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Design of Water and Heat Recovery Networks for the Simultaneous Minimisation of Water and Energy Consumption

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Good process design can be characterised by a number of properties. Amongst the most important are efficient use of raw materials, low capital cost and good operability. In this paper we describe procedures for the design of processes in which water and energy costs form a large part of operating cost. With the properties of good design in mind we propose the following heuristics:

1. water consumption should be minimised
2. best use of temperature driving force should be maintained, so non-isothermal mixing should be avoided
3. where possible, heat recovery should be between streams that are available in the same locality
4. heat exchanger technology appropriate to the required duty should be used
5. the designer should seek to minimise the cost of piping

Capital Cost Considerations for Water Systems

Shell-and-tube heat exchangers are not the appropriate choice for this type of duty. Not only are such units expensive (in relation to other available types) but they usually have multiple tube-passes which, when close temperature approaches are being made, leads to the need for multiple shells in series. For water/water duties plate-and-frame heat exchangers provide an inexpensive alternative. There is a multi-stream option when using such units [Haslego & Polley, 2002]. However, plate-and-frame exchangers are not suitable when the water streams are contaminated with fibres. Under these circumstances spiral exchangers should be used. These units also have a significant cost advantage over shell-and-tube exchangers. Given that plate-and-frame exchangers are relatively inexpensive, the capital cost of water networks is likely to be dominated by the cost of piping.

Example from the Literature

Savulescu et al [2005] have posed a problem, based on a water minimisation problem originally proposed by Wang & Smith [1994], consisting of four operations that have differing contamination constraints and differing operating temperatures (table 1). The water supply temperature is 20 C and waste water must be cooled to 30 C (or, below) before discharge. The concentration pinch is at a water concentration of 100 ppm and the minimum water flow is 90 kg/s. They offer the solution shown in Figure 1. It

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consumes 4265 kW of hot utility whilst rejecting 485 kW of heat to cold utility. Five heat exchangers are used in the system. The system also contains six non-isothermal mixing junctions. The design also appears to involve a lot of piping. Control is an important consideration in virtually all processes. In this example it is reasonable to assume that the operator would want to control both the quantity of water used in an operation and the temperature at which the operation is conducted. Since, in the proposed design local temperatures need to be controlled by flow, it may prove difficult to control all of the process conditions using the proposed structure.

Table 1. Example Problem

Operation	Max.Inlet Concn. ppm	Max Outlet Concn. ppm	Contaminant Load g/s	Operating Temp. C	Limiting flow kg/s
1	0	100	2	40	20
2	50	100	5	100	100
3	50	800	30	75	40
4	400	800	4	50	10

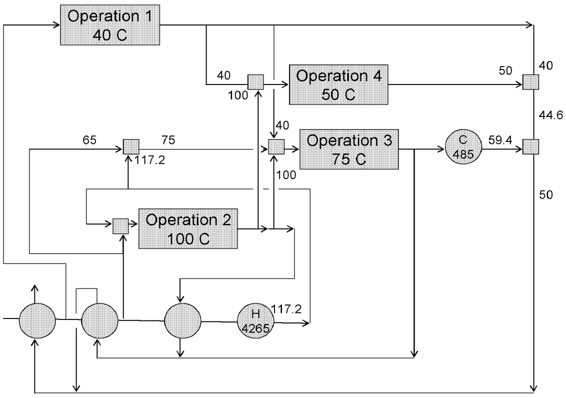

Figure 1. Solution Proposed by Savulescu et al

In Figure 2 we show an alternative solution to the design problem. This design uses 3780 kW of hot utility. This is the minimum possible consumption for a minimum temperature approach of 10 C. Like the design proposed by Savulescu et al, it uses just five heat exchangers. The piping arrangement is considerably simpler. This system is very easy to control. The quantities of water consumed in each operation are controlled in the normal manner (flow control). The temperature at which water is supplied to each operation can be controlled by either deliberate over-sizing of exchangers with operation of a partial bypass around the unit or by adjusting the heat provided to the heaters positioned immediately prior to the operations.

