DEVELOPMENT OF NEW SYSTEMATIC TECHNIQUES FOR RETROFIT OF WATER NETWORK

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DEVELOPMENT OF NEW SYSTEMATIC TECHNIQUES FOR RETROFIT OF WATER NETWORK

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To my beloved parents, brother and Derek

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ABSTRACT

Grassroots synthesis of maximum water recovery network based on Pinch Analysis has been rather well established. In contrast, less work has been done on retrofit of water network. There is a clear need to develop procedures to retrofit an existing water network. Four new systematic techniques for retrofit of water network based on Pinch Analysis concept have been developed in this work, i.e. retrofit of water network for mass transfer-based operations; retrofit of water network for non-mass transfer-based operations; retrofit of water network with regeneration unit(s) optimisation; retrofit of water network with the addition of new regeneration unit(s). Retrofit technique for water network with mass transfer-based operations involves two key steps namely utility targeting and network design. During targeting, utility and capital cost targets were determined for a particular capital expenditure. Lastly, the existing network was retrofitted to meet the targets. Retrofit method for non-mass transfer-based operations precludes targeting and only requires retrofit design. A new graphical tool called concentration block diagram (CBD) has been introduced to diagnose, retrofit and evolve the existing water network. The new techniques proposed for retrofit of water network with existing regeneration unit(s) optimisation/ additional new regeneration unit(s) consist of two stages. The first stage locates the various retrofit targets, where utility savings and capital investment were determined for a range of process parameters (i.e. total flowrate and/or outlet concentration of the regeneration unit). Next, the existing water network was re-designed to achieve the chosen targets. Application of the new retrofit techniques on paper mill plants proves that the techniques are both highly interactive as well as viable for implementation.

ABSTRAK

Sintesis asas bagi rangkaian perolehan air yang maksimum berdasarkan Analisis Pinch telah banyak diterokai. Sebaliknya, hanya sedikit kajian yang telah dilakukan terhadap pengubahsuaian rangkaian air. Ini jelas menunjukkan bahawa prosedur pengubahsuaian rangkaian air amat diperlukan. Empat teknik baru yang sistematik bagi pengubahsuaian rangkaian air telah dibangunkan, khususnya, pengubahsuaian rangkaian air bagi operasi yang melibatkan pindah jisim; pengubahsuaian rangkaian air bagi operasi yang tidak melibatkan pindah jisim; pengubahsuaian rangkaian air dengan pengoptimuman unit penjanaan semula; pengubahsuaian rangkaian air dengan penambahan unit penjanaan semula. Teknik pengubahsuaian rangkaian air bagi operasi yang melibatkan pindah jisim melibatkan dua langkah utama iaitu penetapan sasaran dan rekadentuk rangkaian air. Semasa penetapan sasaran, sasaran utility dan kos modal telah diperolehi berdasarkan pelaburan yang tetap. Akhirnya, rangkaian yang sedia ada diubahsuai untuk mencapai sasaran yang ditetapkan. Pengubahsuaian rangkaian air bagi operasi yang tidak melibatkan pindah jisim hanya memerlukan pengubahsuaian rangkaian. Gambar rajah blok kepekatan telah diperkenalkan untuk menganalisis, mengubahsuai dan membangunkan rangkaian air yang sedia ada. Teknik-teknik baru yang dicadangkan bagi pengubahsuaian rangkaian air dengan pengoptimuman unit penjanaan semula/ penambahan unit penjanaan semula melibatkan dua peringkat. Dalam peringkat pertama, beberapa sasaran pengubahsuaian termasuk pengurangan utiliti dan pelaburan telah diperolehi bagi satu lingkungan parameter proses. Seterusnya, rangkaian air yang sedia ada diubahsuai bagi mencapai sasaran yang telah ditetapkan. Penggunaan teknik-teknik pengubahsuaian baru ini ke atas beberapa kajian kes kilang kertas telah membuktikan bahawa teknik-teknik ini adalah amat interaktif dan praktikal untuk dilaksanakan.

