HEFAT2011
8th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
11 – 13 July 2011
Pointe Aux Piments, Mauritius

STEAM SYSTEM SYNTHESIS USING PROCESS INTEGRATION TECHNIQUES: A GRAPHICAL APPROACH FOR MULTIPLE STEAM LEVELS

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ABSTRACT

Steam is commonly used as the hot utility in the processing industry. The common method of designing the hot utility heat exchanger network (HEN) is to place all of the heat exchangers in a parallel configuration, and to utilize the latent heat of saturated steam. Recent work has shown how process integration and the use of hot condensate can minimize the flowrate of steam through the hot utility. This leads to debottlenecking of the boiler in retrofit designs, or the ability to purchase a smaller and cheaper boiler in a grassroots design.

The purpose of this work stems from two main observations. Firstly, the work in published literature has been limited largely to only a single steam level. Many plants have more than one level of steam available, especially if a portion of high level steam is used to operate a turbine which produces exhaust steam at a lower level. Secondly, most modern process integration is conducted as a black-box design using mathematical models. Not all engineers who might want to apply these techniques have access to the expensive solvers and computers required to solve these models. The purpose of this study was therefore to develop a graphical technique that will allow one to design a HEN for minimum steam flowrate in the presence of multiple steam levels. This will be useful both as an educational tool, and to enable engineers with limited access to facilities to apply these techniques using basic drawing packages. The methodology used to apply these techniques involves constructing a limiting feasible utility curve of the cold process streams, and then systematically shifting a number of utility lines to fulfill the energy requirements. In an illustrative example of a grassroots design, application of this synthesis method resulted in a 24% reduction in steam flowrate, a 13% reduction in the capital cost of the steam system and an 8% reduction in the energy demanded from the boiler by the process.

INTRODUCTION

Pinch analysis has become a well known term when considering process integration and the design of HENs. Given the steady increase in the cost of energy as well as the cost of process equipment, a great emphasis has been placed on finding techniques to reduce the capital and operating costs of a plant. Pinch analysis is well suited to help optimize processes in order to meet these demands.

In the area of heat integration, pinch analysis was first popularized by Linnhoff and Hindmarsh [1] through process-process heat integration. In their method, heat is transferred from hot process streams to cold process streams in order to reduce the duties of the external hot and cold utilities. Separate composite curves are drawn to represent the hot and the cold process streams. These two curves are shifted closer until at some point they are separated by some predefined minimum driving force for heat transfer ΔT_{min}. This point is then referred to as the pinch point. The area where the two curves overlap indicates where process-process heat integration can be applied, with the two utilities being applied to the remainder of the curves (Figure 1).

NOMENCLATURE

C_p	[kJ/kg·K]	Heat capacity of water
$\dot{m}$	[kg/s]	Steam mass flowrate
T	[°C]	Temperature
Q	[kW]	Duty or heat transferred

Special characters

λ	[kJ/kg]	Latent heat of evaporation

Subscripts

L	Liquid/condensate
s	Supply
SS	Saturated steam
t	Target

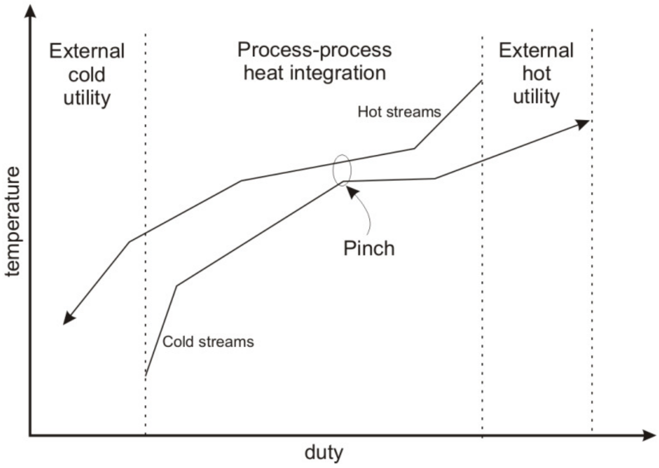

Figure 1 Different regions for the application of heat integration.

