104 condensing commercial turbines with sizes from 8 to 60 MW. There are 335 operating states at the range of 40–100% load. The mean error is about 2.1% for back pressure turbine model.

The new steam turbine performance model can be integrated with utility system design and optimization without initial information about any special steam turbine choice to obtain an initial system configuration. It also can be applied in operational optimization and system retrofit including complex turbines, allowing for changes in steam header conditions, and overcoming problems in operational optimization from previous correlations, which did not account for changes in steam mains pressures. Coefficients would be regressed based on turbine operational performance for retrofit problem and operational condition adjustment. The model parameters can be derived more elaborately using data from practical operation in the operational problem.



P<5MW P≥ 5MW

Figure 11 Back-pressure Turbine Model Validation



P<20MW P≥ 20MW

Figure 12 Condensing Turbine Model Validation

Table 1 shows the comparison of different models. It is clear that the new model is consistently accurate.

Table 1 Comparison of Different Models

Model	ST1		ST2		ST3	
	W_{cal} (MW)	Error (%)	W_{cal} (MW)	Error (%)	W_{cal} (MW)	Error (%)
Mavromatis and Kokossis, 2010	10.7	-2.8	25.15	0.6	2.72	-10.3
Varbanov et al. 2004	11.77	6.5	26.81	6.8	3.17	5.4
Flores and Nunez 2010	10.97	0.3	25.04	0.2	3.00	0
Proposed model	10.91	0.8	25.13	0.5	2.97	0.9

Note: Turbine data from Flores and Nunez, 2010

4.2 Gas turbines and HRSGs

Gas turbines have two basic types: aeroderivative gas turbines and industrial gas turbines. Gas turbines have standard models with sizes ranging from micro-turbine of 25 kW to 250 MW. Gas turbine drivers have become normal practice in some industries.

Gas turbine integration provides high grade exhaust heat for steam generation and process heating. Higher thermodynamic efficiency can be obtained with a heat recovery steam generator (HRSG).

Gas turbines are standard equipments. Their performance can be expressed as a discrete variables based on equipment characters in the utility system optimization. The following gas turbine performance model was developed to involve in the utility system optimization as continues variables.

$$W_{gt}=(n*m_f-W_{INT)*}\ (A+ B*T_{amb}) \qquad (14)$$

For ISO conditions,

$$A+B*T_{amb} =1 \qquad (15)$$

Where

W= the power generation by gas turbines, MW

m_f = actual fuel flowrate, kg/s

T_{amb} = ambient temperature, °C

The mass flowrate of the exhaust for the heat recovery is calculated as following:

$$m_{ex}=(m_f*NHV-W)/(C_p*(T_{ex}-T_{amb})) \quad (16)$$

Where

m_{ex} = the mass flowrate of the exhaust from gas turbines, kg/s

T_{ex} = the exhaust temperature, °C

NHV = fuel net heat value, kJ/kg

Including the ambient temperature in the new model can make the model more accurate and reliable when ambient conditions vary.

4.3 Boilers

Boilers are employed within industrial utility plants and power generation cycles, to extract the energy contained in a fuel (or fuel mixture) and heat the condensate or feed water until steam is generated at the required temperature. Depending on their application, combustion boilers are often classified as institutional (when they serve public buildings) and industrial if they are used within transformation processes.

The previous boiler model used in total site integration does not capture such important factors as combustion conditions and fuel quality, which is not consistent with the real data. For boilers, a series of industrial standards (ASME, DIN, BS, etc) have been built and are well established. A boiler model complying with these well verified codes should be integrated with the total site design and optimisation in order to get more realistic and reliable results. However, these boiler performance test codes were not developed for the purpose of the total site integration and optimisation. A detailed boiler performance calculation following the codes exactly is impossible to implement in the total site methodology.

Accordingly, a simplified boiler performance model has been developed that is characterised by the key factors involved in the standard complex model. This new model is suitable for the total site design and optimisation, and at the same time includes the key parameters from the industrial standard codes. An important feature of the new model is that it inherently characterises part-load performance through regression parameters that vary with the load

For process integration, what is really concerned about the boiler model is the relationship between the main steam load and fuel consumption. Therefore, it would be preferable if the proportions of main steam energy output in the total energy output and of fuel combustion energy in the total energy input can be estimated or given. Alternatively, a simplified efficiency can be introduced as the percentage of the energy credit by main steam to the input fuel combustion energy.

