OPTIMIZATION OF CHP SYSTEMS USING PINCH TECHNOLOGY

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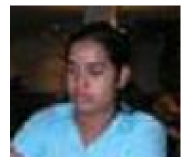

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ABSTRACT:

Pinch Technology is the state of the art technique for design of energy efficient processing plants. This technique is used to compute the theoretically minimum utilities consumption for a process based on the thermal data of process streams i.e. their temperatures and heat duties in the process. This analysis establishes the Grand Composite Curve of the process, which represents the net deficit or surplus of heat in the process as a function of temperature. Pinch Point is defined as the temperature where the net deficit or surplus is 'zero'.

All processes require energy in the form of both heat and power. Cogeneration of heat and power minimizes the wastage of heat associated with power generation. Such systems are termed Combined Heat and Power (CHP) systems. Optimization of CHP systems is the area which offers maximum scope for energy cost savings in any industry.

The insight gained from the Grand Composite Curve for any process aids in selecting the optimum CHP system so that the overall energy consumption of the process is minimized. In this paper we have outlined the methodology for Pinch Analysis and optimization of CHP systems. Several real life examples have been presented to illustrate the energy conservation opportunities in CHP systems, which we have discovered during course of the Pinch Studies conducted by us.

BASICS OF PINCH TECHNOLOGY:

Pinch Technology was introduced by Linnhoff and Vredeveld in 1979.It represents a set of thermodynamically based methods that guarantee minimum energy levels in design of heat exchanger networks. The term 'Pinch Analysis' is often used to represent the application of the tools and algorithms of Pinch Technology for studying industrial processes. Some of the software packages which have been developed for carrying out Pinch Analysis are – *Pinch express, Super Target, Aspen pinch etc.*

Pinch Analysis presents a simple methodology for systematically analyzing chemical processes and surrounding utility systems with the help of First and Second laws of Thermodynamics. In practice a minimum temperature difference (DTmin) has to be maintained between the 'hot' process streams (which have to be cooled to specified temperatures) and 'cold' process streams (which have to be heated to specified temperatures). This technique is used to compute the theoretically minimum utilities consumption for a process based on the thermal data of process streams i.e. their temperatures and heat duties in the process. The temperature level at which DTmin is observed in the process is referred to as 'Pinch Point'. The pinch defines the minimum driving force (DTmin) allowed in the exchanger unit. .

Pinch Technology gives three rules that form the basis for practical process design:

i. No external (utility) cooling above the Pinch Temperature.
ii. No external (utility) heating below the Pinch Temperature.
iii. No heat transfer between process streams across the Pinch Temperature.

Violation of any of the above rules results in higher energy requirements than the theoretical minimum requirements and will adversely affect the energy efficiency.

Pinch Technology has been extensively employed all over the world to improve energy efficiency of various processes including Petrochemicals, Petroleum, Bulk Chemicals, Pulp and paper, Sugar, Alumina, Food Processing etc. The process equipments which have been studied and optimized using Pinch Technology are Heat Exchangers, Distillation Columns, Evaporators, Refrigeration Systems etc.

One of the major application of Pinch Technology is for configuration of Energy Efficient Combined Heat and Power (CHP) cogeneration systems. These are typically termed Power Plants for any process or Industrial Site. CHP systems include heat engines such as gas turbines, steam turbines, DG sets and steam generators such as fuel fired boilers and heat recovery steam generators. The steam distribution system including deaerators, steam headers at multiple pressure levels and condensate recovery systems are also part of CHP systems.

In this paper we will outline the methodology of optimization of CHP systems in Processing Plants utilizing the information obtained during the Pinch Analysis of the process. Proper Integration of CHP system with the processing plants can result in a substantial saving in overall energy consumption We have presented numerous real life case studies to illustrate the methodology. We have also summarized our experiences in a set of "Innovative Projects", which we believe would be very effective in achieving savings in energy cost with attractive economic payback.

COMBINED HEAT AND POWER SYSTEMS:

All processing plants consume energy in the form of "heat" and "power". The requirement of heat for the process is fulfilled by "hot" utilities which include direct heating in furnaces or indirect heating through steam, hot water or circulating thermic fluids. Many larger processing plants have a CHP system or Power Plant where steam and electrical power are cogenerated in a system of steam boilers and steam turbines. This power generation cycle is termed as 'Rankine Cycle'. The general term used for power generating equipment is Heat Engines.

The steam turbines are of three types. Back Pressure turbines (Figure 1a) utilize high pressure steam and discharge steam at lower pressure for utilization for process heating. Extraction turbines operate with high pressure steam and discharge steam at two or more intermediate and lower pressure levels. Extraction-cum-condensing turbines (Figure 1b) have an additional condensing stage where steam is exhausted under vacuum and condensed. The amount of electrical power generated is directly proportional to pressure ratio between higher and lower pressure levels. Typically in a large multiprocess complex, there is a network for distribution of steam at two or more pressure levels – High Pressure (25-40 bar), Medium Pressure (10-18 bar) and Low Pressure (2-4 bar). Different process equipments consume steam at appropriate level depending on the temperature at which heat is required.

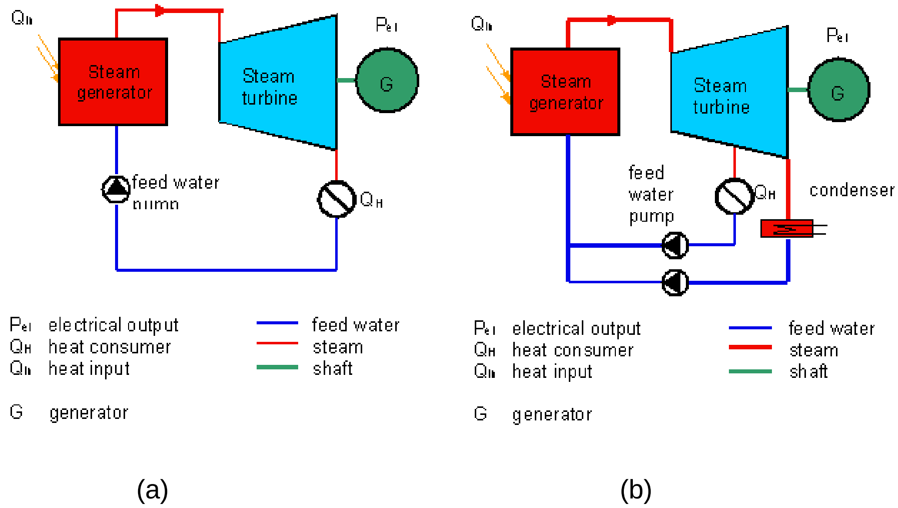


Figure 1: Different configurations of Rankine Cycle based CHP systems
(a) Back Pressure (b) Extraction-cum-condensing Turbine

The extraction and back pressure turbines are thermodynamically very efficient because the conversion of heat to power in these machines is at a very high efficiency (around 90%) . However, the specific power generated per MT of steam flow in back pressure modes is low and generally not sufficient to meet the entire power requirement for the process. Many plants are dependent on the local power utilities to meet this balance requirement. However, the quality of power from State Power Grids is extremely poor and causes frequent disruption in plant operations. This has necessitated most of the major industrial sites such as steel plants, petrochemical plants, paper plants etc to establish captive condensing steam turbines and become self sufficient in power generation capabilities so that they are isolated from the State Power Grids.

Condensing Turbines have much lower thermal efficiency (around 30%) than back pressure turbines since majority of heat in steam is rejected in the condensers. Despite this the overall thermal efficiency of a typical CHP plant (40-60%) comprising of steam boilers and turbines is much better than the efficiency of a power utility (35-37%).

With the advent of aero-derivative gas turbines, “Combined Power Cycles” based on a combination of gas and steam turbines have dramatically improved the energy efficiency of CHP systems. In a Gas Turbine (Figure 2) , the flue gas after extraction of power is still at a high enough temperature to be utilized for steam generation in a heat recovery steam generator (HRSG).