More recently, Kim and Smith [2] have applied heat integration to the design of a cooling water system. Their work was inspired by evidence that the efficiency of a cooling tower can be improved by reducing the flowrate of cooling water and increasing the return temperature of the water. They developed a method using pinch analysis whereby cooling water could be reused from one heat exchanger to another. By adding reuse streams to the HEN, the flowrate of cooling water required is reduced. Since the cooling duty remains constant, the return temperature of the water also increases. This in turn raises the efficiency of the cooling tower.

Very little has been done on applying similar concepts to the design of a steam system. Coetzee and Majozi [3] proposed that the flowrate of steam could be minimised by using the sensible heat of the hot condensate to perform some heating. They presented a graphical method of targeting the minimum steam flowrate, but resorted to a mathematical model to synthesize the layout of the HEN and all the reuse streams. Their work was, however, limited to a single level of steam.

Price and Majozi [4-6] developed a number of models that included the boiler in the design procedure, especially the boiler efficiency. Their work aimed to minimise the flowrate of steam while maintaining the boiler efficiency. In their one paper [5], they consider a model that included multiple steam levels, but the result is a rather complicated mixed integer nonlinear programme.

In the context of this paper, the steam system will comprise of the boiler and the associated network of heat exchangers that provide heating. From this point onwards, the “hot utility” will refer exclusively to the steam system. Although other fluids can been used for heating purposes, this work looks only at steam and how the phase change can be exploited. Presented is a graphical method of targeting the minimum steam flowrate, and then designing the layout of the corresponding HEN. The main advantage of the graphical approach is that it gives one insight into the process and allows the designer to be fully involved in the procedure.

PROBLEM STATEMENT

The problem which this synthesis procedure addresses can be stated as follows:

Given

(i) A set of heat exchangers
(ii) The fixed duties of the respective heat exchangers
(iii) The limiting inlet and outlet temperatures of the hot utility passing through each heat exchanger
(iv) The minimum global driving force ΔT_{min} for all the heat exchangers in the system
(v) The thermophysical properties of all the available steam levels from the boiler(s)
(vi) The thermophysical properties and fixed flowrates of all present turbine exhaust streams.

Determine the minimum flowrate of steam required from each steam level and design the layout of the HEN that will achieve this target.

TARGETING THE MINIMUM FLOWRATE

Targeting for a single steam level

The following is a brief description of the method employed by Coetzee and Majozi [3] to graphically target the minimum flowrate of a single level of steam. The very first task is to construct a limiting feasible utility curve. This is accomplished by adding ΔT_{min} to the temperatures in the cold process data set, and constructing what looks like the cold process composite curve shifted up by ΔT_{min}. This creates a feasible boundary, as any utility line that crosses this boundary is in violation of the minimum driving force for heat transfer. It also means that a pinch is easily observed when two lines touch, rather than by judging a gap as in Figure 1. Take note of the direction in which the limiting utility curve is drawn in Figure 2.

The utility line for the steam/condensate is made up of two parts: one horizontal line to represent the latent heat and one slanting line to represent the sensible heat (Figure 2). These two lines are represented respectively by the following two equations

$$Q_{SS} = \dot{m}\,\lambda \tag{1}$$
$$Q_L = \dot{m}\,c_p(T_{SS} - T) \tag{2}$$

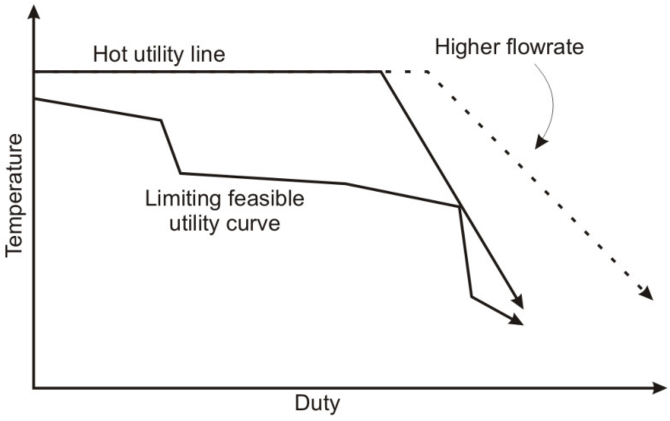

Figure 2 Limiting feasible utility curve and a hot utility line representing one steam level.