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LIST OF SYMBOLS

SYMBOLS

AF - Approach flow

b_j - Intercept of equilibrium line for the j^{th} MSA

C - Contaminant concentration

C_i - Contaminant concentration of source *i*

$C_{max,j}$ - Maximum acceptable concentration of demand *j*

C_n - Contaminant concentration

$C_{PROC,IN}$ - Inlet concentration of process stream

$C_{PROC,OUT}$ - Outlet concentration of process stream

$C_{W,IN}$ - Inlet concentration of water stream

$C_{W,OUT}$ - Outlet concentration of water stream

$(C_{W,IN})_{max}$ - Maximum inlet concentration of water stream

$(C_{W,OUT})_{max}$ - Maximum outlet concentration of water stream

C^{W}_{in} - Inlet concentration of water stream

C^{W}_{out} - Outlet concentration of water stream

CIT - Composite interval table

D - Diameter of a column

DAF - Dissolved air flotation

DIP - De-inking pulper

f - Flowrate

f_c - Total flowrate

F - Flowrate

F_c - Cumulative net water source or demand for a process

$F_{D,j}$ - Total flowrate of demand at each concentration
F_i - Total flowrate available from source i
F_j - Total flowrate required by demand j
$F_{S,i}$ - Total flowrate of source at each concentration
F_{FW} - Total flowrate of fresh water
F_{WW} - Total flowrate of wastewater
G_i - Rich (waste) stream flowrate
h - hour
H - Height of a column
HEN - Heat exchange networks
HENs - Heat exchange networks synthesis
HTU_x - Overall height of transfer units on the lean phase
HTU_y - Overall height of transfer units on the rich phase
i - Source
j - Demand
k - Interval
kg - Kilogram
kmol - Kilo mole
L_j - Lean (waste) stream flowrate
L^{c}_{j} - Maximum flowrate of MSA
M - Mass Load
m_c - Total mass load
m_j - Slope of equilibrium line of component in lean stream j
MSA - Mass separating agents
MEN - Mass exchange networks
MENS - Mass exchange networks synthesis
N_r - Number of real trays
N_R - Number of rich (waste) streams
N_S - Number of lean (MSA) streams
N_{SE} - Number of external MSAs streams
N_{SP} - Number of internal MSAs streams

$N_{unit,pinch}$ - Minimum number of mass exchange units

NAP - Number of actual plate

NTP - Total number of plate

NTU_x - Overall number of transfer units on the lean phase

NTU_y - Overall number of transfer units on the rich phase

$optimum$ - Optimum condition

P - Purity

ppm - Parts per million

R - Set of rich streams

RTD - Retrofit thermodynamic diagram

s - second

S - Set of lean streams

S - Tray spacing

ST - Stream

ton - Tonne

X - Limiting water composition

x^s_j - Supply (inlet) composition of lean (MSA) stream

x^t_j - Target (outlet) composition of lena (MSA) stream

x^*_j - Maximum theoretically attainable composition of the MSA

x_j^{in} - Inlet composition of lean (MSA) stream

x_j^{out} - Outlet composition of lean (MSA) stream

$x_j^{out,*}$ - Maximum theoretically attainable outlet composition of the MSA

yr - Year

y_i - Rich (waste) stream composition

y^s_i - Supply (inlet) composition of rich (waste) stream

y^t_i - Target (outlet) composition of rich (waste) stream

y_i^{in} - Inlet composition of rich (waste) stream

y_j^{out} - Outlet composition of rich (waste) stream

$y^{int}_{existing}$ - Intermediate composition of the rich stream leaving the existing column

y^{int}_{new} - Intermediate composition of the rich stream leaving the new column

y^{out}_{MEN} - Outlet composition of mass exchange network

GREEK LETTERS

α - Total efficiency

u - Velocity

? - Density

w - Trade off composition difference

e - Minimum allowable composition difference

h_o - Overall exchanger efficiency

h_y - Stage efficiency for the rich phase

? - Difference

$\sum$ - Summation

SUBSCRIPTS

D - Water demand

existing - Existing column

i - Rich (waste) stream

IN - Inlet

j - Lean (MSA) stream

l - liquid

max - Maximum

Mass Load - Total mass load accumulated

MEN - Mass exchange networks

new - New column
o - Initial
OUT - Outlet
PROC - Process
R - Rich streams
Regen - Regeneration
S - Water demand
S - Lean streams
SE - External MSA streams
SR - Internal MSA streams
Stages - Number of stages in a column
v - vapour
W - Water
x - Lean phase
y - Rich phase