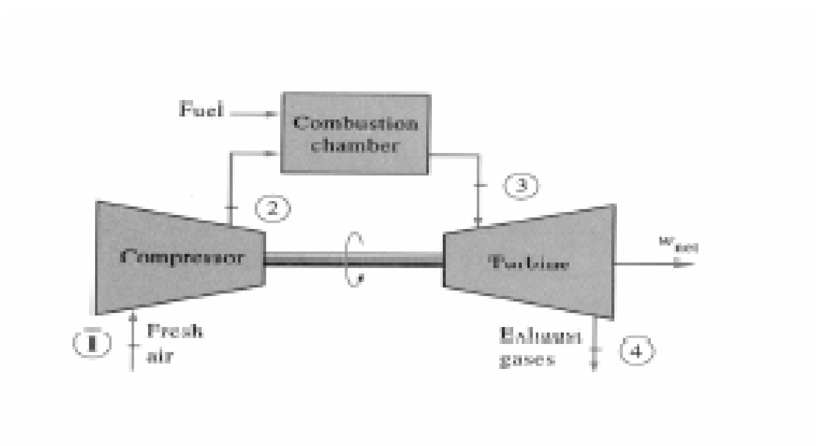


Figure 2: Gas Turbine Generator

The advantage of combined cycle CHP systems is that most of the heat input in the form of fuel is converted to “useful” form i.e. electrical power or steam. The thermal efficiency of Combined Cycle CHP systems may be as high as 80%. However, Combined Cycle Power Plants require gaseous or liquid petroleum fuels and their cost of steam and power is economical compared to conventional coal based CHP systems only where natural gas is available at competitive prices. In medium sized plants, Diesel Generator Sets based on Furnace Oil or Diesel and Gas Engines have also be used for power generation in a combined cycle.

The fundamental parameters which affect the design of optimal CHP systems are:

(1) The ratio of Heat to Power requirement of the industrial site:

A steam Rankine Cycle is generally suitable where heat to power ratio of the site is high (greater than 3). The majority of power required for the process can be generated in back pressure and extraction turbines and the heat loss in the condensing turbines is minimum. When heat to power ratio is lower, Rankine Cycle based CHP systems have lower thermal efficiency because a major fraction of power is generated in condensing sets at a very low thermal efficiency. Combined Cycle based CHP systems will be substantially beneficial in such cases.

(2) The relative temperature levels at which heat is required:

The steam Rankine Cycle is favourable when most of the heat requirement is at lower temperatures and substantial power can be generated in extraction turbines. On the contrary, Combined Cycle CHP plants are warranted, despite their higher capital cost, when most of the heat is required at higher temperatures.

In recent times a third dimension has been added to CHP systems, i.e. the generation of ‘cold’ along with heat and power. This has been made possible by introduction of Vapour Absorption Machines (VAM) systems which utilize heat at low temperatures and can be operated using the hot water generated in DG sets. The concept is termed ‘Trigeneration’ and it has become very popular in smaller installations such as office buildings and hotels.

Many larger processing plants also require cold utilities such as chilled water or direct refrigeration but most of the installations utilize Vapour Compression Machines (VCM) . However, opportunities exist to substitute these by VAM using process waste heat, thereby reducing the consumption of electrical power.

Another innovative component of CHP systems are ‘Heat Pumps’. Heat pumps can be utilized to upgrade low grade process waste heat to useful temperature levels so that the overall requirement of heat in the process is reduced at the expense of marginal increase in requirement of power. Typical examples of heat pumps are mechanical or thermal vapour compressors which are popular in equipment such as evaporators and distillation columns. As per second law of thermodynamics, Heat Pumps are energy efficient only for such cases where the temperature lift required is small. Both VAM and VCM refrigeration units are also examples of heat pumps where heat is removed from the colder streams below ambient temperature to ambient water.

Lastly, CHP systems also include Power Recovery Trains (PRT) which are becoming increasingly popular. In most processes there are numerous valves which let down the pressure of vapour and liquid process streams. In cases where the flowrates of these streams is large, pressure reduction can be carried out in a turbine and power can be generated. This power can either be utilized directly to operate other centrifugal equipment such as blowers, pumps and compressors, or to generate electrical power. Typical applications of PRT include turboexpanders installed in Blast Furnaces and Fluidized Bed Catalytic Cracking Units to recover power from hot exhaust flue gases.

To summarize, CHP system is the most crucial section of any processing plant and its configuration will greatly influence the energy efficiency of the process. In large Industrial Complexes which have several processing plants, the design of optimum CHP system is of paramount importance because marginal energy saving in percentage terms could yield substantial increase in overall operating margins.

GRAND COMPOSITE CURVE AND ITS IMPORTANCE:

Pinch analysis establishes the Grand Composite Curve (GCC) of the process (Figure 3). This is effectively the net process heating or cooling requirement as a function of temperature based on the assumption that all feasible heat recovery will be implemented. Pinch Point is the temperature where the net deficit or surplus is 'zero'.

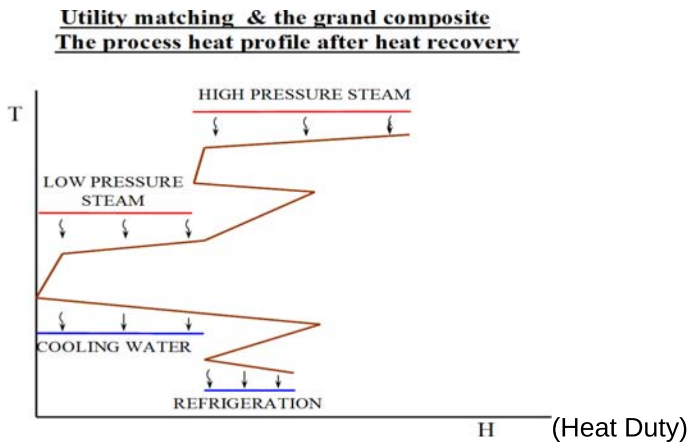


Figure 3: Grand composite curve:

Pinch analysis recognizes the significance of temperature in process thermal duties. Thermal utilities are increasingly expensive as their temperature is increasingly far away from ambient (both for heating and for cooling). The concept of utility pinches can be used to analyze which utilities should be applied to specific thermal duties. In order to minimize utility costs it is important that heat transfer does not cross either a process or a utility pinch. GCC can be used to examine the most efficient thermal utility temperatures for a given process. One significant aspect of this form of analysis is that thermal utility targets can be determined before the heat recovery configuration is defined.

MULTIPLE UTILITY TARGETING USING GCC:

The grand composite curve provides a convenient tool for setting the targets for utilities at different temperature levels as illustrated in Figure 4.

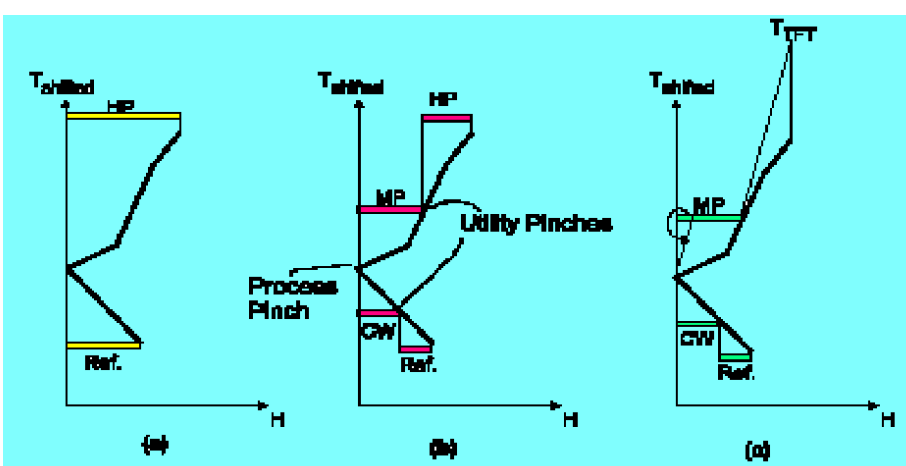


Figure 4: *Using the Grand Composite Curve for Multiple Utilities Targeting*

Figure 4(a) shows a situation where HP steam is used for heating and refrigeration is used for cooling the process. In order to reduce the utilities cost, intermediate utilities MP steam and cooling water (CW) are introduced. Figure 4(b) shows the construction on the grand composite curve providing targets for all the utilities. The target for MP steam is set by simply drawing a horizontal line at the MP steam temperature level starting from the vertical (shifted temperature) axis until it touches the grand composite curve. The remaining heating duty is then satisfied by the HP steam. This maximises the MP consumption prior to the use of the HP steam and therefore minimises the total utilities cost. Similar construction is performed below the pinch to maximise the use of cooling water prior to the use of refrigeration as shown in Figure 4(b).

The points where the MP and CW levels touch the grand composite curve are called the “Utility Pinches” since these are caused by utility levels. A violation of a utility pinch (cross utility pinch heat flow) results in shifting of heat load from a cheaper utility level to a more expensive utility level. A “Process Pinch” is caused by the process streams, and as discussed earlier violation of a process pinch results in an overall heat load penalty for the utilities
.

Figure 4(c) shows a different possibility of utility levels where furnace heating is used instead of HP steam. Considering that furnace heating is more expensive than MP steam, the use of MP steam is maximised. In the temperature range above the MP steam level, the heating duty has to be supplied by the furnace flue gas. The flue gas flowrate is set as shown in Figure 4(c) by drawing a sloping line starting from the MP steam temperature to theoretical flame temperature (TTFT). If the process pinch temperature is above the flue gas corrosion temperature, the heat available from the flue gas between MP steam and pinch temperature.

