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Optimal Selection of Steam Mains in Total Site Utility Systems

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This paper examines the optimal location (pressure) and the number of steam levels required to meet the external heating and cooling demands of individual site processes. The model developed makes use of Mixed Integer Linear Programming (MILP) techniques, implemented in a Visual Basic/Excel environment and linked to existing simulation software in order to extract the appropriate data for the total site. The model makes use of various methods of calculating shaftwork produced from the expansion of steam from simple single stage turbines operating between the steam levels involved. The shaftwork targeting methods include the TH model (Raissi, 1994), simple isentropic expansion, Willans' line methods, and methods developed recently by Ghannadzadeh et al (2012) . Different models of shaftwork calculation are required depending on the nature of the data available.
Results from various case studies are validated by comparison with simulation, and show that the optimal location of a fixed number of steam levels can significantly change depending on the method of shaftwork calculation used. Similarly the number of steam levels has an influence on the overall site heat recovery through the steam mains and the steam needed to be supplied by the boiler. This new approach to the selection of the appropriate and optimal pressure of the steam mains across total sites can also be applied to existing total sites in order to improve operational performance. The procedure can also be applied in the total site context to examine improvements in waste heat utilisation and consequently in distributed energy systems.

1. Introduction

Total Site technology was developed initially by Dhole and Linnhoff (1993) and later expanded by Raissi (1994) and Klemes et al. (1997), as an extension of Process Integration/Pinch technology developed by Linnhoff et al (1982). Total Site technology extends Process Integration techniques from single processes to multiple processes which make up chemical processing sites. The graphical tools developed, supporting the technology, are based on extracting the heating and cooling demands of individual processes which are not met by process heat recovery, and have to be met by external heating and cooling utilities. These tools include the Site Profiles, the Site Composites, and the Site Utility Grand Composite curves (SUGCC). In using these graphical tools, targets can be set for the steam used and generated by the site processes at particular pressures (levels), heat recovery across the site through steam use and generation, the steam required to be produced by the boiler, and the shaftwork produced by steam turbines in relation to site cogeneration. The steam used and generated at different pressure levels, the heat recovery through the steam levels, steam demand from the boiler, and shaftwork produced depends however on the number and pressure of the steam levels involved, which previously has been performed in a relatively ad-hoc manner dependent on existing practices.

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Therefore an important element of the methodology required for the determination of the optimal location (pressure) of the steam mains and the number of steam mains, is the amount of cogeneration that can be generated by the steam produced by the boiler and expanded through steam turbines linking the steam mains. There are a number of shaftwork targeting models that have been forward for the purpose of determining the potential cogeneration of total sites. Dhole and Linnhoff (1993) introduced a model based on the site source-sink profiles and using exergy. Later, Raissi (1994), put forward a model (T-H model) making use of observations made by Salisbury (1942) and which related cogeneration linearly proportional to the difference between the saturation temperatures of the inlet and outlet steam conditions. Marechal and Kalitventzeff (1997) extended these previous models and proposed an approach based on the carnot factor to estimate the power that can be recovered using the exergy available in the process. Mavromatis and Kokossis (1998) introduced the non-linear model (THM model) based on the Willans' Line relationship to include part-load performance and turbine size, which was later extended by Varbanov et al. (2004). Sorin and Hammache (2005) again used an exergy based approach and showed that power is not a linear function of the saturation temperature differences. Medina-Flores and Picon-Nunez (2010) presented a modified thermodynamic model based on the previous work of Mavromatis and Kokossis and Bandyopadhyay et al. (2010) developed a linear model based on the observations of Salisbury (1942). Finally Ghannadzadeh et al (2012) proposed the Iterative Bottom-to-Top Model (IBTM) making use of the SUGCC and constant isentropic efficiency for the turbine expansion zones.

