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Exploitation of Low-Grade Heat in Site Utility Systems

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Low-grade heat is available in large amounts across process industry from temperatures of 30 ^{o}C to 250 ^{o}C as gases (e.g. flue gas) and/or liquids (e.g. cooling water). Various technologies are available for generating, distributing, utilizing and disposing of low grade energy. The integration of these technologies with the site has not been fully studied, with regards to engineering and practical limitations for retrofit, the use of non-conventional sources of energy in energy generation, and consideration of variable energy demand loads. The identification of cogeneration potentials is one of the key performance indicators for screening various energy-saving technologies using low-grade heat and evaluating the integration-ability of these technologies to the overall site. The work in this study is therefore carried out to improve heat integration models which can systematically identify realistic cogeneration potentials, and provide the most appropriate strategies for exploiting low-grade energy technologies for the viewpoint of system analysis. An improved model has been proposed for the evaluation of power output by a combination of bottom-up and top-down procedure for the evaluation of steam header temperature and steam flow rates respectively. The applicability of the developed model is tested with other existing design methods and STAR® software through a case study. The proposed method is shown to give comparable results, and the targeting method is used for obtaining optimal steam levels. Identifying optimal conditions of steam levels is very important in the design of utility systems, as the selection of steam levels heavily influence the potential for cogeneration and energy recovery for the site. In this work, the optimization of steam levels of site utility systems has been carried out in the case study, in which the usefulness of the optimisation framework is clearly demonstrated for reducing the overall energy consumption for the site. Heat loads and steam levels can then be further used for subsequent evaluation of design options for low grade heat integration.

1. Introduction

Process integration methodologies based on pinch analysis has proved to be effective to assess potentials for energy savings in retrofit as well as grassroot design in process industries. Accurate estimation of the cogeneration potential is vital for the total site

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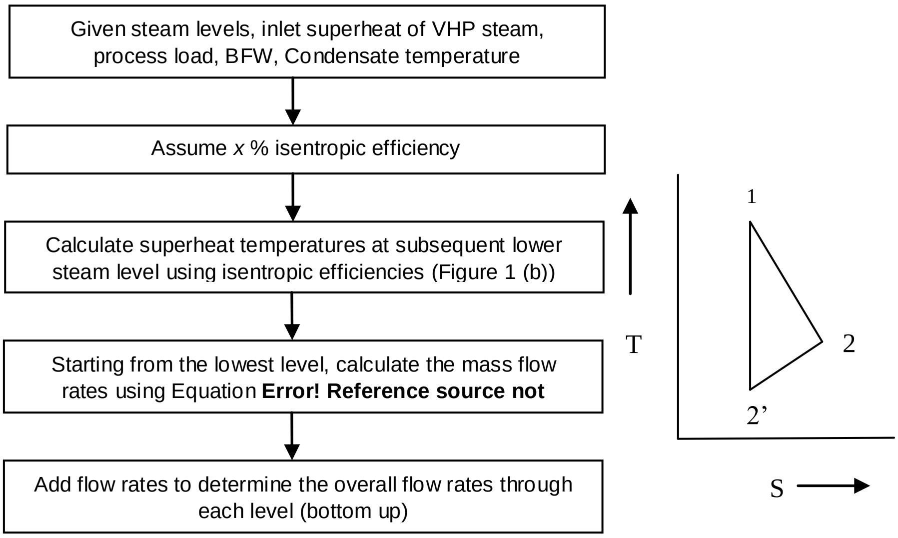
analysis. The estimation of targets for cogeneration is further utilized to improve the performance and profitability of the energy systems. Optimum management and distribution of steam between various steam levels should be made to achieve overall cost-effectiveness of power and heat from the site, and this can be further used for obtaining the import and export targets for electricity. Also, energy efficiency for utilisation of low grade heat will be strongly influenced by operating and design conditions of existing energy systems, and therefore, the accurate estimation of cogeneration potential is essential for perform a meaningful economic evaluation of the design options considered for heat upgrading and/or waste heat recovery.