In many processes particularly in petrochemical industry, Pinch Temperature is high enough such that there is surplus waste heat available at high enough temperatures for generation of steam in waste heat steam generators.
These steam generators are also a part of the CHP system. Steam acts as a cooling utility in such cases. However, the use of steam generators should follow the Pinch Principles, i.e. they should be placed below the Pinch Point. A case study of a petroleum refinery has been presented in [1] where steam generators were located above the process pinch temperature and their relocation and addition of new heat exchangers resulted in a substantial increase in crude preheat temperature and crude throughput without requirement of an additional furnace.

APPROPRIATE PLACEMENT OF HEAT ENGINES:

Process Grand Composite Curve gives an insight as to how the CHP system should be integrated with the process. Figure 5 shows three methods in which a heat engine can be integrated with the process. In the first case, the engine draws heat from fuel and rejects heat at a temperature which is below the pinch temperature. This is the most inappropriate configuration because the entire waste heat from the engine is rejected into cooling water below the pinch point and no advantage of cogeneration is taken.

The correct placement of heat engines i.e their operating temperatures, are selected in such a way that either the waste heat from the engine is at a higher temperature than the Pinch Point (Figure 5b) or the engine draws process waste heat below the Pinch Temperature (Figure 5c).

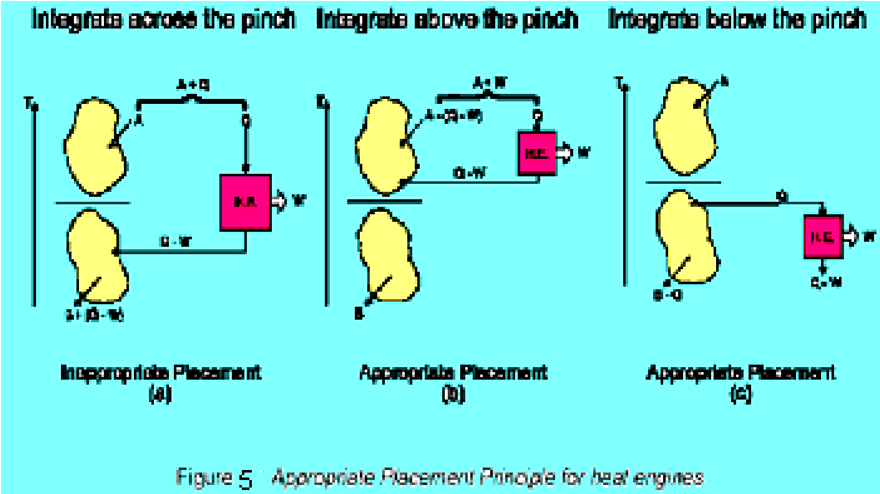


Figure 5 Appropriate Placement Principle for heat engines

Figure 5

In the first case (Figure 5b), waste heat from the engine gets completely utilized in the process resulting in maximum thermal efficiency of the CHP system. All the back pressure and extraction steam turbines fall in this category. Gas turbines with Heat Recovery Steam generators or Furnace Firing systems also fall in this category.

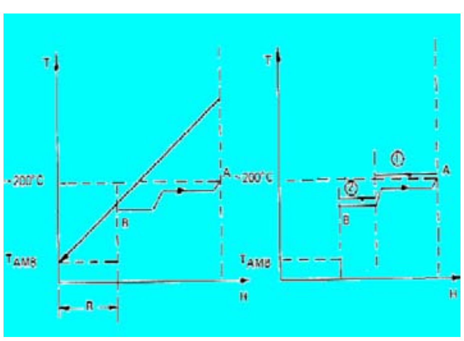
In the second case, the engine is driven by the excess heat available from the process which would have otherwise being rejected to cooling water. So power generated in these turbines is generated from 'free' heat for which fuel is not separately consumed. There are several processes such as Ammonia, Naphtha or Gas Crackers, Methanol etc. where CHP systems are predominantly operated using waste heat from hot product gases which leave the reactors at very high temperatures and are cooled in steam generators.

Therefore, the essential feature of appropriate placement of Heat Engines is that the engine should not transfer heat across the pinch (Figure 5a) but should lie either completely above the Pinch (Figure 5b) or completely below the pinch (Figure 5c).

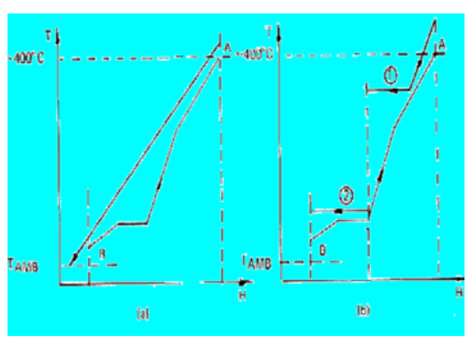
The Grand Composite Curve represents the net heating and cooling requirement for the process as a function of temperature. This information can be used to compute a target for the highest possible power which can be cogenerated while meeting the process heating or cooling requirements. This useful feature is available in most of the Software Packages on Pinch Technology. The details of the computation procedure used for this analysis are given below:

(1) Above the Pinch Point:

Depending on the heat to power ratio and the shape of the grand composite curve, we have to select whether a gas turbine based system is suitable or steam turbines will be able to deliver maximum cogeneration efficiency. Figure 6 illustrates how the shape of GCC affects the type of suitable CHP system:



(a)



(b)

Figure 6: GCC matched with gas turbine exhaust and exhaust steam from turbines GCC (a) is suitable for steam turbines while GCC(b) is suitable for gas turbines

In case of steam turbines, we have to select the suitable working pressure for the boilers, which will in turn define the motive steam pressure for turbines. Higher the motive pressure, higher is quantum of power generation. With the advent of better materials of construction, the maximum permissible working pressure for boilers is steadily increasing and boilers with operating pressures of 135 barg are now available. The selection is usually done based on the quality of fuel used, availability of capital and the economics.

Theoretically, the maximum cogeneration of power will be achieved when there are indefinite number of small extraction steam turbines, from which steam is extracted at different temperature levels to exactly meet the process heat requirement at that temperature level. Since GCC represents the heat duty versus temperature profile, the software package integrates the power generated from all these tiny turbines and computes the maximum possible power which can be generated. Suitable thermodynamic models of steam turbines are used for this purpose. The user can then select appropriate operating pressure for extraction steam levels which are realistically possible. The requirement of steam for each extraction level is targeted as discussed earlier and the associated power generation is also computed and compared with the theoretical target.

Gas turbine calculations are based on the data provided for different models by the manufacturers. For each GT model, curves are available for GT exhaust temperature and flow rate as a function of total power loading, duly corrected for ambient temperature, elevation and other factors. Once the exhaust flowrate and temperature are known, GT exhaust heat profile can be matched with the process GCC. The model which gives the best matching is selected and the power generation potential is computed. The matching of GCC with combined cycle CPP systems can also be done in a similar fashion and the cogeneration potential can be calculated.

(2) Below the Pinch Point:

Some processes such as Ammonia and Methanol feature a relatively high Pinch Point (above 1000 deg C) and quenching of hot gases is necessary. This is done in steam generators known as transfer line exchangers where steam is generated at a high pressure, extracted partially to meet low temperature process requirements and balance is condensed in the turbine(s). The computation of power generation potential is done in a similar fashion as discussed earlier based on the GCC.

Pinch Technology is one of the few systematic techniques through which a designer can determine the maximum potential for cogeneration of power. This insight gives confidence in efficacy of the proposed design of CHP system.

Although this procedure is ideally suited for design of CHP plants for new Industrial Processes and Complexes, it can also be used to evaluate the CHP systems of existing sites. We have conducted Pinch studies of CHP systems for a few major petrochemical sites and have identified several energy conservation schemes.

APPROPRIATE PLACEMENT OF HEAT PUMPS:

Heat Pumps are used to upgrade low grade waste heat to higher temperature so that it can be utilized for process heating. Figure 7 shows different possibilities of integration of heat pumps with a process.