In terms of water distribution, the design shown in Figure 2 is that referred to by Savulescu et al as "water network 1" in their analysis of the problem. These workers developed a "minimum energy" solution to this problem. This solution had three heaters, six heat recovery units and used two stream splits. So, the question is "how can simple systems that utilise both minimum water and minimum energy be derived?"
Where a processes involves the heating of water streams to a variety of temperature levels followed by discharge of that water to the environment the overall energy needs are easily calculated from the water balance. For instance, for a process in which water is not consumed and supply and discharge flows are the same, the energy demand is a function of the water throughput and the difference between discharge and supply temperatures and is given by:

$$Q = Mc_p\left(T_{dis} - T_{\sup ply}\right)$$

Consequently, the energy demand is minimised if the water throughput is minimised. So, the first stage in developing a simple solution is the development of a simple water network. Several methods are available for the design of such networks [e.g. Wang & Smith, 1994, Olesen & Polley, 1997]. For the example problem posed above there are three potential solutions. These are shown in Figures 3 to 6.

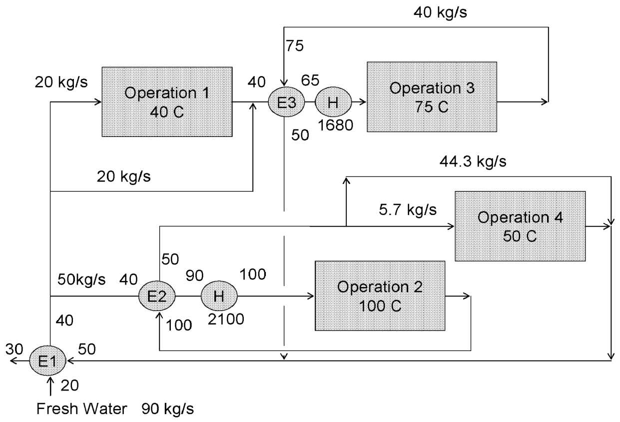

Figure 2. Alternative Solution

Thermodynamic Analysis & Heat Recovery System Design

To apply thermal pinch analysis at this stage would be a mistake (it is what lead to the complex solution offered by Savulescu et al). We need to understand the basic heat balances associated with the problem. We have already seen that for this type of system (only one water source is used and water discharge equals the water supply) ***the minimum energy requirement is given by water flow multiplied by the difference between supply and discharge temperatures.*** But we can extend this understanding. It

applies to all elements of the network that can be separated into an independent system.

Consider design option 1 (Figure 3). This option can be decomposed into two separate systems: a sub-system having operations 1 and 3, a sub-system having operations 2 and 4. The first of these sub-systems consumes 40 kg/s of water. Given a 10 degree difference between supply and discharge temperature, this sub-system will require 1680 kW of hot utility. The second sub-system consumes 50 kg/s of water and will therefore require 2100kW of hot utility. Together the sub-systems require 3 780 kW which equates with the minimum requirement (already identified). Similar analysis can be conducted to the design options shown in Figures 4 and 5 with similar result.

The design of the heat recovery system for such simple independent components is simple and does not require a special methodology. Good operability is achieved if heaters are positioned immediately prior to operations. Simple plant structures are achieved if heat recovery is undertaken "locally".

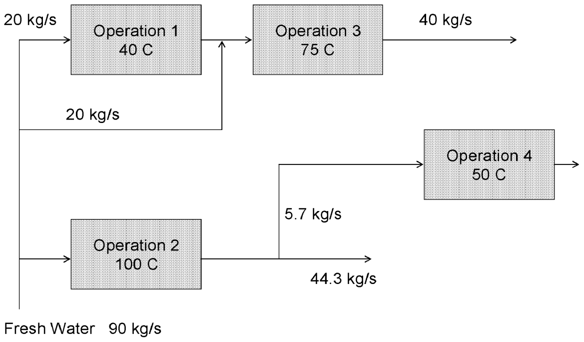

Figure 3. Water Network: Option 1

Returning to option 1, following these guidelines we obtain the heat recovery system illustrated in Figure 6 for the first sub-system and in Figure 7 for sub-system 2. When the two designs are merged together the result is the system shown in Figure 2.

