WATER PINCH ANALYSIS: A STRATEGIC TOOL FOR WATER MANAGEMENT IN THE FOOD PROCESSING INDUSTRY

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Summary

Water pinch analysis can be used to guide water and effluent management decisions while at the same time improving the efficiency of processes. It can be used for the initial design of the process, or as a tool to guide process modifications due to changing circumstances (financial, process or environmental). The procedure enables the minimum amount of water to be determined by considering the introduction of recycle loops and reuse cascades. It then highlights the operations that should be investigated for the improvement of their internal efficiencies of water management.

Keywords

Waste minimisation, water pinch

INTRODUCTION

The drive in industry is towards environmentally sustainability. To achieve this it is necessary to reduce the environmental impact per unit of money spent by a factor of 10. A reduction in environmental impact of factor 4 is considered achievable using current technology. The balance of the reduction will have to be achieved by changing the attitudes and habits of the population and rethinking the provision of goods and services (Jackson, 1996). Cleaner production is the approach used to achieve this objective. For current processes, the hierarchy of pollution prevention measures is: replace, reduce, recover, reuse, recycle and finally, treat. This approach must be used whenever any waste minimisation options are being contemplated.

Prior to developing or modifying configurations, it is necessary to consider the interactions between the three main factors of a reuse/recycle system, i.e. effluent source, treatment process and reuse process. Water pinch (Wang and Smith, 1994, 1995a, b; Olleson and Polley, 1997), is a convenient tool for the rational analysis of a water network in order to identify bottlenecks, and where recycle/reuse loops should be located. In simple terms, the current water and effluent network should be analysed to determine if the optimal flow configuration is being used. For sufficiently simple systems, a graphical approach can be used, in which the pinch diagram is a plot of stream concentration as a function of mass flow. The pinch diagram is constructed by considering the process requirements or constraints, and not the current effluent flows and qualities. If the optimal network is not being used, then simple measures such as effluent rerouting, cascading and recycling (without any treatment) should be considered. The pinch analysis will also lead to the identification of the pinch point, is the bottleneck in the effluent/water network, and which sets the minimum water requirements for the network of processed. The pinch point might correspond to the quality of the inlet water, the outlet water (final effluent) or some intermediate quality. Once an optimal arrangement has been achieved with existing processes, it will be necessary to modify the processes for any further reduction in the water requirements, so that they are able to use or produce streams of different qualities. Alternatively, additional cleanup processes must be introduced, to modify the quality of the streams so that they will be acceptable to the current processes. The pinch analysis will also reveal the process streams that should be modified (treated). A consequence of the analysis is that streams on either side of the pinch should not be treated and reuse on the same side of the pinch point. Streams should be treated and reused across the pinch point. This emphasises the importance of segregating streams and treating them to a particular reuse standard. Such systematic analysis will also avoid treating too great a flow, or treating a stream to an excessively high standard.

A further consideration, prior to a detailed investigation into reuse/recycling, is to ensure that a total cost accounting procedure is used to evaluate the costs associated with all effluent
streams. It stands to reason that if the accounting procedures are not true and accurate, then the decisions made using financial considerations will also not be true and accurate. For example, if a very inexpensive chemical such as sodium chloride is used as an ion exchange regenerant, the motivation for recovering and reusing it is very low. It is only when it is noted that, for instance, a downstream vessel is suffering from chloride induced stress corrosion, due in part to the chloride load from the ion exchange plant, that the true benefits of reducing sodium chloride consumption become evident. When the savings that accrue due to reduced stress corrosion are offset by the costs associated with the reduction of sodium chloride use, by using nanofiltration for example, then the true financial picture emerges.

**WATERPINCH**

There are four general approaches to water minimisation.

1) **Process changes**
Replacing the technology employed in a process can reduce the inherent demand for water. Examples might be replacing a wet cooling system with air coolers or increasing the number of stages in a washing operation. Sometimes it is possible to reduce water demand by changing the way existing equipment is operated, rather than replacing or modifying it.

2) **Water re-use**
Wastewater from one operation can be directly used in another operation, provided the level of contamination from the previous process does not interfere with the subsequent process. This will reduce overall fresh water and wastewater volumes, but not affect contaminant loads in the overall effluent from the system.

Generally, re-use excludes returning, either directly or indirectly, to operations through which it has already passed, in order to avoid build-up of minor contaminants which have not been considered in the analysis.

