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Cogeneration Improvement Based on Steam Cascade Analysis

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In site utility systems, very high pressure (VHP) steam is generated from fuel combustion in boilers and gas turbines heat recovery steam generators. VHP steam is distributed to lower pressure steam mains to satisfy process heating demand. The 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. Steam mains selection, process heating and cooling demands, and process indirect heat recovery affect utility VHP steam target, the steam cascade and cogeneration. This work presents an extended graphical approach based on steam cascade analysis to explore how steam mains selection influences cogeneration improvement. The interaction among process heating and cooling demands, processes indirect heat recovery, and utility targets of VHP steam demand and cooling medium are quantified graphically. This graphical method would be helpful to scope the potential cogeneration improvement by variation of steam mains. The insights gained can be used to simplify the optimization of the utility system.

1. Introduction

In the utility system, one of the methods to implement high efficiency fuel combustion is cogeneration. Cogeneration interacts with utility VHP steam target and the steam cascade. Steam mains selection plays a significant role in the integration.

Both graphical approaches and mathematical programming methodologies have been developed to improve power and energy targets. Based on the Pinch Analysis approach (Linnhoff, 1982), Linnhoff et al. (1994) introduced the Grand Composite Curves as a tool for system Heat Integration. Dhole and Linnhoff (1993) constructed Site Source-Sink Profiles for the implementation of processes and utility system integration and provided the process quantified heating and cooling targets graphically, but the site steam saving due to process indirect heat recovery cannot be obtained from the profiles. Site Composite Curves (Klemeš et al., 1997) are constructed following the zero approach between the utility loads, and provides the targets for indirect process heat recovery and the minimum site VHP steam demand from the utility system, but trial and error is required to construct the curves. Site Utility Grand Composite Curves (Raissi, 1994) are constructed from the steam cascade extracted from the Site Composite Curves, and allow the potential shaft power to be calculated by the enclosed area in the curves. However, the interaction among steam mains selection, site VHP steam target, site VHP steam saving due to process indirect heat recovery, and the cogeneration are obtained only when all these three curves are available simultaneously.

The application of site targeting graphical methods has been explored by a number of studied. Perry et al. (2008) applied it in locally integrated energy sector design. Hackl et al. (2011) employed this method to improve energy collaboration between different companies. Fodor et al. (2012) extended the approach to total site targeting by the overall selection of minimum temperature differences for total site utility systems and explored how it affected the heat recovery networks of the individual process.

However, there was no straightforward method to understand the interaction between steam mains selection and the cogeneration.

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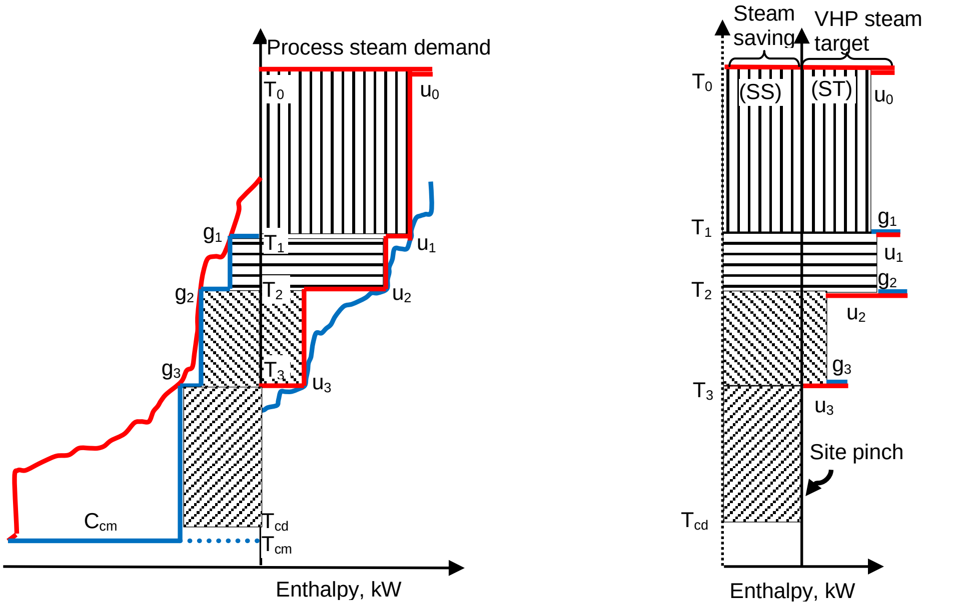
Mathematical programming methodology has been developed for utility system optimization by Papoulias and Grossmann (1983), followed by Petroulas and Reklaitis (1984) and later by Colmenares and Seide (1989). Linear models (Raissi, 1994) extended by Bandyopadhyay et al. (2010) and non-linear models (Mavromatis 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 Sorin and Hammache (2005) extended by (Medina-Flores and Picon-Nunez, 2010; 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.