Selection of Options

Examination of the water network options (shown in Figures 3-5) allow us to identify the utility needs for each option, geographical location of operations, and ease and simplicity of design. Selection of best option would be made using a consideration of all of these factors.

Systems with Evaporators

The example considered above relates to a process in which water is being heated and cooled. As such it is typical of processes in the textile and leather industries. The procedures in the present form do not apply to the pulp & paper industry. The problems of this industry have been widely explored by a number of workers (Wising et al, 2005, Nordman & Berntsson, 2006, Savulescu et al, 2008).

Conclusions

The design of water systems that require significant heat input should start with the identification of the minimum water consumption and the structures that achieve this target. The engineer should then seek to identify how these water networks can be broken down into simple self contained components. The design options should then be compared in terms of energy demand, required hot utility, geographical locations and ease of design. The design of individual components should proceed by placing heaters immediately prior to operations and by undertaking heat recovery locally. Non-isothermal mixing of streams should be avoided.

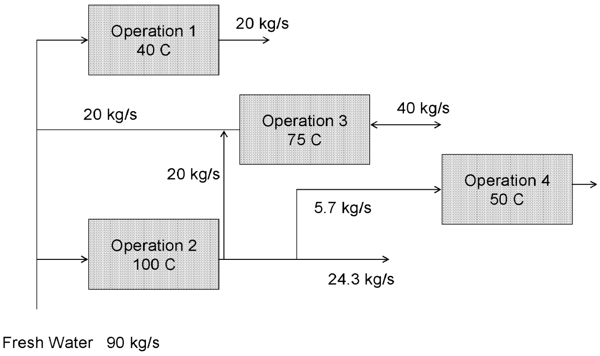

Figure 4. Water Network: Option 2

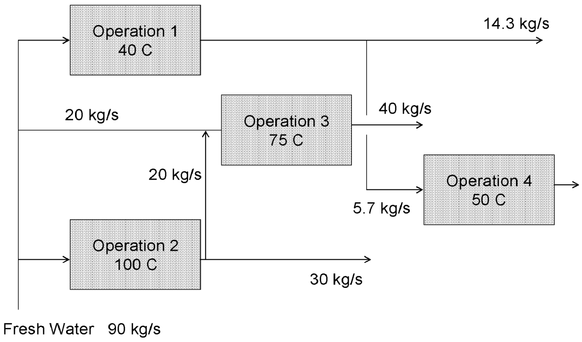

Figure 5. Water Network: Option 3

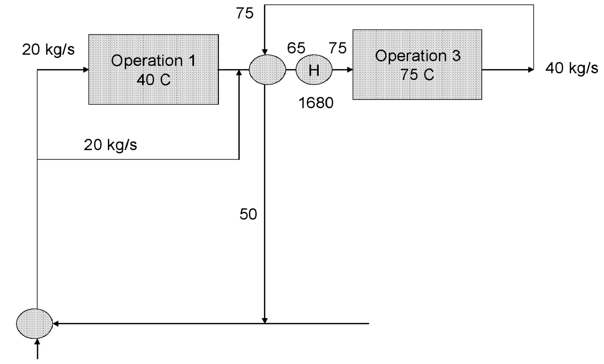

Figure 6. Heat Recovery System for Sub-System 1

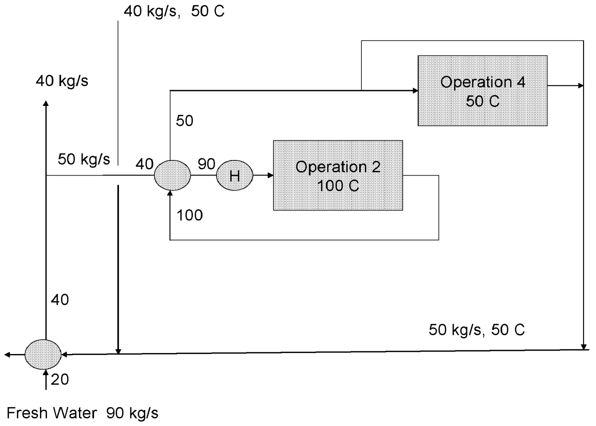

Figure 7. Heat Recovery System for Sub-System 2.

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