3) **Regeneration re-use**
Partial treatment of wastewater can remove contaminants which would otherwise prevent reuse. The regeneration process might be filtration, stream-stripping, carbon adsorption or other such processes. In this case both volumes and contaminant loads will be reduced.

4) **Regeneration recycling**
Recycling refers to the situation where water is re-used in an operation through which it has already passed. In this case, the regeneration step must be capable of removing all contaminants which build up in the system.

**Targeting minimum water**

The water pinch analysis methodology provides a systematic way of applying the above basic techniques to achieve the minimum use of water in a particular system of operations. It should be noted that pinch analysis is only useful for a system of several such operations, it cannot be applied to a single operation.

In principle, the analysis starts from consideration of the water requirements, in terms of quantity and quality, of each process in the system, and these have to be established beforehand. Quality is represented by the concentration of critical contaminants, and the effect of each process on the water it uses is represented by the load of contaminant that is transferred to the water that passes through it. The concept is more easily understood in the context of the design of a new system; using it to reduce water consumption of an existing system brings in some additional considerations.

**New System design**

Limits on the contaminant levels for each process, together with contaminant loads introduced by each process would be established by the designer. From this data, a composite water demand curve can be plotted on concentration/contaminant–load axes (Wang and Smith, 1994), which allows determination of the minimum fresh water supply which is able to satisfy
all the process requirements, using \textit{water re-use only}. This minimum water requirement is called the \textit{target} and the critical process concentration limit which prevents any further reduction of the target is called the \textit{pinch-point}.

Once the pinch point and the target supply have been determined, it is relatively straightforward to design a water re-use cascade which will achieve the target. The resulting network of flows between the operations can then be evaluated in terms of cost, practicability and operability and trade-offs established between water use and other such engineering criteria.

Only at this stage will the use of regeneration processes be considered, and their only justification in the overall scheme will be to \textit{overcome the limitation imposed by the pinch point} so as to further the water supply target. Thus it can be demonstrated that to offer any benefit to the system, a regeneration process must take water of a quality worse than the pinch concentration, and regenerate it to a quality better than the pinch concentration. This is referred to as \textit{appropriate placement} of the regeneration process.

\textit{Modification of an existing system}

Somewhat different considerations apply when using water pinch analysis to improve water use in an existing system.

The first is that flow and concentration data for the various operations will be available as measurements from the existing system rather than design specifications. These will have the advantage of being proven in practice, but the disadvantage that, as they probably come from a non-optimal system, they do not represent genuine limits for the processes. If they are treated as such, it may well happen that the pinch analysis will not be able to come up with significant water savings.

Secondly, unlike the new design which starts from a clean slate, any changes towards a more efficient configuration are likely to incur costs, so it is advantageous to retain as much of the existing equipment and pipework as possible.

Hence, the approach that is usually adopted involves imposing process constraints that reflect the current operation of the system, and determining the re-use network which will achieve minimum water use within those constraints. One of these constraints will constitute a \textit{pseudo-pinch} and, since this constitutes the chief obstacle to achieving lower water use, it will be subject to closer investigation to determine whether it can be relaxed. If it is, the relaxed limit is substituted and the pinch point will probably move to another part of the system, whereupon the process is repeated.

In this way the retro-fit design evolves from the prior configuration of the system along a path which only has to consider the most critical parts of the system. It is probable that this evolution will stop short of achieving the minimum target for the system, at some point where the additional water and effluent savings no longer justify the additional expense of modifications.

Regeneration processes, once again, are not considered until all practicable re-use opportunities have been exhausted, and are only considered with appropriate placement in mind. The same ideas apply to replacing existing equipment: if this is to be justified purely in terms of reducing water consumption, then only equipment which affects the position of the pinch point should be considered.

It should be mentioned that, in a non-optimal system, introducing an inappropriately placed regeneration process, or replacing some water-inefficient equipment may result in overall water savings, however these savings will have been achievable by simple re-use.

\textbf{THE FOOD INDUSTRY}
As may be seen from the above discussion, water pinch analysis is a very general methodology, and it should be applicable to any industry. Adaptation to any particular system chiefly involves dealing with the water quality and quantity limitations for the operations involved. The experience of the authors has been in the chemical industry, and we have no specific understanding of the particular considerations that must be taken into account in food processing. Clearly there will be operation where avoiding contamination is of particular concern. It may be that, for such processes, it would be better to work with risks of contamination in the place of contaminant concentrations, or it may be that such high risk processes should be completely excluded from the analysis, which will then deal only with more peripheral water-using processes.