Several methods have been proposed for the estimation of the cogeneration potential. Dhole and Linhoff (1993) introduced a cogeneration targeting method based on exergy analysis. The exergetic efficiency is considered to be a constant value, irrespective of the load and inlet-outlet conditions. This methodology approximated the steam conditions by the saturated conditions and does not include the superheat in the inlet and outlet steam conditions (Kundra, 2005). This results in considerable error, upto 30% compared with simulations based on THM model, which is discussed in details later (Mavromatis and Kokossis, 1998). TH model (Raissi, 1994) for cogeneration potential targeting is based on the assumption of constant specific load (q) of steam with variation in exhaust pressure specific power is linearly proportional to the difference of inlet and outlet saturation temperatures. TH model for targeting does not include the superheat conditions at each level which results in significant error for the mass flow rate along with the cogeneration potential. Mavromatis and Kokossis (1998) proposed a new shaftwork targeting tool called the Turbine hardware model (THM) based on the principle of Willans line. Willans line approximates a linear relationship between steam flow rate and the power output. Sorin and Hammache (2005) introduced a new targeting method based on thermodynamic insights and Rankine cycle. The ideal shaftwork is expressed as a function of outlet heat loads and the difference in Carnot factor between the heat source and heat sink. Isentropic efficiency is used to account for the deviation of the actual expansion from the ideal expansion. Power produced by the system is calculated based on the isentropic efficiency, heat supply and Rankine cycle inlet and outlet thermodynamic temperatures. However, there is no justification for the assumption that each steam turbine acts as a Rankine cycle.

2. New Method

One of the main tasks for cogeneration targeting in utility systems is to determine fuel consumptions, shaftwork production and cooling requirement ahead of the actual design of the utility systems (Sorin and Hammache, 2005). The detailed design procedure for utility system design built in STAR® requires information about steam flow rates, heat supply and loads, VHP (very high pressure) steam specification such as minimum and maximum flow rate and temperature at the outlet of the boiler. Some of these parameters are not known at the initial targeting stage. The algorithm for this procedure is given in Figure 1. Temperature at each steam level is calculated, starting from the superheat temperature of the steam from the boiler. It is assumed that heat to the process is supplied by the superheated steam at the given pressure level. Temperature entropy diagram for the process is shown in Figure 1(b). Point 1 represents the initial conditions of superheated steam at higher pressure and temperature level. Point 2' on the curve represents conditions for the steam at lower pressure level for an isentropic expansion. The enthalpy at point 2 is calculated on the basis of the isentropic expansion with x% efficiency. It is assumed during targeting stage that all the steam turbines are operating at their full load. The cogeneration potential of the system is dependent on the expansion efficiency of x. This parameter is dependent on the capacity of the turbine. However, 70% efficiency of expansion has been assumed for calculation of the cogeneration potential of the system. This is an engineering design decision as at the initial targeting stage the efficiency of the turbine is not known. Steam properties are calculated for the given entropy and pressure at the lower steam level.



(a)
(b)

Figure 1: a) Algorithm for new method based on isentropic expansion b) Temperature Entropy diagram

Mass flow rate in each section is calculated bottom up, starting with lowest temperature domain. The flow rate in the lower levels is added to determine the flow rate at the subsequent higher levels. The flow rate at each steam level is a function of the heat load at that level and the enthalpy change to the condensate temperature at the given level. It is assumed that process heat is supplied by superheated steam which condenses to condensate return temperature.

3. Optimization of steam levels

The temperature and pressure of the steam level has a very significant impact on the performance of the site utility systems. Both the heat recovery through the steam system and the cogeneration potential of the steam turbine are affected by the pressure of the steam levels. Steam level pressures can be optimized for a new design. Increasing number of steam mains increases the heat recovery potential and hence decreases the VHP steam generation in the boiler and therefore the fuel costs in the utility boilers. It also affects the cogeneration potential. Therefore, an optimal design is to be found to minimise fuel cost with maintaining high cogeneration potential.

4. Results and discussions

The methodologies will be tested in detail through an illustrative example as shown in Table 1. The four steam levels considered in this example are very high pressure (VHP), high pressure (HP), medium pressure (MP), low pressure (LP) at 120, 50, 14 and 3 bars absolute respectively. The heat load at HP, MP and LP steam levels is 50, 40 and 85 MW respectively. The efficiency of the boiler is assumed to be 100% and it is supplying steam at a temperature of 550^{o}C. Water supplied to the boiler and the condensate return are both assumed to be at a temperature of 105^{o}C.

Table 1. Problem Data Parameters

	VHP	HP	MP	LP
Pressure (bara)	120	50	14	3
Saturation Temperature (°C)	324.7	264	195.1	133.6
Heat Demand (MW)	0	50	40	85

Assumptions: The following assumptions were made in the calculation of the shaftwork. The isentropic efficiency was assumed to 70 %, while the mechanical efficiency was assumed to be 100%.