This work has developed a graphical approach to extend Pinch Analysis to offer the effect of steam mains selection on the cogeneration improvement based on extended steam cascade curves. Variations of process heating demands, process indirect heat recovery via the steam mains, utility VHP steam target, shaft power potential by the steam expansion, as well as the site pinch, are all obtained through steam mains changes by steam cascade analysis.

2. Cogeneration analysis based on steam cascade curves

The steam cascade curves are constructed analogous to the Site Utility Grand Composite Curves, but are extracted from the Site Source-Sink Profiles directly in stead of the Site Composite Curves in the previous approach.

As shown in Figure 1, the steam cascade is obtained under the total process steam demand, instead of utility VHP steam target. Process heating demand is satisfied by the utility steam at different pressures. The process heat recovery can supply heat to processes, implying both utility 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. It is a key parameter. 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*

Figure 1: Site Targets and Site Pinch in Steam Cascade Curves

Utility VHP target = Total process steam demand – utility steam saving (1)

Total process steam demand= Σu_i (2)

It is not possible to cascade steam from lower to higher pressure. Therefore, the minimum steam cascade would be no flow. In steam cascade curves, the maximum utility VHP steam saving is the minimum steam cascade in the steam expansion zone and condensing zone in Figure 1(b). The utility VHP steam target is achieved by removing utility VHP steam saving from the total process steam demand. As shown in Figure 1(b), under the new ordinate axis by the utility steam saving removal to implement an empty steam cascade within one zone, both the steam saving and utility VHP steam target can be identified in the profiles.

2.1 Site Pinch in Steam Cascade Curves

The no flow steam cascade zone is the Site Pinch. There is no potential shaft power at the Site Pinch. In Figure 1, the Site Pinch lies in the condensing zone. It divides the steam mains into two sections: above Site Pinch, where the heat deficit of the system needs to be supplied by the boiler steam; and at and below the Site Pinch, where the system steam can satisfy the process heating requirement. The cold medium cools the process hot streams below the Pinch.

2.2 The shaft power expression

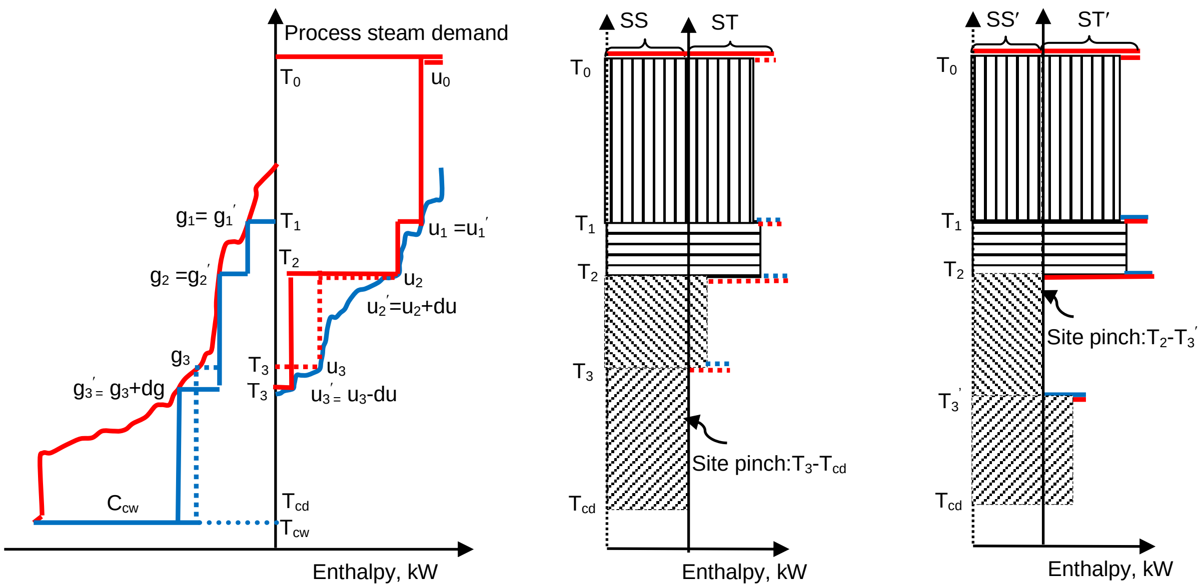
The potential shaft power generation by steam expansion in steam turbines is a function of the steam load and saturation temperature drop between the inlet and outlet steam of the steam turbine based on the temperature enthalpy (T–H) model (Raissi, 1994). It is proportional to the rectangular area in the steam cascade curves. This estimation ignores the superheat both of the inlet and outlet steam of the steam turbine. The enthalpy in each zone implies steam cascade from the higher pressure steam main. Eq (3) gives the potential power generation.