SUPERSCRIPTS

c - Maximum
in - Inlet
int - Intermediate
NTP - Total number of plate
out - Outlet
s - Supply
t - Target
W - Water

CHAPTER 1

INTRODUCTION

1.1 Problem background

Water is largely taken for granted as it is perceived as the most widely occurring substance in the Earth. It is reported that 2.5 % of world water is freshwater while the rest is salt. However, only 0.3 % of the world's freshwater is available in rivers or lake. Almost all the rest is held up by icecaps and glaciers or buried deep in underground aquifers (Figure 1.1) (Shiklomanov, 1999).

Global freshwater consumption raised six fold between 1990 and 1995, which is more than twice the rate of population growth. Thus, about one-third of the world's population already lives in countries with moderate to high water stress (UNEP, 1999). Current predictions are that by 2050 at least one in four people is likely to live in countries affected by chronic or recurring shortages of freshwater (World Water Assessment Programme, WWAP, 2000).

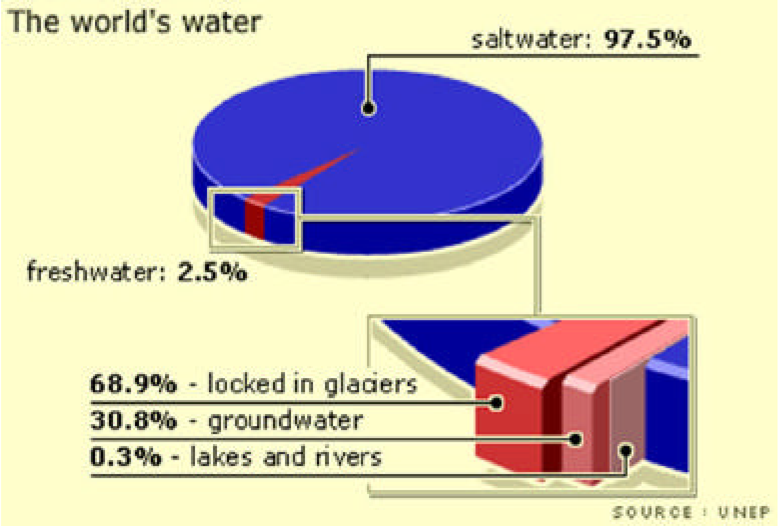

Figure 1.1: The water resources of earth (Shiklomanov, 1999)

Demands for water come not only from the need to drink and the need to deal with waste. The primary consumers of water include industry as well as agriculture sectors (Figure 1.2). Consequently, water pollution created from these demands has significantly contributed towards the scarcity of freshwater in the world. About two million tons of waste is dumped everyday into rivers, lakes and streams, with one litre of wastes sufficient to pollute about eight litre of water (WWAP, 2000).

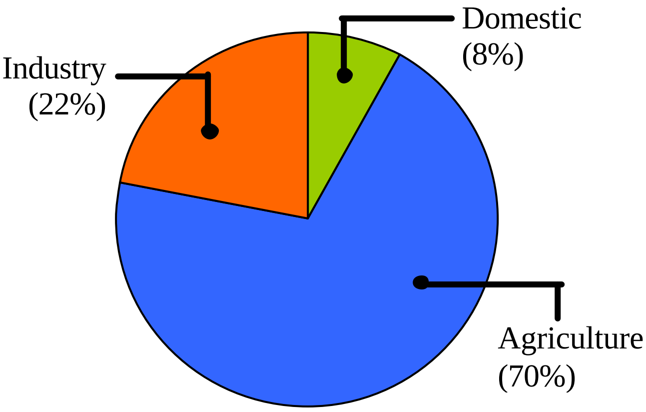

Figure 1.2: Global water use (UNEP, 1999)