2. Methodology

A variety of models are deployed in order to calculate the amount of shaftwork from the expansion of steam from one pressure level (steam main) to another. The methodology employs a new software called SLOTS, which is developed as a combination of EXCEL and Visual Basic. The software determines the SUGCC from the Total Site Profiles, calculates the power produced by expanding steam from the shaftwork targeting model, and finally determines the Total Utility Cost. The total utility cost of the site utility system is given by:

$$\text{Total Utility Cost (TUC)} = C_{cu} + C_{fuel} + C_{power} \tag{1}$$

Where C_{cu} is the cost of cooling utility, C_{fuel} is the cost of fuel and C_{power} is the cost of power.
The trade-off between the fuel consumption and cogeneration gives the minimum utility cost. The overall fuel requirement, the cooling utility requirement, and the cogeneration potential can be targeted by using various targeting models.
The boiler is modelled to determine the fuel requirement of the site utility system. The model is based on the basic thermodynamic principles. The fuel required (Q_{fuel}) by the boiler is dependent on the boiler efficiency (η) and the steam load (Q_{steam}).

$$Q_{fuel} = \frac{Q_{steam}}{\eta} \tag{2}$$

The shaftwork targeting models included in the methodology are the Temperature Enthalpy (T-H) model, the Willan's Line model, and what is referred to as the New Model based on the previous work of Ghannadzadeh et al. (2012). The T-H shaftpower Targets are based on the observation that the power is proportional to the heat load of steam and the difference between the inlet and outlet saturation temperatures (Raissi, 1994).
The Willan's Line model gives the relationship between shaftpower and mass flow through a heat engine. Initially pressure is assumed at each level. Superheated enthalpy H_{N+1}^{Sup} and entropy S_{N+1}^{Sup} at the inlet of J^{th} turbine is given by steam table as a function of superheated temperature T_{N+1} and pressure P_{N+1}. Then saturated enthalpy H_{N+1}^{Sat} and liquid enthalpy H_{N+1}^{L} at the inlet of J^{th} turbine is given by steam table as a function of pressure P_{N+1}. Mass flow rate through the J^{th} turbine is then calculated as function of net heat load Q_N at pressure P_N and difference of superheated enthalpy and liquid enthalpy at the turbine inlet.

$$m_J = \frac{Q_N}{H_{N+1}^{Sup} - H_{N+1}^{L}} \quad (3)$$

Assuming isentropic expansion superheated enthalpy H_N^{Sup} at the exit of J[th] turbine is given by the steam table as a function of superheated entropy S_{N+1}^{Sup} at the turbine inlet and the pressure P_N at the turbine outlet. Isentropic enthalpy change ΔH_{IS} is given by:

$$\Delta H_{IS} = H_{N+1}^{Sup} - H_N^{Sup} \quad (4)$$

Slope of Willan's Line is given by:

$$n = \frac{(L+1)}{b}\left(\Delta H_{IS} - \frac{a}{m_{max}}\right) \quad (5)$$

where L is the intercept ratio and it depends upon a number of factors such as turbine design, turbine size, application etc. It usually lies in the range of 0.05 – 2^9 (Smith, 2005). Intercept of the Willan's Line is then given by:

$$W_{INT} = \frac{L}{b}(\Delta H_{IS} m_{max} - a) \quad (6)$$

The overall shaftwork power produced in the expansion interval is then;

$$W_J = n \cdot m_J - W_{INT} \quad (7)$$

The actual enthalpy at the exit of J[th] turbine is given by the energy balance using mechanical efficiency.

$$H_N^{Actual} = H_{N+1}^{Sup} - \frac{W}{\eta_{MECH} m} \quad (8)$$

The mass flow rate through the J[th] turbine is again calculated as function of net heat load Q_N at pressure P_N and difference of actual superheated enthalpy and liquid enthalpy at the turbine outlet.

$$m_J' = \frac{Q_N}{H_N^{Actual} - H_N^{L}} \quad (9)$$

The m_J' calculated above is compared with m_J given in equation 3. If the difference between these two is greater than the error, then m_J in equation 3 is replaced with m_J' calculated in equation 9. The J[th] turbine efficiency is given by:

$$\eta_{IS}^{J} = \frac{H_{N+1}^{Sup} - H_N^{Actual}}{H_{N+1}^{Sup} - H_N^{Sup}} \quad (10)$$

The supersaturated temperature T_N at the exit of Jth turbine and inlet of (J−1)[th] turbine is given by the steam table as a function of actual superheated enthalpy H_N^{Actual} and pressure P_N.