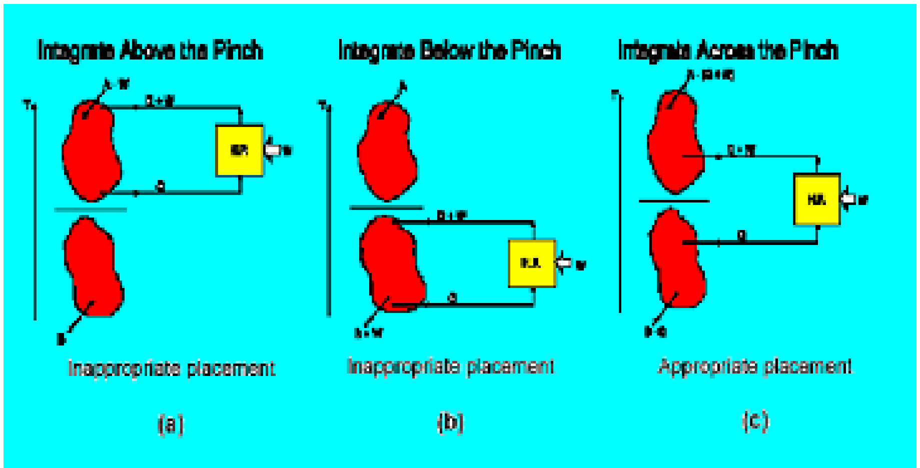


Figure 7 *Placement of heat pumps*

In Figures 7 (a) and (b), the heat pumps are located either entirely above the pinch or entirely below the pinch. In both these instances, use of heat pumps does not result in any reduction in utilities requirement. In Figure 7 (a), the heat which is upgraded could be utilized for process heating as such without any increase in temperature and the pump just acts as an expensive electric heater. In Figure 7 (b), the upgraded heat is still below the pinch point and will have to be rejected into cold utility. Figure 7 (c) shows that the correct way to place the heat pump is that it transfers heat across the pinch, i.e. it upgrades waste heat below the pinch to a temperature higher than pinch point, so that it can be used for process heating and reduce the consumption of hot utility by an equivalent amount. Steam Ejectors are the most commonly used heat pumps which are found in many evaporator systems to upgrade the evaporated vapours so as to partially replace the live steam. However, an interesting case study of a food processing plant has been reported in [1] where Pinch Analysis showed that the ejector is not transferring heat across the Pinch Point. A simple shift in process operating conditions such that the ejector is shifted across the pinch resulted in a saving of nearly 40% in steam consumption.

Figure 8 shows the shapes of GCC which make use of heat pumps attractive. In the process shown in Figure 8 (a), the upgradation of heat is required over a narrow temperature range and the power consumption will be a small fraction of the total quantity of waste heat which can be gainfully utilized for process heating. On the contrary, the process shown in Figure 8 (b) is not suitable for use of heat pumps because the temperature lift required is quite large and the consumption of power will be very high, making a heat pump economically unviable.

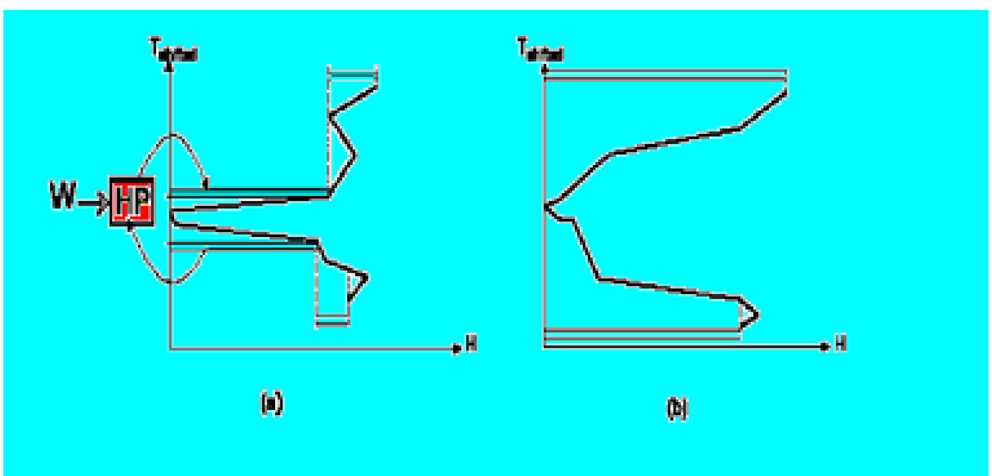


Figure 8 *A pointed 'nose' at the process or utility pinch indicates a good heat pump opportunity.*

ONLINE OPTIMIZATION OF CHP SYSTEMS:

The utility requirements of any Industrial Complex constantly vary and proper monitoring and optimization of CHP systems can yield substantial benefits. In most large industrial sites, CHP system is a complex mix of Gas and Steam Turbines, Boilers and Heat Recovery Steam Generators Pressure Reducing Desuperheater (PRDS) Stations, etc. A typical steam distribution diagram of a large industrial complex is shown in Figure 9 .

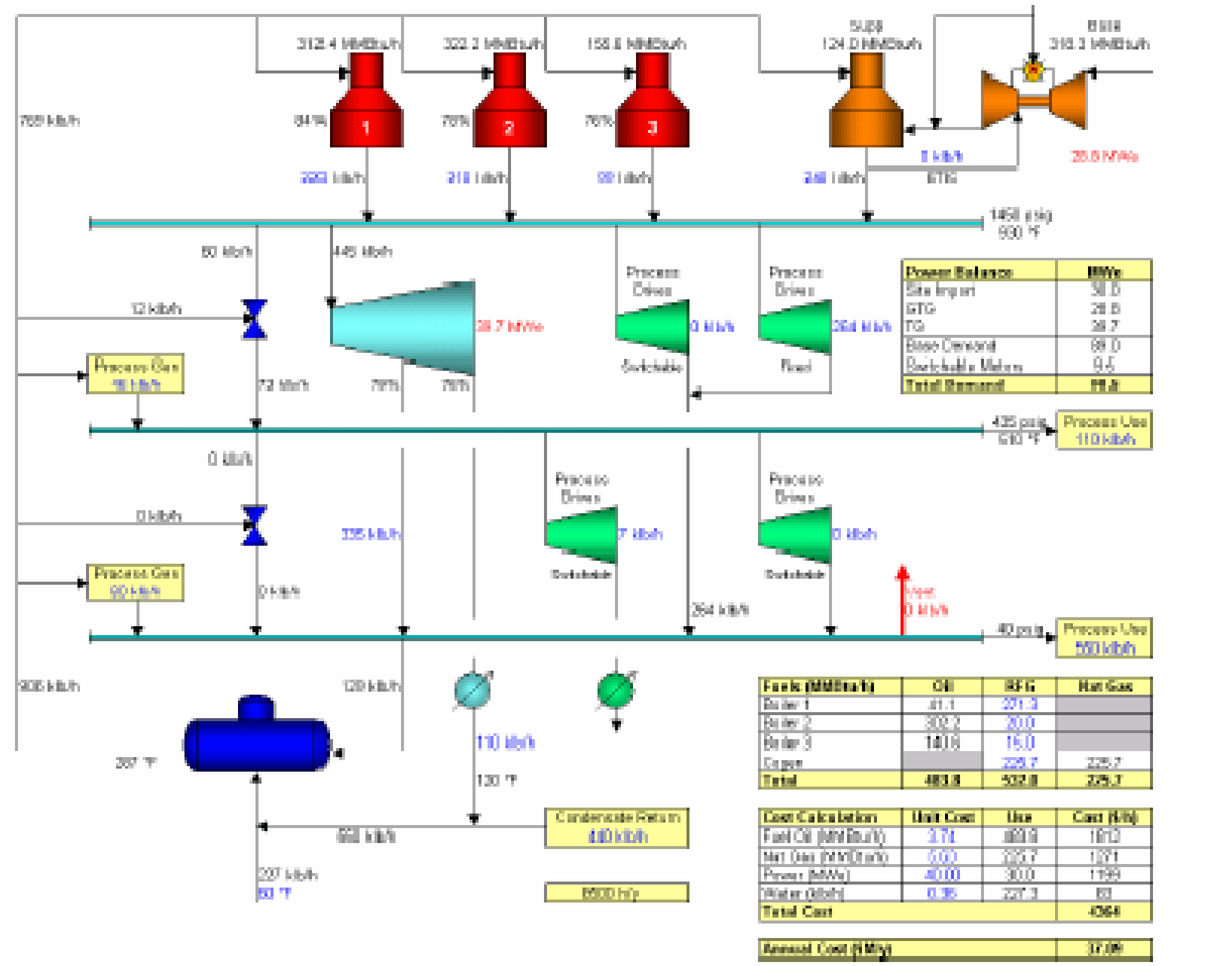


Figure 9. CHP system of a large industrial complex which includes Gas Turbine and HRSG, Boilers, Steam Turbo Generators, Steam Driven Process Drives, Deaerators etc.

The objective of optimization of CHP system is to minimize the combined cost of fuel and imported power. Commonly used fuels are fuel oil, fuel gas, coal and agro waste. Fuel is used in boilers to generate steam and heat engines such as gas turbines or Diesel Generating Sets. Power tariff keeps varying from place to place and even during different times of the day. The boilers and HRSG generate steam at a very high pressure which is let down to lower pressure levels through steam turbines. Steam is also generated at different pressure levels from the process waste heat. Different plants draw steam from these headers to meet their heating requirement. The operating pressure of various steam headers is maintained by letting down steam from higher pressure through Pressure Reducing Desuperheating Stations (PRDS) in case of deficit or by venting off surplus steam. Since venting of steam results in a direct loss of heat and fuel, the system should be tuned to minimize it. However, letting down of steam in PRDS is also undesirable because they reduce the potential to cogenerate power in extraction turbines thereby increasing the requirement of expensive power from grid or condensing turbines.