UNEP has also stated that industrial wastes are significant sources of water pollution. Industrial wastes often give rise to contaminant with heavy metals and persistent organic compounds. Some 300-500 million tons of heavy metals, solvent, toxic sludge and other wastes accumulate each year from industry (United Nations

Industrial Development Organisation, UNIDO, 1998). Figure 1.3 shows the global estimates of emissions of organic water pollutants by different industry sector (World Bank, 2001). A study of 15 Japanese cities showed that 30 % of all groundwater supplies are contaminated by chlorinated solvents from industry. In some cases, the solvents from spills travelled as far as 10 km from the source of pollution. As a result, strict enforcement of environmental regulations has been carried out to minimise the water pollution.

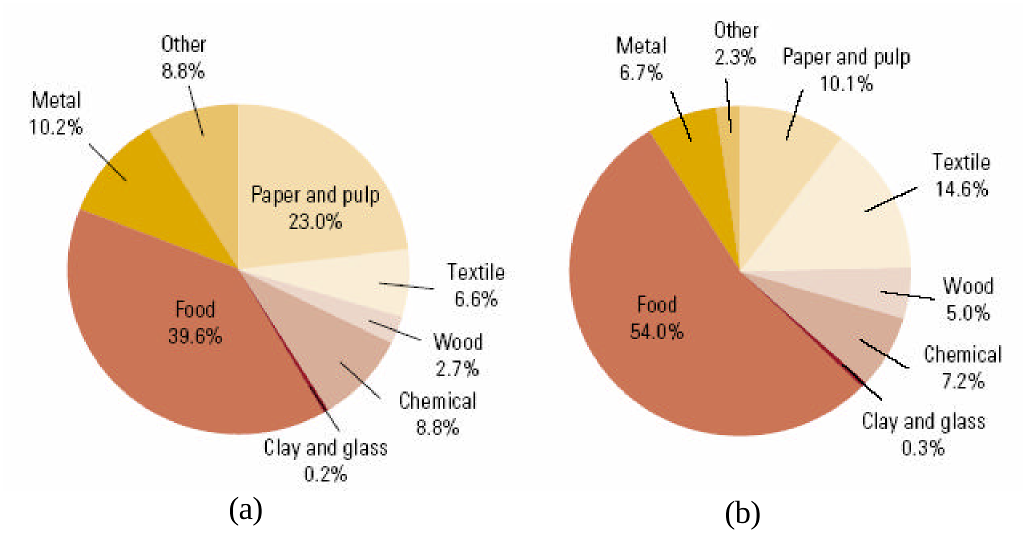

Figure 1.3: Contributions of main industrial sectors to the production of organic water pollutants (a) high-income countries (b) low-income countries

In most countries, industrial water tariff has been increasing from time to time. One of the main reasons that causes this is the current inflation level, which resulted in higher chemical cost, labour cost and construction cost. Besides, the need for more advanced wastewater treatment techniques with higher wastewater treatment costs to treat highly polluted water has also become one of the driving forces towards water tariff increment. The need to fund addition of water utility to meet rising demand for clean fresh water has also causes water supply companies to increase the water tariff.

Therefore, rising cost of industrial freshwater and stringent environmental regulations have been functional to reduce the water requirement from the industry. Thus, it became necessary for the industries to look for better water management system to reduce their freshwater consumption and wastewater generation. To solve this problem, many companies have applied the systematic technique based on water pinch analysis (WPA) through efficient water utilisation.

Our experience and analysis have shown that WPA is well suited for grassroots design but has limitations when applied to existing processes. This is mainly caused by the existence of numerous constraints and problems related to the operability of an existing plant. Consequently, there is a need of new systematic techniques for retrofit of water network.

1.2 The Water Management Hierarchy

It is quite common to find the environmental issue considered during the last stage of process design. Wastewater produced often goes through the *end-of-pipe* treatment where wastewater is treated with treatment processes such as biological treatment, filtration, membranes, etc. to a form suitable for discharged to the environment.

Over the past decade, water minimisation through WPA has become an important issue in the chemical process industries to achieve optimum water utility network. This approach does achieve beneficial goals such as reducing the water utility, bigger process throughput, lower capital and operating costs as well as improving the public perception towards the company.