The new shaft power targeting model is based on thermodynamic equations. Temperature and pressure at each level is calculated starting from the superheated temperature and pressure from the boiler. Superheated enthalpy H_{N+1}^{Actual} and the entropy S_{N+1} at the inlet of turbine J is given by the steam table as a function of superheated temperature T_{N+1} and pressure P_{N+1} from the steam boiler. Assuming isentropic expansion, isentropic enthalpy H_N^{IS} outlet of the turbine J is given by the steam table as a function of pressure P_N and entropy S_{N+1}. Actual enthalpy H_N^{Actual} at the outlet of J[th] turbine is then calculated on the basis of isentropic expansion with efficiency 'η'. The cogeneration potential of the system is dependent on the expansion efficiency of η. The actual enthalpy H_N^{Actual} from the exit of the turbine, when the steam is expanded from pressure P_{N+1} to pressure P_N is given by:

$$H_N^{Actual} = H_{N+1} - \eta\left(H_{N+1} - H_N^{IS}\right) \quad (11)$$

Actual entropy S_N for N[th] steam main is given by steam table as a function of pressure P_N and actual enthalpy H_N^{Actual}. Superheated temperature of the N[th] steam main is given by the steam table as a function of pressure P_N and actual entropy S_N. Mass flow rate is now calculated bottom up, starting with the lowest level temperature (Ghannadzadeh et al., 2012). The mass flow rate from the outlet of J^{th} turbine is calculated by mass balance for N^{th} level.

$$m_J = m_{J-1} + m_N^{Use} - m_N^{Gen} \quad (12)$$

where $m_N^{Use}$the mass flow rate of steam is used by the process and m_N^{Gen} is the mass flow rate of the steam generated by the process. The shaftpower generated by J^{th} turbine is given by:

$$W_J = m_J\left(H_{N+1}^{Actual} - H_N^{Actual}\right) \quad (13)$$

The total shaft power is then given by:

$$W_{Total} = \sum_{J=1}^{J} W_J \quad (14)$$

An algorithm for the enactment of the New Model is shown in Figure1.

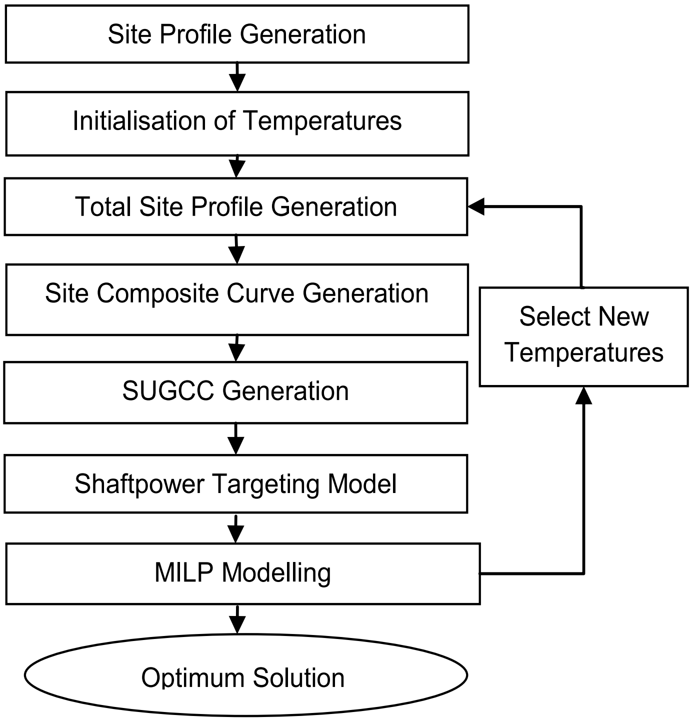

Figure 1: Schematic representation of the optimisation procedure

In order to obtain the minimum utility cost, an MILP model is formulated to minimise the total utility cost.

3. Case Study

To illustrate the applicability of the steam level optimisation models in site utility systems, a case study on a refinery plant was used (Fraser and Gillespie, 1992). The steam system comprises a boiler, four steam levels and a cooling utility. The very high pressure (VHP) steam is raised in the central boiler at 550 °C and 128.58 bar (T_{sat} = 330 °C).