The boiler efficiency calculation can be divided into the input-out method and energy balance method. The combination of the two methods will give a boiler's part-load performance.

Input-out method (direct method)

$$\eta_1 = \frac{Q_1}{BQ_r} \times 100\% \qquad (17)$$

where

η_1=Input-output efficiency，%

Q_r=Energy input，kJ/kg or kJ/m^3

B=Fuel flow rate，kg/h or m^3/h

Q_1=Energy output，kJ/h

Indirect method (Energy balance method)

$$\eta_2 = 100 - (q_2 + q_3 + q_4 + q_5 + q_6) \tag{18}$$

where

η_2=Efficiency based on losses，%

q_2= Flue gas heat loss，%

q_3= Heat loss by unburned combustibles in flue gas，%

q_4= Heat loss by solid unburned combustibles，%

q_5= Surface radiation and convection heat loss，%

q_6= Other losses such as the sensible heat of residues，%

Part-load performance

Since

$$\eta_1 = \eta_2 \tag{19}$$

then,

$$\frac{Q_1}{BQ_r} = 1 - \frac{1}{100}\sum_{i=2}^{6} q_i \tag{20}$$

That is, these two accepted methods for determining the boiler efficiency can be combined to describe the part-load performance of a boiler in operation.

If the energy output Q_1 is expresses as main steam output with some correction (f_1) accounting for the reheat steam, auxiliary steam and blowdown, and the energy input Q_r is represented by the fuel combustion energy with a correction factor (f_2) considering the other forms of input energy, such as the sensible heat in fuel, the additional heat from external heat sources, the heat of atomizing steam, etc., Eq. (20) can be written as:

$$\frac{main\ steam\ \ flowrate \times \Delta h \times f_1}{B \times Q_{net,v,ar} \times f_2} = 1 - \frac{1}{100}\sum_{i=2}^{6} q_i$$

$$\frac{D}{B} = \frac{Q_{net,v,ar}}{\Delta h} \times \frac{f_2}{f_1} \times (1 - \frac{1}{100}\sum_{i=2}^{6} q_i)$$

or $$\frac{D}{B} = \frac{Q_{net,v,ar}}{\Delta h} \times \frac{f_2}{f_1} \times \frac{\eta_2}{100} \quad (21)$$

Where D is the main steam flowrate, kg/h, $Q_{net,v,ar}$ is the fuel net heating value as received basis, kJ/kg or kJ/m^3, and Δh is the specific enthalpy difference between the main steam and feedback water, kJ/kg.

Efficiency determination by the energy balance method (η_2) requires the identification and measurement or estimation of all losses and credits, which need discussion and agreement by all parties. Some losses/credits should be measured; some can be estimated on a percent input basis; and the others may be so minor as to be neglected. In operation, the boiler efficiency can be affected by many factors beyond part-load, such as fuel quality, excess air ratio, monitoring/controlling level, operator, equipment status, etc. Probably the relationship between the boiler efficiency and part-load or between the main steam load and fuel consumption is not straightforward at all. Based on the previous operational data and experience, the guaranteed better or best part-load performance of a boiler and the corresponding operational setting should be identified, which will be recorded and used for the process synthesis. Even several kinds of part-load performances (for example, high, medium, low levels corresponding to different kinds of typical operational conditions) instead of one fixed part-load performance can be taken into consideration.

Table 2 show the simplified efficiency model for coal-fired boiler.