As can be seen in Figure 2, increasing the flowrate makes the horizontal line longer and the slanting line less steep.In order to target the minimum steam flowrate, equations (1) and (2) must be combined to give

$$\dot{m} = \frac{Q}{\lambda + c_p(T_{SS} - T)} \tag{3}$$

One begins at the very right hand node of the composite curve, and substitutes the temperature and duty at that point into equation (3). A mass flowrate of steam is calculated and is used to draw a utility line with the help of equations (1) and (2).

Having drawn the utility line, it is inspected for feasibility. If the utility line forms a pinch with the limiting feasible utility curve then the minimum flowrate has been targeted, but if it crosses the composite curve/feasibility boundary at any point, that solution is infeasible. In the event of an infeasible solution, the calculation needs to be repeated using the node immediately to the left of the previously used node until a feasible solution is found. Figure 3 illustrates this concept.

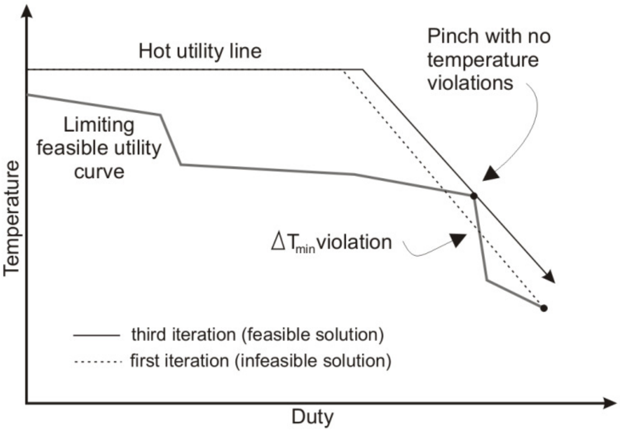

Figure 3 Targeting the minimum steam flowrate. The dots indicate the nodes used in the iterations.

One need not perform many iterations after the utility line has been drawn for the first iteration. The shape of the utility line should give an indication of which node on the limiting feasible utility curve will give the minimum feasible solution.

Targeting for multiple steam levels

One important concept that can be seen from Figure 3 is that the entire composite curve needs to be “covered” by the utility curve to meet the energy demand, while the utility line may not cross the composite curve in the region that it covers. This concept is important when dividing the composite curve between steam levels.

When targeting the minimum flowrate of steam in the presence of multiple levels of steam, one must follow a systematic and hierarchical approach. Lower levels of steam tend to be cheaper, and should be used preferentially. As much use as is possible must be made of the exhaust steam coming out of a turbine. This steam has already served its purpose in the turbine and should be reused for heating before additional steam is taken from the boiler.

Since turbines consume steam at a fixed flowrate dictated by the operating conditions of the turbines, the mass flowrates of these steam levels are known beforehand. The utility lines of these fixed flowrate steam levels can be constructed with the limiting utility curve at the beginning of the procedure (Figure 4).

Starting with the lowest temperature level, the utility line representing the exhaust steam is shifted to the right until its left hand tip just touches the composite curve. If this fixed flowrate hot utility line crosses the composite curve at any point, then it will have to be shifted further to the right until a pinch is formed. Figure 4 shows how a fixed flowrate utility line has been shifted.

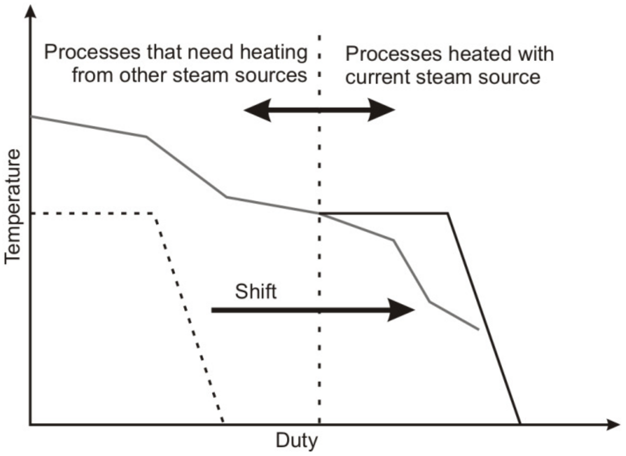

Figure 4 Shifting a fixed flowrate hot utility line to cover part of the process composite curve.