To obtain the optimum water utility design for a water network, Manan *et al.*, (2004b) established a hierarchical approach for fresh water conservation called *ZM water management hierarchy* (Figure 1.4). This is a general guideline for fresh water conservation. The hierarchy consists of five levels, namely source elimination, source reduction, direct reuse, reclamation, and discharge after treatment. Each level represents various water management options. The levels are arranged in order of preference, from the most preferred option at the top of the hierarchy (level 1) to the least preferred at the bottom (level 5). Water minimisation is concerned with the first to the fourth level of the hierarchy.

Source elimination and source reduction at the top of the hierarchy is concerned with the complete avoidance of fresh water usage. When it is not possible to eliminate or reduce fresh water at source, wastewater recycling and regeneration should be considered. Discharge after treatment should only be considered when wastewater cannot be recycled. Through the ZM water management hierarchy, the end-of-pipe treatment may not be eliminated, but it will become economically legitimate.

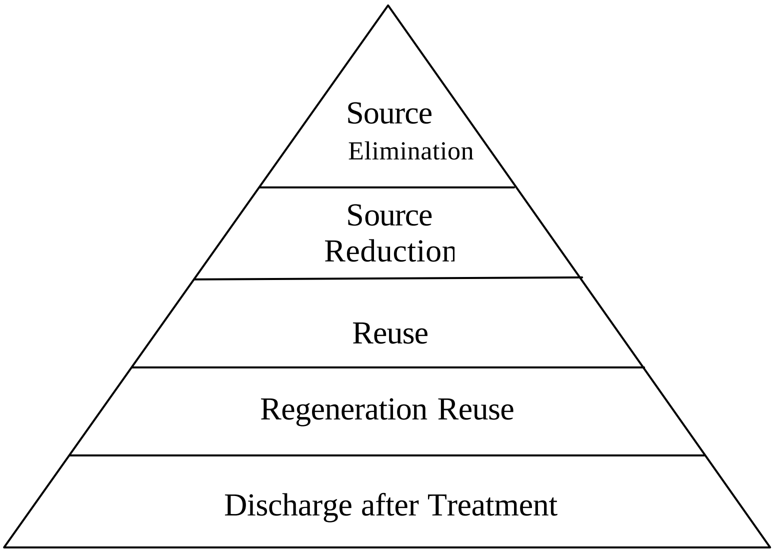

Figure 1.4: A holistic approach for water minimisation through the ZM Water Management Hierarchy (Manan *et al.*, 2004b)

1.3 Problem Statement

Water is used in the process industry for a wide range of applications. Increased cost of wastewater treatment and rising demand for high quality industrial water have created a pressing need for efficient water utilisation and wastewater reuse. The synthesis of optimal water utilisation networks has dealt with grass-root design, where the emphasis is on the minimisation of raw water and maximisation of water reuse and regeneration. To date, very little has been accomplished on the use of heuristic techniques for the retrofit of existing water network in contrast to the work done on grassroots designs. There is a clear need to develop systematic techniques for water network retrofit with and without regeneration to help achieve water savings for existing processes.

The water network retrofit problem is summarised as follows:

> Given a set of mass transfer-based and/or non-mass transfer-based water-using processes, with/without a set of treatment processes, it is desired to perform retrofit synthesis on the existing water network with/without integration of new treatment process(es) or optimisation of existing treatment process(es). The various streams in the process are re-structured to simultaneously accomplish the best savings in operating costs, subject to a minimum payback period or/and maximum capital expenditure.

1.4 Objective

The main objective of this research is to develop new systematic techniques for the retrofit of water network with and without regeneration that includes utility targeting and/or network design.

1.5 Scope of Research

The scopes of this work include:

- Analysis of the state-of-art technique
  It involved analysis of the previous approach for retrofit, their advantages and disadvantages and the improvements required.

- Development of retrofit targeting techniques
  Three new systematic targeting techniques for water network with and/or without regeneration have been established. These procedures are used according to different types of water network. Capital and operating costs as well as piping cost estimations are taken into consideration in these targeting procedures.