The shaftwork targets for VHP-HP, HP-MP and MP-LP sections of 13.49, 12.28 and 8.33 MW respectively. The main difference between the new method and existing TH and THM model is the calculation of superheat temperature for each steam main. TH model does not include the superheat at each steam level in the calculation of the cogeneration potential. THM model uses an iterative procedure based on specific heat loads to calculate the mass flow rate for the turbines.

Table 2. Comparison of cogeneration targeting results

Methodology	Total (MW)	VHP-HP (MW)	HP-MP (MW)	MP-LP (MW)
Sorin's methodology	41.43	18.2	14.46	8.77
New Method	34.11	13.49	12.28	8.33
TH Model in STAR	33.02	14.35	11.62	7.06
THM Model in STAR	14.1	9.4	4.7	0
STAR Simulation – Constant Isentropic Efficiency	34.07	13.47	12.27	8.33

Table 2 shows a comparison of cogeneration targeting results from Sorin's methodology, new method, TH and THM model in STAR®. A detailed design simulation in STAR® with shaftwork by constant isentropic method is used to compare the shaftwork targets from the different methodologies. As shown in Table 2 the total power target of 41.43 MW from Sorin's methodology is significantly different from the detailed design procedure of 34.07 MW with an error of 21 %. The shaftwork target obtained from TH model of 33.02 MW is 3.08 % different from the shaftwork obtained from the detailed design procedure. Similarly

THM model target is 58.9 % different from the actual shaftwork from the detailed design procedure. These discrepancies in the shaftwork targets are due to the assumptions used in these models. The shaftwork target obtained from the new method of 34.11 MW is only 0.12% different from the detailed design procedure in STAR.

Optimization of steam levels

Site data was taken from an example available in literature (PIRC workshop energy integration, 2009).. Steam is available at four levels very high pressure (VHP), high pressure (HP), low pressure (LP) and medium pressure (MP) respectively. Enthalpy difference between the source and sink profiles is calculated for each of the steam levels. Sink profile is shifted by the minimum of the enthalpy difference between the source and sink corresponding to the pinch point for the system.

Table 3 shows the base case conditions for the four steam levels. Optimum steam level pressure and temperature along with heat load at each level is shown in Table 3. The optimum pressure in the steam mains for the lowest utility cost are 180, 46.55, 12.26 and 2.25 bar in the VHP, HP, MP and LP steam loads respectively. The optimum heat load supplied by the VHP steam from the boiler is 70.66 MW, while the VHP steam flow rate requirement from the boiler is 98.49 t/hr. Utility system energy requirement was reduced from 105.20 MW to 70.22 MW for the optimized case. However, the cogeneration potential reduced from 8.8 MW for base case to 7.1 MW for the optimized case. Therefore, increasing the heat recovery reduces the utility energy from the boiler as well as the cogeneration potential for this example.

Table 3. Steam levels data (optimization)

Pressure (bar)	Temperature (^oC)	Heat Load (MW)		Saturation temperature (^oC)	
		Base	Optimum	Base	Optimum
180	500	105.20	70.22	357.14	357.14
50	336.73	137.01	113.45	264.09	259.79
10	185.99	125.29	107.57	180.04	189.09
2	120.36	81.98	55.34	120.36	124.10

The number, pressure, and superheat conditions of the steam level are important parameters that effect the optimization of the design and operating conditions. Cogeneration targeting model are employed before the detailed design stage for the optimization of steam levels.

5. Conclusions

The number, pressure, and superheat conditions of the steam level are important parameters that effect the optimization of the design and operating conditions. Cogeneration targeting model are employed before the detailed design stage for the optimization of steam levels. Existing models for cogeneration targeting in literature include Sorin's model, TH model, THM model in STAR®. However, existing models have been shown to give misleading results in comparison to detailed design procedure. A new cogeneration targeting model was developed in this work for the optimization of steam levels for subsequent design stage. This new model is based on isentropic expansion. The results have been compared to the results of the detailed STAR® simulation based on constant isentropic model. The results obtained from the new model have been shown to match with the results from the detailed simulation isentropic method. This new method has been further incorporated into STAR® for the shaftwork targeting. The new method has been used for determining the optimization of steam levels for the minimum utility requirement.

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