The power requirement of the sites is largely met by captive gas and steam turbogenerators. Many large and critical process equipment such as compressors, boiler feed water pumps etc are directly driven by steam or gas turbines. The power generated in gas turbines and extraction steam turbines is usually cheaper than the power supplied by utility grid and load on these turbines is maximized as long as there is no venting of extracted steam. Many sites in India are not connected to utility grids and power load is balanced by operation of condensing stages of the turbines. In cases where utility power is available and cost effective, the steam flow through condensing stages of turbines is minimized subject to design constraints.

This 'delicate' balance needs to be constantly tuned and many software packages are available for online optimization of CHP systems. The dynamic steam and power scenario makes online monitoring and optimization essential in any modern CHP system. We present a real life industrial case study to illustrate the kind of decision making required on a day to day basis to maintain efficient operations of CHP system.

For any real example, the situation is continually changing in terms of operating conditions, equipment availability etc. For this paper, we have focused on snapshots of the site operation in order to demonstrate the typical results from the optimizer.

This case study focuses on a European refinery which, at the time chosen for this case study, was faced with a low power price. The key equipment items on the refinery are shown in Figure 10.

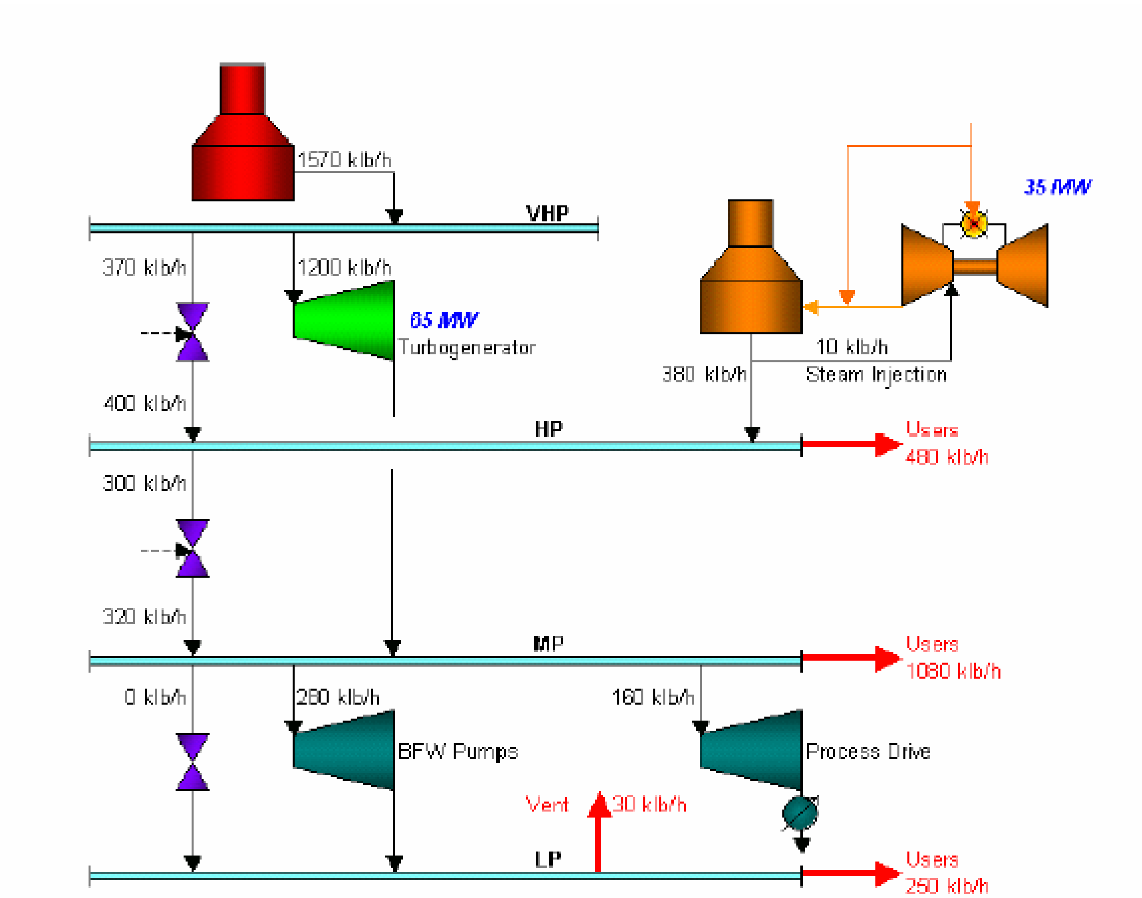


Figure 10. European Refinery Base Case Operation

The site is limited in terms of power production by only having one turbogenerator installed between the VHP and MP levels. This turbogenerator was running at its maximum throughput but the site had questioned whether this was correct given that power was cheap at the time.

From the MP level, the boiler feedwater (BFW) pumps were using 280 klb/h in MP to LP turbine drives. A further 160000 lb/h of MP steam was used in a condensing turbine to provide part of the power for a major process drive. Despite the fact that no letdown exists between MP and LP, the site was still venting 30000 lb/h of LP steam as a result of the imbalance between the steam flow from the BFW pumps and the demand from the LP users. The optimized case is shown in Figure 11.

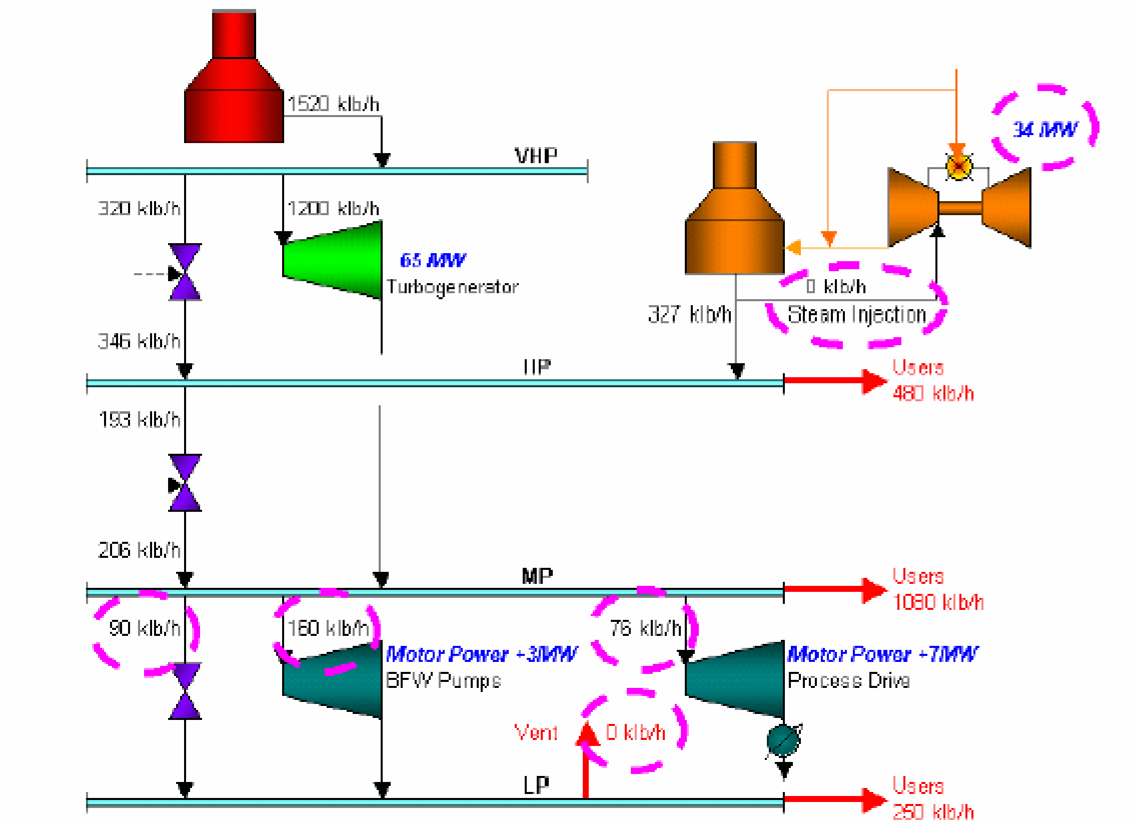


Figure 11. Optimized Operation for the case study

The first point to note is that the central turbogenerator continues to run at maximum throughput. Even though power is cheap, the demand for MP steam both from the processes and to drive turbines is such that reducing the throughput would simply increase the amount of steam which needed to be let down to the MP level. The first change to note is that the steam injection into the gas turbine has been turned off. This results in a reduction in power generation from the gas turbine of around 1 MW but it is better economically to supply the steam into the HP header. A change has also occurred in the BFW pumps. The steam flow has reduced from 280000 lb/hour to 160000 lb/hour as a result of switching one pump over to its equivalent electric motor. The electric power required to drive this motor is approximately 3 MW. Another major change has occurred in the major process drive where the amount of steam used in the condensing turbine has reduced from 160000 lb/hour to 76000 lb/hour. This is a flexible machine that can, within operational limits, use any combination of steam in the condensing turbine and power in electric motors to drive it. In this case, the power consumption in the electric motor increases by 7 MW. This change, and that to the BFW pumps, is driven by the cheap power price.