The objective was to determine the optimum pressure of steam mains in a total site utility system using the software developed in order to minimise the total utility cost.

The optimisation determines the optimal pressure of each steam level, the power output of each turbine, the site heat recovery, the heat load balance of each steam level, the cooling duty requirement, the heat duty and fuel requirement of boiler. In this case study it was assumed that the temperature of both BFW and condensate return was 105 °C. The isentropic efficiency η_{is} for the New Model in the SLOTS software was given by the efficiency calculated from the Willan's Line model using the same software. There is also flexibility in choosing the isentropic efficiency by the user. The shaftpower target and minimum utility cost obtained from STAR and SLOTS for four intermediate steam levels are shown in Table 1.

Table 1: Shaftpower targeting models for 4 intermediate steam levels

Parameter	STAR		SLOTS		
	TH Model	TM Model	TH Model	Willan's Line Model	New Model
Shaftpower Target (MW)	1.66	4.86	1.63	2.13	2.14
Minimum Utility Cost (£/y)	18,657.40	17,464.1	18,837.49	19,071.66	19,071.66

The optimum pressure and temperature obtained for 4 intermediate steam levels from various models are shown in Table 2.

Table 2: Optimum pressure and temperature for 4 intermediate steam levels in various models

Optimisation Model		**VHP**	**Level 2**	**Level 3**	**Level 4**
TH Model in STAR	Pressure (bar)	128.58	40.57	14.50	2.70
	Temperature (°C)	330	251.2	196.7	130
TM Model in STAR	Pressure (bar)	128.58	2.70	2.70	2.70
	Temperature (°C)	330	130	130	130
TH Model in SLOTS	Pressure (bar)	128.58	40.43	14.42	2.70
	Temperature (°C)	330	250.99	196.44	130
Willan's Line Model in SLOTS	Pressure (bar)	128.58	40.43	14.65	2.70
	Temperature (°C)	330	250.99	197.18	130
	Superheated Temperature (°C)	550	395.39	281.12	140.12
New Model in SLOTS	Pressure (bar)	128.58	40.43	15.54	2.70
	Temperature (°C)	330	250.99	199.97	130
	Superheated Temperature (°C)	550	394.82	288.59	138.08

From Table 1 it was observed that the TH Model shaftpower for a particular level obtained from STAR software and SLOTS software are approximately equal. It was also observed that the shaftpower for a particular level for Willan's Line model and New Model are almost equal. The Willan's Line model is capable of predicting the real efficiency trends of units by considering the dependency of the efficiency on load. The New Model is based on isentropic efficiency and in this case study accurate efficiency obtained from the Willan's Line model and uses it to calculate the shaftwork. The main difference between the shaftpower obtained from the New Model and existing TH and TM Model is the calculation of superheat temperature for each steam main. The TH model for targeting doesn't include the superheat conditions at each level which results in significant error for the calculation of mass flow rate along with the cogeneration potential. The minimum utility cost (MUC) is the function of fuel cost, power cost and cooling utility cost. Since the fuel cost is directly related with the mass flow rate of steam from the boiler, discrepancies can be seen in the minimum utilities cost for the existing models and new models. Heat recovery increases with the increase in number of steam main whereas cogeneration potential might increase or decrease. For the given case study, optimisation was performed for 2, 3 and 4 intermediate steam mains and the total utilities cost obtained as the result of optimisation is plotted against the respective number of steam mains. It was observed from the graph that the utility cost was at a minimum for the 4 intermediate steam mains.

4. Conclusion

Optimising the critical parameters of the steam mains is one of the most difficult tasks in the utility system design due to the complexity of the utility systems and interdependency of the various equipments and their parameters. This study deals with this particular aspect of the total site utility design. The software developed during this work called SLOTS-Steam Level Optimisation of Total Site has various functionalities. On providing the software with the stream data and other basic assumptions such as boiler efficiency and boiler feed water temperature, site heat recovery and minimum VHP demand can be calculated along with other parameters on the utility system. It is also successful in determining the optimum number of steam mains required and their operating pressure on setting the temperature range of the steam levels. Also, the cogeneration potential can be estimated with considerable accuracy for any given site utility data. Three different models can be used

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