As can be seen from Figure 4, the left hand point of the fixed flowrate creates a division line. The part of the limiting utility curve that is covered by the utility line will be heated with this fixed flowrate steam level, while the section that is not covered will have to be heated by steam at a higher level, be it a higher level of exhaust steam, or steam directly from the boiler.

The section to the right of the division line in Figure 4 has been covered, and is removed from further consideration. Any further fixed flowrate hot utility lines that were drawn in the beginning must also be shifted to cover whatever remains of the composite curve.

The steam coming out the exhaust of a turbine must be condensed before it can return to the boiler, either by using it to heat process streams or with cooling water. It may happen that more energy is available at a given level than can be used. In this case only a portion of the available latent heat is used and the rest must pass through a condenser. One might consider reducing the amount of condensate used from a lower level, shifting that line further to the right and then using more of the available higher level steam (compare Figure 5a with 5b). Given this fact, it is advantageous to shift all the fixed flowrate utility lines simultaneously and to shuffle them around to find an optimum configuration

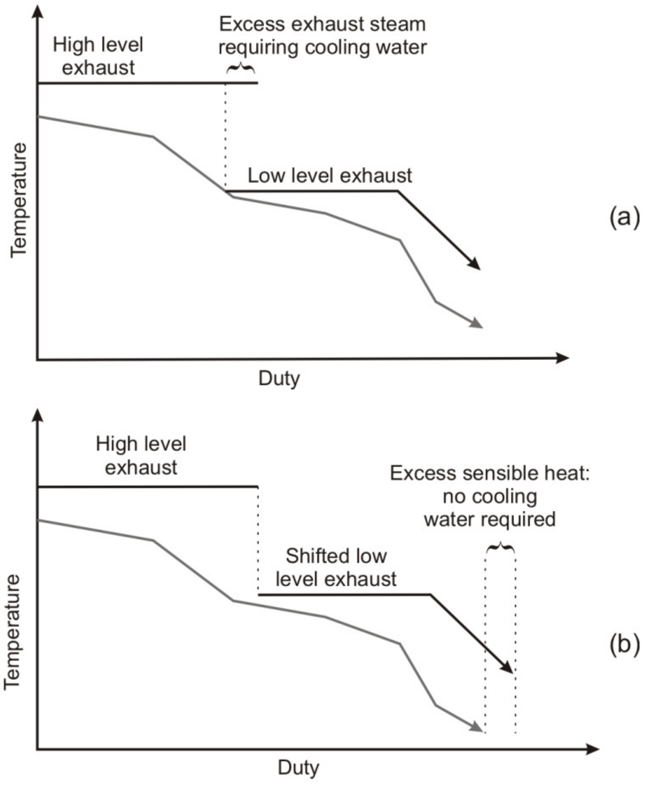

Figure 5 (a) Possibility of having too much steam at a particular level. (b) Shuffling adjacent utility lines to prevent the need for cooling water.

The portion of the limiting feasible utility curve that remains after all of the turbine exhaust streams have been used has to be heated using steam from a boiler. What separates this from the turbine exhaust steam is the fact that the flowrate of steam from the boiler is not limited by the operating conditions of a turbine. The flowrate of the steam is not known initially, and its utility line cannot be drawn and shifted at the beginning of the design process. Each level of steam has to be minimized separately according to the method described above. Each level of steam is assigned its own section of the composite curve to heat, and must be minimized in this section.

The temperatures of the various levels of steam are used to divide the remainder of the limiting feasible utility curve between the steam levels. Each region will be bounded on the left by the temperature of the steam level in question, and on the right by the temperature of the steam level immediately below, as in Figure 6.

By dividing the limiting feasible utility curve in this fashion, one ensures that each level of steam is used only where it is needed without overlapping into an area that could be heated using a lower steam level. In the end, the various utility lines will resemble Figure 7, each one representing the minimum flowrate of that level of steam.