- Establishment of retrofit design procedure
  A systematic retrofit design methodology has been introduced to meet the retrofit targets. This methodology is also applicable for cases without retrofit targeting procedure.

1.6 Research Contributions

The main contributions of this research are summarised as follows:

i. As far as it can be found in the literature, this is the first work on the Water Cascade Analysis (WCA)-based water network retrofit synthesis. The basic concept of pinch analysis for heat exchange network, mass exchange network and water network are the basic of this work.

ii. A new systematic retrofit technique for water network with mass transfer-based operations involving two key steps namely utility (water) targeting and network design has been established. In the targeting stage, fresh water and wastewater targets, and capital cost targets were determined for a particular capital expenditure. Lastly the existing network was retrofitted to meet the targets.

iii. A new systematic retrofit design methodology for non-mass transfer-based operations has been established. A new graphical tool called concentration block diagram (CBD) has been introduced to diagnose, retrofit and evolve the existing water network.

iv. A new two-stage systematic technique for the retrofit of water network with existing regeneration unit(s) optimisation has been developed. The first stage of the retrofit task was to locate the various retrofit targets, where utility savings and capital investment were determined for a range of process parameters (flowrate increment or outlet concentration reduction of the existing regeneration unit). Next, the existing water network was re-designed to achieve the chosen targets.

v. A new systematic retrofit methodology, which incorporates new regeneration unit(s) into water network retrofit has been developed. In the targeting stage, retrofit targets (utility savings and capital investment) were determined for a range of process parameters (total flowrate and/or outlet concentration of the new regeneration unit) to obtain a savings versus investment curve. Lastly the existing network was retrofitted to meet the targets.

1.7 Summary of This Thesis

In this thesis, a set of new systematic targeting and design techniques for the retrofit of water network have been developed. The basic concept of pinch technology utilised for retrofit of heat integration and mass integration has been extended to retrofit of water network.

Chapter 2 provides a review of the relevant theories of this thesis related to the development in pinch technology for heat exchange network, mass exchange network and water network.

A review of the relevant literatures of this thesis is provided in Chapter 3. The development of pinch technology for heat exchange network, mass exchange network and water network are reviewed. Mathematical approaches for heat integration are also covered in these chapters.

Chapter 4 gives an overview of the new retrofit methodologies for water network developed in this work. Two new methods for retrofit water network are discussed. These involve retrofit with mass transfer-based and of non-mass transfer-based operations. Retrofit targeting and design procedure for water network with mass transfer-based operations, which includes capital and operating costs constraints are presented. For water network with non-mass transfer-based operations, only network design is described since no equipment investment other than those for pipework modifications is usually required during retrofit.

The methodologies for water network retrofit with optimisation of existing regeneration units and addition of new regeneration units are also discussed in Chapter 4. During retrofit targeting, various retrofit alternatives based on the different combinations of constraints to establish the optimum retrofit targets are examined. To achieve the targets, retrofit design is then conducted.

The detailed methodologies for retrofit of water network as well as the analysis and discussions of the results of applying the systematic retrofit techniques on different case studies are presented in Chapter 5.

Chapter 6 concluded the thesis by summarising the main points and contributions discussed and exploring the potential area for future development for water network retrofit.