$$W = c^*[\Sigma g_i(T_i - T_{cd}) + \Sigma u_i(T_0 - T_i) - SS(T_0 - T_{cd})] \quad (3)$$

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. The effect of variation of steam mains on the cogeneration

Steam mains selection change the process heating and cooling loads, process indirect heat recovery, and utility VHP steam target. Correspondingly, the variation of the steam cascade induces the fluctuation of shaft power potential by steam expansion.



(a) Processes heating demand and heat recovery

(b) Steam cascade at LP saturation temperature of T

(c) Site Pinch variation at LP temperature of T′

Figure 2: Site Pinch variation by steam mains fluctuation

$T_i - T_i' = dT_i$
$u_i' = u_i - du_i$
$g_i' = g_i + dg_i$
$u_{i-1}' = u_{i-1} + du_i$
$\Delta W = c*[\,dg_i*(T_i - T_{i+1}) - du_i*(T_{i-1} - T_i) + (u_i' - g_i')*dT]$ (4)

Figure 2 illustrates the fluctuation of LP steam from saturation temperature T_3 to T_3'. The steam mains variation affects the site pinch in this case. More site VHP steam saving implies lower site VHP steam target and less fuel consumption.
To look for the improvements in the cogeneration, the steam main would be adjusted to achieve more boiler steam saving, meaning more steam cascade at the fixed fuel combustion.

4. New steam mains introduction and the cogeneration improvement

Adding a new steam main 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 away from the Site Pinch.

4.1 A new main introduction at the site pinch

A new steam main added at the site pinch will produce an increased steam cascade. The new site pinch by the removal of the extra steam cascade implies utility VHP steam target reduction and fuel saving. As shown in Figure 3, the reduction of utility VHP steam target is the minimum of (g_{IN}, u_{IN}). It means attractive system economy with less waste emission.
At the fixed fuel consumption in the utility system, the shaft power improvement is the combination of two extra rectangular areas based on the previous site pinch:

$\Delta t_1 = T_{N+1} - T_N$
$\Delta t_2 = T_N - T_{N-1}$
$\Delta t_1 + \Delta t_2 = T_{N+1} - T_{N-1}$
$\Delta W = c*((T_{N+1} - T_N)*u_N + (T_N - T_{N-1})*g_N)$ (5)

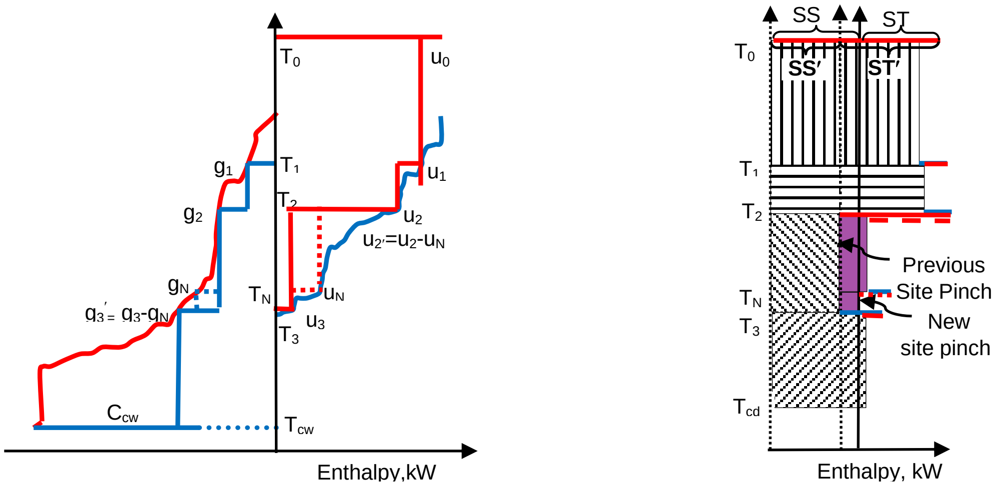


Figure 3: New steam main introduction at the Site Pinch

4.2 A new main introduction away from the site pinch

A new steam main added away from the site pinch does not change the site pinch. That has no effect on the boiler steam saving, site VHP target, and fuel combustion.
As shown in Figure 4, extra power is generated from more higher pressure steam generation g_N from the process heat recovery and lower pressure steam load u_N to heat the processes.