One surprising result from the optimizer is that a letdown has opened up between MP and LP steam. This is required in order to balance the header following the reduction in steam flow from the BFW pumps. This may seem wrong but setting the system up in this way eliminates the LP vent and ultimately reduces the steam demands from the boilers. The benefit achieved from this more than offsets the additional power requirement to drive the BFW pump motor.

In this example, the savings achieved were $380 per hour (3.8% of the site utility bill). On an annualized basis, this would equate to a cost savings of $3.2M per year.

The complexity of CHP systems makes utility pricing of a site a very complicated exercise. To evaluate projects on the basis of saving of energy costs is a crucial issue which every Industry faces. The traditional approach is to calculate utility prices on the basis of enthalpy and exergy of steam. Average cost of power is determined based on the cost of steam consumed in steam turbogenerators and cost of fuel input to GTs. This methodology does not give the actual marginal cost of utilities. The optimizer packages are very useful in this respect since they compute the impact of any increase or decrease in steam or power consumption on total cost of fuel or purchased power, thereby giving a realistic marginal cost of utilities. In absence of optimizer packages, we recommend that the marginal cost of utilities should be calculated based on the highest cost of the concerned utility. For example, if the condensing turbines are operated above the minimum condensing load, the marginal cost of power should be calculated from the specific steam consumption in condensing sets. In case of lower pressure steam, cost should be computed based on High Pressure Steam cost after giving credit for power generated through extraction. However, in case the PRDS is letting down steam directly, the cost of steam is same as that of the higher pressure steam after accounting for the reduction in enthalpy. We find that at very low pressure levels, steam venting is a common feature because most of large amount of steam generation from process waste heat. In such a scenario, marginal steam cost becomes zero. We will discuss certain schemes which will address this situation in the next section.

Another common myth about CHP systems is that cogenerated power is ‘free’. It should be noted that first law of thermodynamics states that energy cannot be created from nothing. The cost of cogenerated power is determined by the cost of fuel consumed to raise the steam in steam turbines or burnt directly in the gas turbines per unit of electricity. The actual thermal efficiency of cogeneration is computed below:

Fuel to power conversion for 100% cogeneration:

Efficiency of Electric generators	: 0.97
Efficiency of boilers	: 0.90
Overall efficiency	: 0.87

INNOVATIVE ENCON OPPORTUNITIES FOR CHP SYSTEMS:

We have carried out Pinch Analysis of a number of large Petrochemical and Petroleum Refining Complexes where we have conducted detailed Pinch Analysis of their CHP systems. A major feature of most Industrial Sites is their dynamic nature because of constant addition of new plants, expansion projects etc. As a result, the CHP systems also have to be periodically upgraded. Every revamp gives the designer an opportunity to correct past mistakes and improve the energy efficiency of the site.
We have identified several opportunities which can be seized to achieve dramatic savings in energy consumption. Each of these has been illustrated with the help of a real life case study.

(1) Condensate and Blowdown Flash System :

Condensate generated from steam as well as blowdown from steam drum , contain a substantial quantity of useful heat particularly at high pressures. The most common arrangement for condensate and blowdown handling is to install a series of flash drums where they are successively flashed to lower pressures. Steam generated is connected to the steam headers of appropriate pressure so that the flashed vapours are properly utilized. The condensate after the last flash vessel is returned to the CPP for polishing and recycling whereas the blowdown is discarded.

In processes where steam is generated in waste heat steam generators, the condensate can be pumped back into the steam drum without flashing at lower pressure. This results in substantial saving not only because it avoids cooling and reheating of water, but it also obviates the requirement of expensive water treatment chemicals or deaeration because there is no chance for oxygen to dissolve in high pressure condensate.

Condensate system is an area where we have found scope for improvement at all the sites where we have conducted Pinch Studies. Most petrochemical processes have one or more steam generators for cooling the reaction products and traditionally treated Boiler Feed Water has been used for raising steam. Several projects for recycle of condensate as boiler feed water have been satisfactorily commissioned in petrochemical plants.

Heat from continuous blowdown can be utilized for preheating DM water or makeup water after removal of flash vapours. In boilers where economizer is not present, a heat exchanger can be installed to recover heat from blowdown into the feed water itself without any flashing. For example, in a 100 MT/hour boiler generating steam at 120 Barg pressure, and having 4% Continuous Blowdown, the installation of blowdown/feed water heat exchanger will result in an increased steam generation around 1MT/hour.

(2)Use of lower pressure steam for process requirements instead of higher pressure:

In many process applications there is a possibility to use lower pressure steam instead of higher pressure steam by modification of heat exchangers or operating conditions. In many cases these opportunities open up because of the changes in operating conditions of equipment compared to design values which happen over a period of time.

We have recommended several such projects which have been implemented and yielded substantial results. An example is the stripping column in diesel and VGO hydrotreaters in petroleum refineries where injection of HP steam for stripping has been replaced by MP steam. This project has resulted in a shift of 25 MT/hour steam consumption from HP to MP levels. The extra extraction power generated reduced the load on condensing stage by 3MT/hour of VHP steam, resulting in an annual saving of Rs. 135 lakhs.

(3) Use of Thermocompressors:

In most large industrial sites with multiple processing plants, steam distribution headers are laid throughout the complex at three different pressure levels - HP, MP and LP. However, because the plants are usually designed by different licensors, they often have their own internal steam headers at pressures which lie between these three levels.

For example, in a particular site, the header pressures for HP, MP and LP steam are 42 barg, 17 barg and 4 barg respectively. Some plants require steam at 7 barg which is obtained by reducing pressure of MP steam. There is significant difference in cost of MP and LP steam (Rs. 120 per MT) because of the impact of cogenerated power. In this particular plant , the total consumption of MP steam which is let down to 7barg is 15MT/hour and a thermocompressor can be installed which will upgrade 6MT/hour of LP steam to 7barg level using 9MT/hour of MP steam. The resulting annual saving is projected as Rs. 60 lakhs and the estimated project cost is Rs. 25 lakhs.

One word of caution for installation of thermocompresssors is that although they are simple steam diffusers without any moving parts, their design is very critical and their operating range is quite narrow both in terms of operating pressure as well as flows. The prevalent variations in plant operating conditions should be accounted for during design stage and a suitable control scheme should be incorporated.

(4) Optimization of Process Steam generators:

In most chemical plants, large quantity of steam is generated through recovery of process waste heat. Although these steam generators are an integral part of CHP system, the selection of their operating conditions are usually done by the process licensor without detailed knowledge of the CHP system. We have found several opportunities where higher pressure steam can be generated instead of lower pressure steam and substantial cost savings can be achieved. Licensor just selects the steam pressure based on internal process requirement and it is economical to export the higher pressure steam to the CHP system and import lower pressure steam to fulfill process requirement. However, in most cases it is very difficult to replace these steam generators because of space constraints and long shutdown time required. We recommend that whenever a new plant is set up, the process operating conditions and steam generation pressure should be selected after careful analysis of CHP system.

The boiler feed water required for these steam generators is usually imported from the deaerators of the CHP system. In many cases, opportunity exists to preheat this process water using waste process heat before it is injected into the boiler. The quantity of steam generated is enhanced by an equivalent amount. One example is the Fluidized Catalytic Cracker Unit (FCCU) of a large refinery where feedstock is hot Vacuum Gas Oil from a hydrotreating unit. In the Hydrotreater, product VGO stream is cooled to 170 deg C in an LP steam generator before it is fed to the FCCU. We proposed a scheme for bypassing the LP steam generator, feeding the VGO stream at 210 deg C and preheating the High Pressure BFW in FCCU from 172 deg C to 190 deg C. The result is an increase in HP steam generation in FCCU by 4 MT/hour at the expense of equivalent amount of LP steam in VGO Hydrotreater. The annual savings is Rs. 65 Lakhs and the cost of the proposed VGO/BFW heat exchanger is Rs. 35 lakhs.