DESIGNING THE NETWORK LAYOUT

The difficulty in designing the layout of the HEN lies in the fact that both vapour and liquid are used as heating media. The point in which the utility line bends indicates where heating crosses from the latent heat of steam to the sensible heat of the condensate. Steam is first fed to a number of heat exchangers where it condenses, and then the hot condensate from this sub-network is sent to another set of heat exchangers that will utilize the sensible heat of the condensate. The heat exchangers utilizing steam are still arranged in a parallel configuration, and the saturated condensate sent to the second set of heat exchangers. The layout of the second set of heat exchangers might require a few series connections or reuse streams. Figure 8 illustrates this concept. It must be noted that a cold process stream might have to pass through more than one heat exchanger, each one heated by a different heating medium.

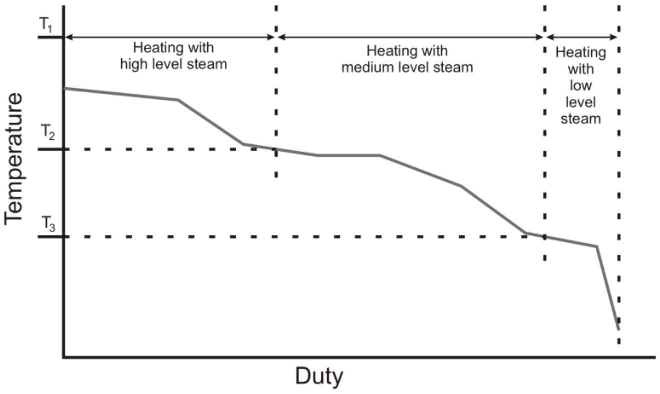

Figure 6 Dividing the limiting feasible utility curve between high level (T_1), medium level (T_2) and low level (T_3) steam.

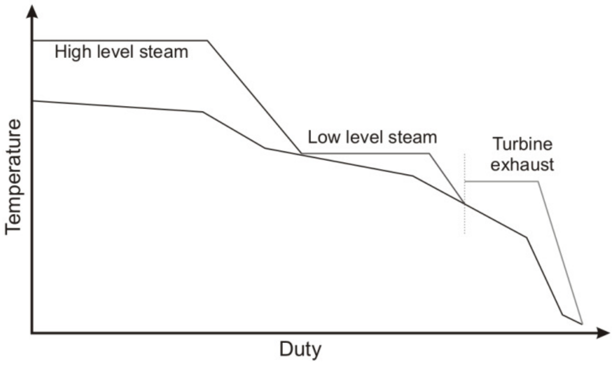

Figure 7 Example of how a limiting feasible utility curve might look after all the steam levels have been minimised.

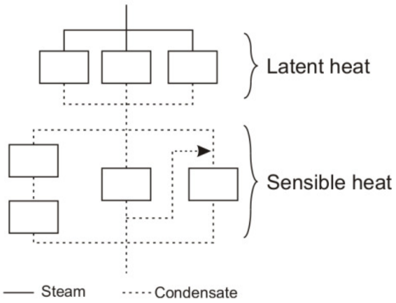

Figure 8 Arrangement of heat exchangers within the HEN

Designing the layout of the latent heat region is simple enough in that all heat exchangers must be placed in the traditional parallel configuration. Designing the reuse streams in the sensible heat region is a little more complicated as some streams need to be combined to ensure the minimum flowrate is met. A mathematical programme is available to determine where to place the reuse streams [3], but for the purposes of this work, a new graphical method is used.

The method by which the configurations of reuse and series connections are synthesized is an adaptation of the "water mains" method developed by Kim and Smith [2] for designing the reuse streams in a cooling water network. The method was adapted for use with hot water, and is used to determine a set of hot water mains that supply the heat exchangers with water at various temperatures. Figure 9 shows a heat exchanger network for four process streams, and illustrates how the water mains method was used to find the position and flowrate of reuse and series connections.