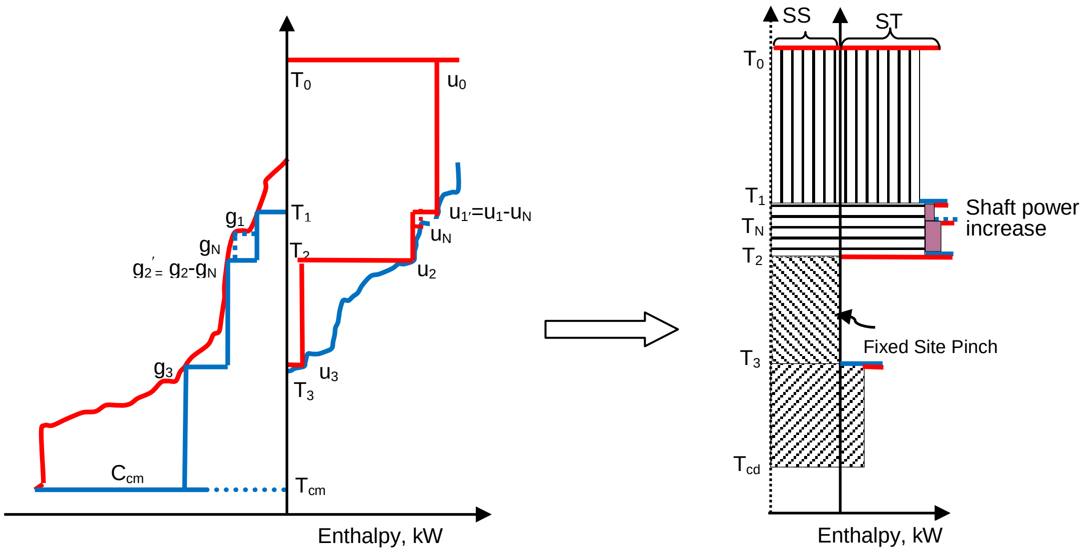


Figure 4: New steam mains introduction away from the Site Pinch

$$\Delta t_1 = T_{N+1} - T_N$$
$$\Delta t_2 = T_N - T_{N-1}$$
$$\Delta t_1 + \Delta t_2 = T_{N+1} - T_{N-1}$$
$$\Delta W_1 = c^*\Delta t_1{}^*u_N$$
$$\Delta W_2 = c^*\Delta t_2{}^*g_N \qquad (6)$$

The new steam main is added to improve the cogeneration.

$$\Delta W = c^*((T_{N+1} - T_N)^*u_N + (T_N - T_{N-1})^*g_N) \qquad (7)$$

Even though the shaft power improvement has the same equation as adding the new steam main at or away from the Site Pinch, the first case in practice will save fuel combustion, and has far reaching significance.

5. Conclusions and discussion

The extended graphical approach of steam cascade curves clarifies utility system targets, process heating and cooling demands, as well as process indirect heat recovery.
Steam mains selection influences utility targets greatly. The introduction of new steam mains is beneficial for process indirect heat recovery. The effect on the boiler steam saving, utility VHP steam target and cogeneration depend on the introduction of new steam mains introduction within or away from the site pinch.
The graphical method can be used for conceptual design and optimization as a visualization tool to better understand the integration processes and utility systems.

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Nomenclature

c - the power conversion coefficient based on concept of T-H model,°C^{-1}
C - cooling target, kW
g- steam generation by process indirect heat recovery at individual steam main, kW
Q - the heat duty of the inlet steam of the steam turbine, kW
ST - utility VHP steam target, kW
SS – utility steam saving due to process indirect heat recovery, kW

T - steam saturation temperature, °C
u- heating demand at each steam main, kW
W - shaft power potential by the steam expansion or condensation, kW

Subscripts

cm- cold utility medium
cd- condensation
i=0, 1, 2, 3- VHP, HP, MP, and LP steam main, respectively
IN - the introduction of a new steam main

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