(5) Use of Process Waste heat for heating makeup water in CHP systems:

In large industrial complexes the recovered condensate is returned to the CHP system where it is cooled and passed through a condensate polishing unit to remove the ionic impurities. In addition, demineralized water is injected to make up for the losses. The cold water is pumped to a deaerator vessel in which live steam is injected to strip off dissolved gases, as well as heat the boiler feed water to a temperature of 105-130 deg C. This increase in temperature is beneficial because higher the boiler feed water temperature, higher is the generation of VHP steam. Deaerators are usually the largest single consumers of LP steam in any site.

We have found that most processes have substantial amount of waste heat available in temperature range from 60-100 deg C. This heat can be gainfully utilized to preheat make up water and return condensate from 40 deg C to 90 deg C thereby saving LP steam. Pinch Analysis of a large petrochemical complex revealed that deaerators were consuming 65 MT/hour of LP steam. A new aromatics processing facility was being commissioned which had three distillation columns whose condensers would reject around 25 MMkcal/hour heat in fin-fan coolers. We designed a heat recovery project which involved pumping of 400 m3/hour of water to the aromatics plant and preheating the water from 30 deg C to 85 deg C. A 12 inch pipeline of 4 KM length was laid down for this purpose alongwith a vacuum deaerator to remove dissolved gases from preheated water. The project resulted in a saving of 45 MT/hour of LP steam and an annual cost saving of Rs. 10 crores. The total project cost was Rs. 6.50 crores.
In Gas Turbines where natural gas is used as fuel, the flue gas temperature in Heat Recovery Steam Generators (HRSG) can be brought down safely to 100 deg C without any fear of acidic corrosion. A substantial amount of heat is available in flue gas eve after preheating the boiler feed water to the saturation temperature. This heat should be used to preheat cold DM water entering the deaerator and will reduce the requirement of LP steam. In one petrochemical complex, HRSG were designed for a stack temperature of 160 deg C since they were on liquid fuel firing. After switching over to natural gas, HRSG were retrofitted with new makeup water heating coils saving about 7 MT/hour of LP steam in each HRSG.

(6) Use of waste process heat for operation of Vapour Absorption Machines:

Most Industrial Complexes have requirement of chilled water for process and Humidification, Ventilation and Air Conditioning (HVAC) requirements for which Vapour Compression Chillers are installed. There are ample sources of waste process heat which reject heat to atmosphere in fin fan or water cooled heat exchangers. Opportunities exist for utilization of this waste heat to generate chilled water in VAM. The result will be a significant reduction in power consumption because of off-loading of vapour compression chillers.

VAM based on hot water (80-90 deg C) or Very Low Pressure – VLP (0.5 barg) steam are now available. Typical heat duty required to operate 500TR VAM to produce chilled water at 7 deg C is 2 MMkcal/hour or 4 MT/hour of steam. This will offset the electric power requirement by 300KW.

In a recent study of a PTA (Purified Pthalic Acid) Plant, we have proposed a 1100 TR VAM to generate chilled water using 10 MT/hour process vent steam. The chilled water will used in the neighbouring Polyester plant and achieve a reduction of 660 KW in power requirement, saving Rs. 1.2 crores annually. The total project cost is estimated at Rs. 2.0 crores.

A major constraint for installation of VAM is their large requirement of cooling water. However in applications where VAM replaces a water cooled process heat exchanger, the cooling water requirement remains essentially unchanged.

(7) Power Generation using waste process heat:

Enthalpy balance on processing plants show that the energy input to the process equals the energy output after accounting for the chemical energy released in the process. A large amount of heat is rejected into the atmosphere through fin fan coolers, cooling water, direct release of process vapours or through refrigeration. The surplus heat in the process streams below the pinch point has to be necessarily rejected to a cold utility.

In many processing plants a large quantity of surplus heat is available between 80-110 deg C which is presently lost to the atmosphere. Two methods for utilization of low level heat namely VAM and Boiler Feed Water Preheating were discussed earlier. Recently some manufacturers are offering Organic Rankin Cycle based power generating systems for such applications. These systems use organic compounds such as pentane and cyclopentane as working fluids and have a typical heat to power conversion efficiency of 10-15%.

In some processes such as PTA and Crude Distillation Units, a large quantity of surplus heat is available which can generate saturated LP/VLP steam. Steam Condensing Turbines operating on saturated LP/VLP steam are now available. Thermal efficiency of such turbines is 18-20% and they can be directly coupled with rotating equipment such as centrifugal pumps or compressors.

Based on the experience gained by us through Pinch Studies of several Petrochemical sites, we strongly recommend that the turbo generators installed in modern CHP systems should have a facility to inject MP and LP steam to recover power from them in the condensing stage of the turbine. In most sites energy conservation projects are commissioned which gradually decrease the consumption of LP and MP steam or increase their generation in process steam generators. This leads to an imbalance in the system and sometimes steam may even have to be vented. One method to address this imbalance is to convert some drives such as BFW pumps from steam turbines to electric motors. But if there is a provision to inject MP or LP steam in the turbo generators, venting of steam will never be necessary.

(8) Direct Heat Recovery from Gas Turbine exhaust gases:

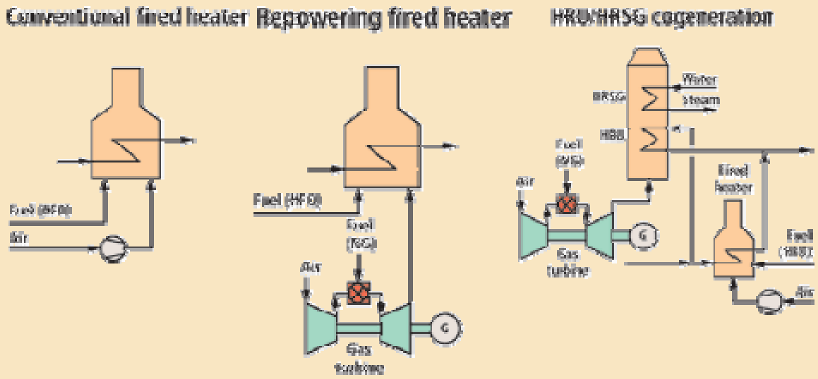
Traditionally, GT exhaust has been utilized to generate steam in HRSG with or without additional fuel firing. There have been some installations where GT exhaust has been utilized as combustion medium in fired furnaces. A novel approach has recently been adopted in a Petroleum Refinery where GT exhaust has been utilized both for crude heating in a heat recovery unit (HRU) as well as steam generation (HRSG).

Compared to repowering fired heaters or traditional cogeneration, HRU/HRSG cogeneration saves additional energy, with appropriate emissions reduction, and an improved energy intensity index. Other benefits include improving the refinery's onstream time, reducing fouling/ coking and possibly debottlenecking the refinery unit.

Table 1 provides an overview that also includes a repowering option.

Table 1. Various crude heating options

A comparison:	Conventional fired heater	Repowering fired heater	HRU/HRSG cogeneration
Energy savings	Reference	Approx. 5–10%	Approx. 10–20%
Upstream time	Reference	No improvement	Improved
Capacity increase	Reference	No improvement*	Possible**



* Capacity can even decrease due to limited gas flow through the fired heater.
** A capacity increase is possible if the fired heater represents the bottleneck of the refinery unit.

In traditional cogeneration, heat is recovered into a heat recovery steam generator (HRSG). However, opportunities also exist to recover the heat directly into a process in an HRU, provided there is an appropriate temperature match. Such is the case with most fired heaters in a refinery.

Figure 12 details such a concept for a crude distiller unit (CDU) of a refinery. In essence, the gas turbine (GT) exhaust provides the heat required by the crude in an HRU. The remainder of the heat available in the GT exhaust allows for generating steam in an HRSG. This has the following technical advantages:

· Fouling and coking on the heat transfer area are reduced, because the heat transfer is shifted from radiant to convective.
· The unit may be debottlenecked if the fired heater is the bottleneck of the unit because additional heat transfer area is installed.
· Onstream time can be improved in a parallel arrangement because redundancy is built into the system.
· Aiming for a large fired heater, like a crude heater, allows for economy of scale, which applies to the economics as well as the energy efficiency.
· Onsite steam generation reduces demand on the site's steam boiler.
· Onsite power generation reduces required power import, or even allows for power export.