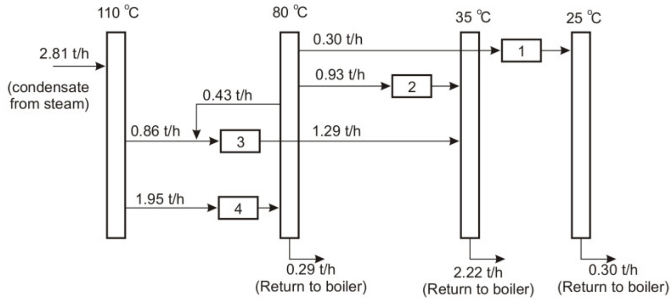

Figure 9 Use of the water mains method to synthesize reuse and series connections.

CASE STUDY

A case study is presented to demonstrate the design procedure and to highlight its benefits. A grassroots design must be created for the hot utility system using multiple steam levels. Table 1 gives the limiting minimum supply and target temperatures of a hot utility, based on the supply and target temperatures of 11 cold process streams. The minimum driving force for heat exchange ΔT_{min} was taken to be 10 °C. A boiler produces steam at 200 °C, part of which will be used to run a small turbine. A stream of exhaust steam is produced at 130 °C with a flowrate of 42.2 tons per hour. The design will first be done in the traditional manner, and then compared with a design for minimum steam flowrate. Steam tables were used for the thermophysical properties of the water and steam.

Table 1: Cold process stream data for case study.

Stream	Limiting utility data (°C)		Duty (kW)
	T_t	T_s	
1	64	106	414
2	174	174	15610
3	135	164	5811
4	89	142	912
5	71	102	358
6	76	76	12923
7	53	106	4312
8	30	154	14239
9	35	78	941
10	106	194	13980
11	64	142	3585

According to the traditional design procedure, all the heat exchangers must be in parallel and fed with steam. Only processes 1, 5, 6, 7 and 9 fall entirely under 130 °C and can be heated with the exhaust steam. Since the exhaust steam has more energy than is required by these cold streams, part of the steam will have to be condensed with cooling water. The remainder of the processes must be heated with steam from the boiler.

Figure 10 shows the final HEN layout. A total of 142.7 t/h of steam has to be produced by the boiler. Furthermore, 6.1 MW of the 79.2 MW of heat coming out of the boiler is lost through the cooling water system.

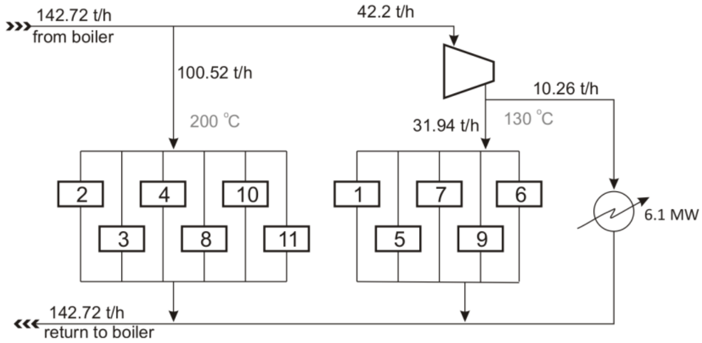

Figure 10 HEN layout for the traditional design.

To begin the new synthesis method, the process data in Table 1 was plotted as a limiting feasible utility curve (Figure 11). The fixed flowrate utility line was drawn and shifted to the right to form a pinch. The flowrate of steam from the boiler was minimised over the portion of the limiting feasible utility curve that still required heating. As can be seen in Figure 11, these two steam levels divide the cold processes between two latent

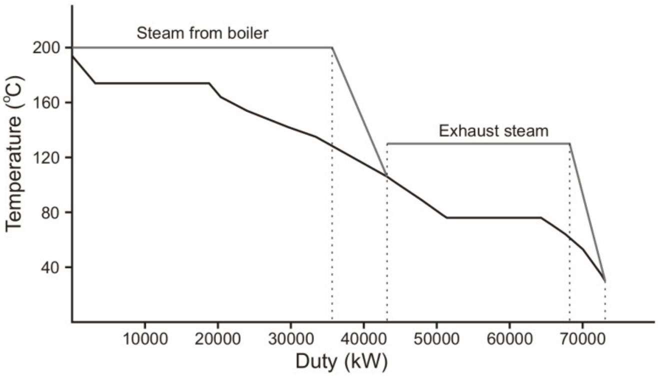

Figure 11 Limiting feasible utility curve and utility lines for new design method

heat networks and two sensible heat networks, each one to be designed separately.