Table 2 Simplified Coal-Fired Boiler Efficiency Model

No.	Symbol	Description	Unit	Calculation

1	$Q_{net,v,ar}$	Net heating value as received basis	kJ/kg	From fuel analysis
2	A_{ar}	Mass fraction of ash in fuel as received basis	%	From fuel analysis
3	C_{lz}	Mass fraction of carbon in residue	%	Measured
4	C_{fh}	Mass fraction of carbon in fly ash	%	Measured
5	a_{lz}	Mass percent ash in residue compared to the total ash in fuel input	%	Measured
6	a_{fh}	Mass percent ash in fly ash compared to the total ash in fuel input	%	Measured
7	t_{py}	Flue gas temperature	°C	Measured
8	t_0	Basis temperature	°C	Taken as air temperature at the FD fan inlet
9	O_2'	Volumetric percent O_2 in flue gas	%	Measured
10	a_{gy}	Excess air ratio	-	$a_{py} = \frac{21}{21 - O_2'}$
11	q_4	Heat loss by solid unburned combustibles	%	$q_4 = (a_{lz} \frac{C_{lz}}{100 - C_{lz}} + a_{fh} \frac{C_{fh}}{100 - C_{fh}}) \times \frac{337.27 A_{ar}}{Q_r}$ where the value of 337.27 may vary a little with fuel, which can be set as parameter K.
12	q_2	Waste gas heat loss	%	$q_2 = (K_1 \times a_{py} + K_2) \times (t_{py} - t_0) \times \frac{100 - q_4}{10000}$ where K_1 and K_2 vary with fuel.
13	Q_3	Heat loss by unburned combustibles in flue gas	%	$q_3 \approx 0$ for coal-fired boiler
14	$q_{5,r}$	Surface radiation and convection heat loss under rating load	%	Taken from the manufacturer user guide or boiler standards

Table 2 Simplified Coal-Fired Boiler Efficiency Model (Cont.)

No.	Symbol	Description	Unit	Calculation

15	D_r	Rating steam output	t/h	From the boiler's label
16	D	Steam output	t/h	Measured
17	q_5	Surface radiation and convection heat loss	%	$q_5 = q_{5,r}(D_r / D)$
18	q_6	Other losses including the sensible heat of residue	%	$q_6 = K_3 \frac{A_{ar}}{Q_{net,v,ar}}$ or given an estimation for q_6, e.g. q_6=0.5%
19	η_2	Boiler thermal efficiency based on losses	%	$\eta_2 = 100 - (q_2 + q_3 + q_4 + q_5 + q_6)$
20	η_1	Boiler thermal efficiency based on direct energy output	%	$\eta_1 = \eta_2$, $\eta_1 = \frac{Q_1}{BQ_r} \times 100\%$
21	f_1	Correction factor	-	Correction for using the main steam output in place of the total energy output Q_1, accounting for the reheat steam, auxiliary steam and blowdown.
22	f_2	Correction factor	-	Correction for using the fuel combustion energy $Q_{net,v,ar}$ to replace the total energy input Q_r, considering the other forms of input energy, such as the sensible heat in fuel, the additional heat from external heat sources, the heat of atomizing steam, etc.
23	B	Fuel consumption	kg/h	Calculated by $\frac{D}{B} = \frac{Q_{net,v,ar}}{\Delta h} \times \frac{f_2}{f_1} \times \frac{\eta_2}{100}$ or measured.

5 Future work

The graphical method development can be used for conceptual design and optimization as a visualization tool to better understand the integration processes and utility systems.

Utility targets of site VHP steam demand, cooling target, site steam saving due to process indirect heat recovery, processes heating loads, power generation potential by steam expansion, and the site pinch can be addressed in the curves. It is useful to understand the variation of processes and steam mains on the site heat and power performance.

More precise model development of components such as boilers, steam turbines can contribute more reliable results both by graphical and mathematical programming methods. The new full load and part load steam turbine performance model considers turbine size, steam inlet pressure and temperature, and extraction steam pressures, and allows for steam pressure varied directly which was not the case for previous models. It can be applied for design with consistent accuracy compared to existing models. It is especially beneficial for operation optimization and retrofit with complex turbines.

The new simplified boiler model has been developed for the total site design and optimisation, and at the same time includes the key parameters from the industrial standard codes to get more realistic and reliable results.

The conceptual design methodology and model developments will be applied to the demonstration activities – case studies in WPs5-8.

The general framework for the methodology on conceptual design for the total site energy analysis has been set up, extensions are possible and model parameters can be derived more elaborately using data from the demonstration activities in this project.

For the further work, more practical parameters would be involved in the system design and optimization. For example, uncertain factors such as utility price fluctuation and product demand variation would cause the optimization under uncertainty. The equipment failure would be considered in the optimization simultaneously. The waste heat recovery systems would be integrated into site utility systems for useful energy production used on-site or off-site.

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