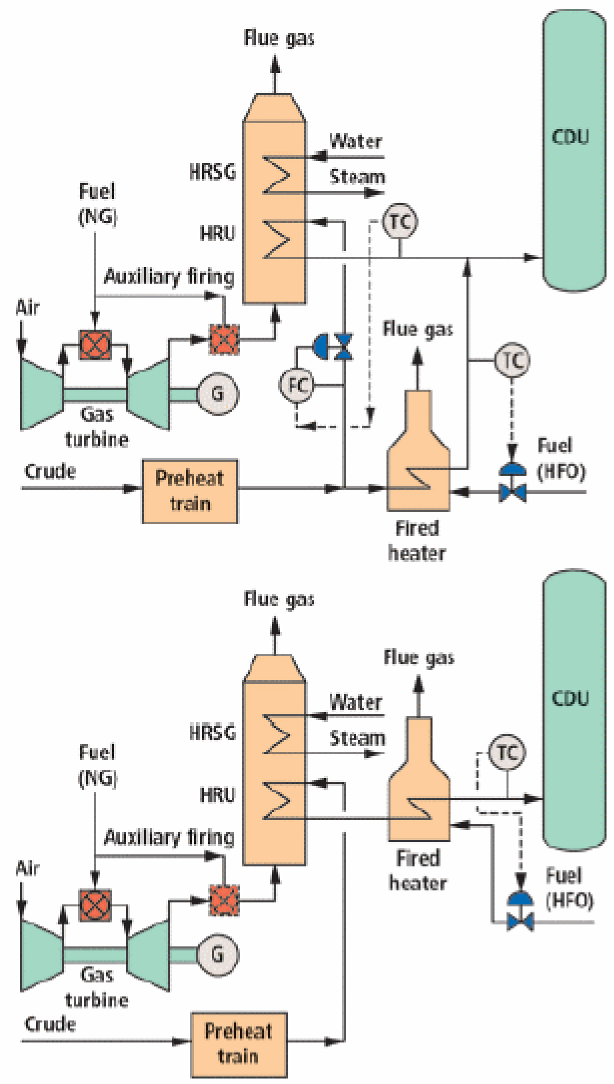


Figure 12: Installation of HRU in a petroleum refining unit
An HRU can be placed in parallel or series to the fired heater.

A case study has been developed based on a 130,000 bpd Crude Oil Distillation Unit (CDU). The base case refinery had a 95 MWth fired heater, from which 50% duty was shifted to the HRU in a parallel arrangement. An average refinery of such a size would consume approximately 45 MWe of power, about 190 tph of steam and around 450 MWth of fuel. Shifting 50% fired heater duty to the HRU requires a typical 70 MWe GT The HRSG correspondingly generates 57 tph of 34 barg steam and 17 tph 4 barg steam. A savings on the utility bill of approximately euro7.4 million/year can be achieved at an estimated investment of about euro;37.7 million, i.e., a simple payout time of 5.1 years.

(9) Power Recovery Turbines:

In many plants there are instances where pressure of vapour or liquid streams are reduced across control valves. Opportunities exist to exploit this pressure reduction to generate power. In Fluidized Catalytic Cracking Units in Petroleum Refineries, power is recovered from exhaust flue gases. The turboexpander is mounted on the same shaft as the process air compressor and delivers part of the power required. Similar turbines are being installed in Steel Blast Furnaces to recover power from the top flue gases.

In a recent study we have proposed installation of turboexpander to recover power from pressure reduction of natural gas from 40 barg (grid supply) to 20 barg (required for Gas Turbine Feed). The total potential for generation of power is around 1100 KW. The natural gas is first preheated using waste heat and MP steam to a temperature of 150 deg C and then expanded in a turbine to exhaust at a temperature around 100 deg C. The hot fuel gas is fed into the gas turbines and HRSG for supplementary firing.

(10) Biomass Gasifiers and Gas Engines:

There has been a lot of interest in utilization of biomass as energy source in small and medium scale industries in India. Biomass such as bagasse, rice husk, wood, groundnut shells, etc. are being used in large quantities in boilers and other furnaces. Many sugar factories, for example, have CHP systems based on bagasse boilers and steam turbines.

A new, more efficient approach has been perfected recently for smaller CHP systems. Biomass is first converted into producer gas (a mixture of CO, Nitrogen and Hydrogen) by reaction with steam and air. The gas is cleaned in scrubbers to remove tar and is used as a fuel in Gas engines. The hot exhaust gases can be used for providing process heat directly or indirectly through steam generation. The heat rejected to water for engine cooling can be utilized for absorption refrigeration. Several companies are offering such systems in India and they are also subsidized by Ministry Of Non-Conventional Energy Sources.

We have discussed at length how Gas Turbines form the corner stones of efficient CHP systems for large petrochemical complexes. However, for smaller industries, Gas Turbines are not viable because of their high capital cost. Gas Engines with waste heat recovery systems are available in India and are being commissioned wherever natural gas is available.

(12) Application of Heat Pumps:

Heat Pumps have been in vogue in process industry for a number of years. One of the most common heat pumps are Vapour Thermocompressors which have been used in multiple effect evaporators to recompress part of the vapours from the first effect for use as heating medium in the first effect itself. A case study of a food processing plant, where such a thermocompressor has been installed, is illustrated in Reference 1.

Another application of heat pumps is in distillation columns where the difference between top and bottom temperature is very small. An example of such a column is Propylene/Propane splitter in Petrochemical plants. The schematic of this column is
shown in Figure 13.

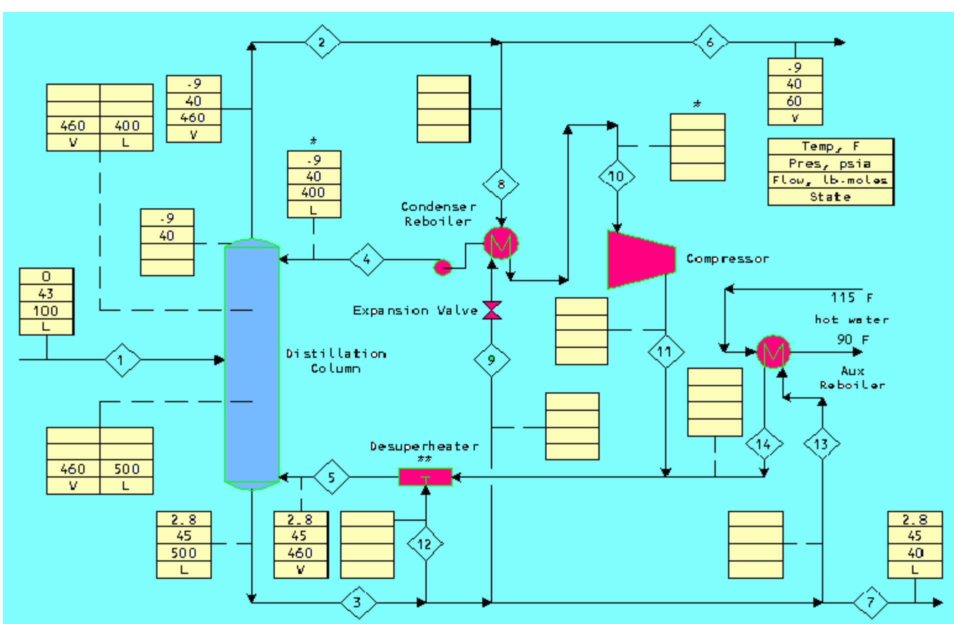


Figure 13: Schematic of Propane/Propylene Splitter Column in Propylene Recovery Unit of a Petrochemical Complex

In this distillation system, the pressure of a part stream of bottom product is reduced across a control valve and the liquid is vapourized by the heat from the condensing top vapours in a heat exchanger termed condenser/reboiler. The vapour generated is then compressed in a centrifugal compressor so that it may be injected back into the column below the bottom tray to provide the reboil necessary for the separation. This column is operated without any heat input from external utility. The energy is input into the system in the form of power consumed in the compressor. In traditional columns which carry out this separation, very large quantities of heat is required in the reboiler in the form of LP steam and this enire heat is wasted at fairly low temperatures in the condensor. The compression ratio required is very small and hence only a small fraction of heat energy required in conventional columns is required in the form of power in the columns equipped with heat pumps..

CONCLUSION:

To summarize, Pinch Technology offers a systematic approach for integration of processing plants with the CHP systems so that the total fuel bill of the complex is minimized. We have presented case studies to highlight some of the opportunities which we have come across for improving the energy efficiency of CHP systems studied by us as part of Pinch Studies. In most of our studies, we have found that CHP systems offer the single largest scope for reduction in energy cost. With the advent of carbon credits, optimization of cogeneration opportunities has become even more lucrative.

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Dr. Alok Saboo is one of the oldest active Pinch Technologists in the world. He has worked with the original team which developed Pinch Technology at ICI, U.K. He has extensive experience in application of Pinch Technology in Processing Plants in India and has conducted Pinch Studies in leading companies such as IPCL, Reliance, Indianoil, Hindustan Petroleum, Hindalco, United Breweries etc.

Ms. Mridul Saboo has carried out an extensive literature survey on Pinch Technology to compile this Paper. She has also carried out a Pinch Study of a Soap and Detergent Plant under the guidance of Dr. Alok Saboo.