There has been a proposal to prepare an ILSI monograph, in collaboration with the Water Research Commission, on the application of water pinch analysis in the food industry. The suggested program will investigate two plants to establish a protocol for undertaking such investigations. Once the protocol has been prepared, it would then be based on the experiences drawn from all these investigations. This plan will rely heavily on input from the food industry players.

**CASE STUDY**

With no food industry cases that we can report, the following case study is taken from the agrochemical industry. It was chosen to illustrate that water pinch analysis can be applied to batch processes as well as to continuous processes.

Sanachem is a South African subsidiary of Dow Chemicals, manufacturing insecticides and herbicides. Its KwaZulu-Natal factory is situated about 30km north of Durban. Toxic effluent arises from water used in the production of mono-sodium methyl arsenate (MSMA), alachlor and bromoxynil octanoate. These products are manufactured in batch processes, which typically involve a sequence of several stages in different reactors. The water is used either as a solvent of for product washing. Disposing of these toxic effluents is a major problem, as there is no suitable landfill site in KwaZulu-Natal, and it has to be transported at considerable expense some 800km to Port Elizabeth. Waste-minimisation to reduce the amount of toxic effluent is consequently a topic of considerable interest.

The illustrative example presented here is based on part of the operation at Sanachem, however certain aspects have been simplified for greater clarity of presentation, as well as for commercial confidentiality. We considered the production of an agrochemical which contains three organic components, identified as A, B and C, which are synthesised in batch reactors. All three reactions form NaCl as a by-product, which has to be separated from the main products. In the case of A, the reaction takes place in an organic solvent, so that water is required purely for washing out the salt. For B and C, however, a portion of the required water is used as the reaction solvent, and further quantity is used for washing the product. While investigation this secondary washing of B and C, it was found that the salt load removed from the products was essentially zero, as a result of the extreme immiscibility of the organic and aqueous phases. However, it was considered that the washing step could not be discarded, as it constituted a quality control precaution in case of process glitches. The timing of the reaction and washing sequenced was considered to be fixed by the product requirements: that is, there was no freedom to change the sequence to optimise the use of water.

The term targeting refers to the procedure of determining the minimum possible values of fresh water and effluent for the system as a whole. Wang and Smith (1995b) presented a graphical targeting method. This procedure consists of dividing the problem into concentration intervals and time intervals, with boundaries set by the endpoints of the individual processes, and grouping together the streams that are required or available for reuse in each subinterval. Water which is available is reused, where possible, in its own subinterval. Any surplus can be reused in higher concentration intervals in the same time interval, or stored for reuse in a later time interval; but cannot be used in lower concentration intervals, or for previous times. Any shortfall can be made up from lower concentration intervals, either from the same or previous time intervals, or from fresh water. The eventual
surplus becomes the system effluent, and the accumulated fresh water make up constitutes
the system intake. This procedure identifies what storage must be provided to achieve the
minimum targets; provision of storage can be traded off against water use and effluent
production.

The solution to the problem had two relevant aspects. For the first operational sequence no
effluent is available for re-use and consequently fresh water must be supplied for the early
processes in the sequence, irrespective of concentration considerations. For subsequent
cycles, it is possible to use effluent from previous cycles if provision is made for storage.
Figures 1 and 2 illustrate corresponding water use networks for these two cases.

![Figure 1: Case study – water use network for first production cycle](image1)

![Figure 2: Case study – water use network for subsequent cycles](image2)

During the course of these investigations, an overall reduction of 96kl per month of toxic
effluent, 216kl of non toxic effluent and an increase of 25% in production capacity (due to
reduced batch times) were achieved as a result of the pinch analysis, together with other
waste minimisation measures.

**CONCLUSIONS**

Water recycling and reuse are becoming increasingly important. Cleaner production and
sustainability will become the criteria by which designs are judged. Pinch analysis is a tool
which provides a logical and systematic framework for determining the best allocation of
resources in a process, or system of processes. Thermal pinch analysis has already evolved
into a mature and powerful methodology for dealing with energy resources; water pinch
analysis is a relatively new field, and is evolving rapidly. Although it presents itself as an
engineering design tool, it may also prove valuable as a regulatory tool, particularly in a co-
regulatory context, by providing an objective determination of the water requirements of a
process. Clearly, the fundamental approach must be applicable to resources other than
energy and water, which suggests a fertile field for future development.
At this time there is no practical experience of the application of water pinch analysis in the South African food industry. The proposed ILSI monograph represents an attempt to address this lack, and the authors would like to invite industrial partners to participate in the project.

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