Fortunately in this example, the two sensible heat networks are simple and do not require any special reuse streams. Figure 12 shows the final HEN layout for the process. The flowrate of steam required from the boiler has been reduced to 108.4 t/h, a reduction of 24% in flowrate. It must be noted that some processes stream will have to move sequentially through increasingly hotter process streams. This sequence is shown as subscripts inside the heat exchangers in Figure 12. The energy that was lost through the use of cooing water is now utilized, reducing the energy demand and the boiler by 8% and eliminating the need for cooling water. The reduction in the steam flowrate and the size of the boiler does, however, come at the cost of an additional 10 heat exchangers.

A trade-off is now visible in the new design method. The cost of the boiler is reduced with the reduced flowrate, but the total cost of the HEN is increased. Literature [8] was used to estimate the purchase cost of the boiler and heat exchangers for the year 2006. Table 2 gives the costs in US dollars (US$). Although the cost of purchasing heat exchangers is higher in the new design, the cost of the boiler is much lower. In total, the new design method reduces the capital cost of the steam system by 13%. This is economically feasible.

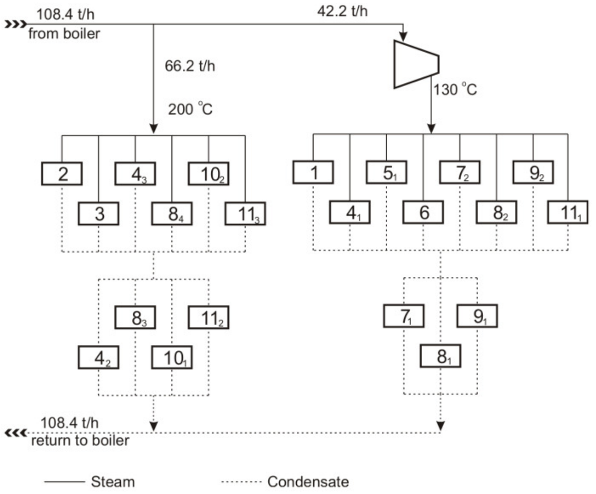

Figure 12 Final HEN layout for the new design procedure. Subscripts in the heat exchangers show the sequence in which the cold streams should pass through.

Table 2 Economic comparison of the old and new designs.

	Traditional design	New design
Boiler cost ($)	2 364 125	1 640 167
HEN cost ($)	581 485	912 792
Total cost ($)	2 945 610	2 552 959

CONCLUSION

A novel graphical technique has been developed to minimize the flowrate of steam through a HEN when multiple levels of steam are available. This is made possible by exploiting the sensible heat of the saturated condensate. Pinch analysis was used to ensure that the minimum steam flowrate was found while maintaining sufficient driving force for heat transfer. This method is an extension of a method created by Coetzee and Majozi [3] for the minimization of a single steam level.

A graphical method was further developed to aid in the synthesis of the networks utilizing sensible heat. These networks are characterised by the occasional use of reuse streams to meet minimum flowrate requirements. By using the concept of imaginary hot water mains, the designer is able to see where reuse streams are needed.

Designing a HEN for minimum steam flowrate by reusing hot condensate has a number of advantages. In an existing plant, the technique can be used to debottleneck the boiler. This will free up steam for use in increased production rates. With a grassroots design, application of this new method will reduce the capital cost of the steam system, and allow for a smaller and more efficient boiler to be purchased. In a plant that uses a portion of its steam to generate power, the new method can reduce the amount of energy that must be dumped into a heat sink. This will reduce the flowrate of cooling water as well as reduce the energy consumption of the boiler.

An example is presented to illustrate the use of the new synthesis method, as well as to demonstrate its advantages. A process with 11 cold streams that required heating was used. A boiler supplied steam for heating, as well as to a power generation turbine. By comparing the new design with the traditional design, it was shown that the flowrate of steam could be reduced by 24%, which reduced the capital cost of the network by 13% and the energy supplied by the boiler by 8%. It was concluded that the new design procedure is economically feasible.

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