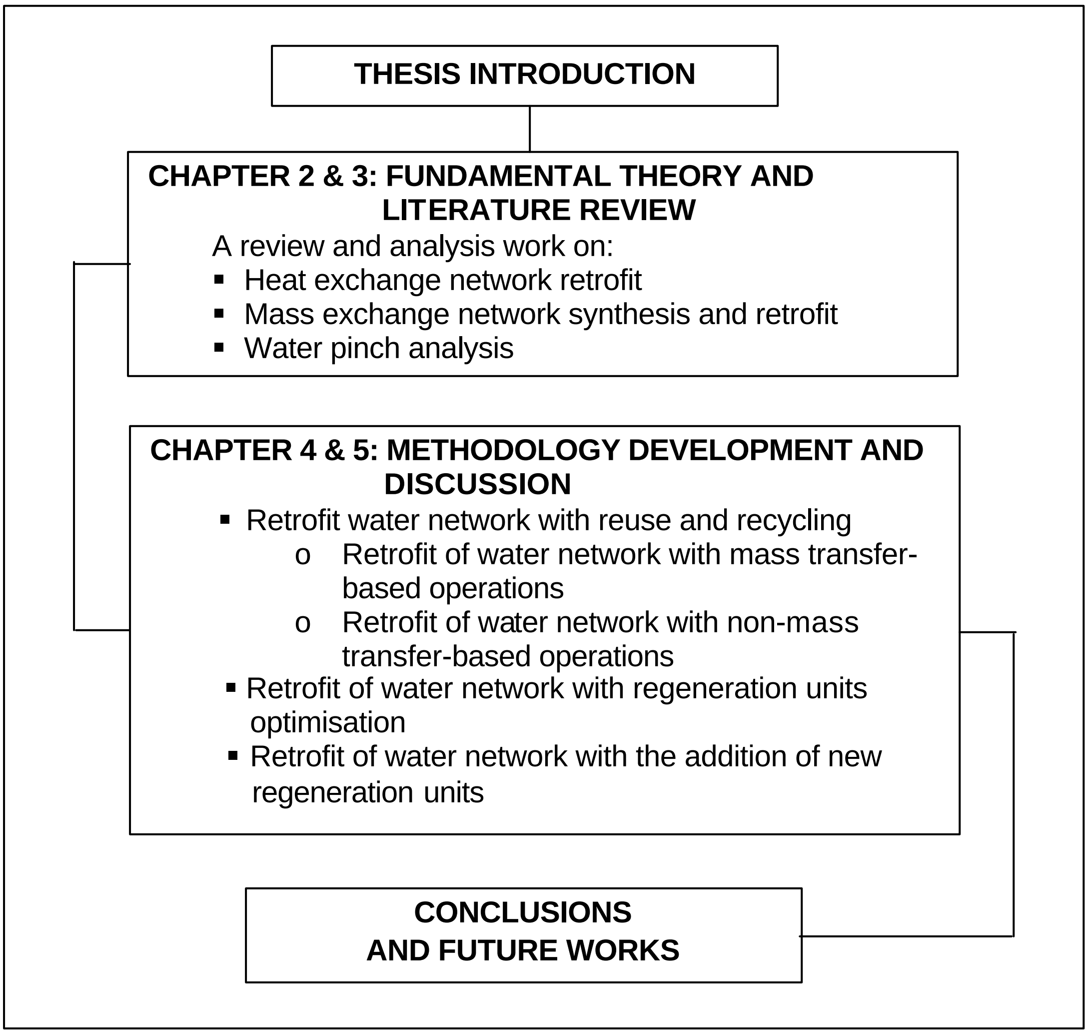

Figure 1.5: A flow diagram illustrating the conceptual link between the chapters

REFERENCES

Ahmad, S. and Polley, G. T. (1990). Debottlenecking of Heat Exchange Networks. *Heat Recovery Systems & CHP*. 10 (4): 369-385.

Alfadala, H. E., Sunol, A. K. and El-Halwagi, M.M. (2001). An Integrated Approach to the Retrofitting of Mass Exchange Networks. *Clean Product and Process* 2. 236-247.

Alva-Argáez, A., Kokossis, A. C. and Smith, R. (1998). Wastewater Minimisation of Industrial Systems Using An Integrated Approach. *Computers and Chemical Engineering*, 22: S741-744.

Arundel, J. (2000) *Sewage and Industrial Effluent Treatment.* 2nd ed. Great Britain: Blackwell Science.

Asante, N. D. K. and Zhu X. X. (1997). An Automated and Interactive Approach for Heat Exchanger Network Retrofit. *TransIChemE.* 75(A): 349-359.

Bagajewicz, M. and Savelski, M. (2001). On the Use of Linear Models for the Design of Water Utilization Systems in Process Plants with A Single Contaminant. *Transactions of the Institute of Chemical Engineers*, Part A, 79: 600-610.

Benko, N., Rév, E., and Fonyó Z. (2000). The Use of Nonlinear Programming to Optimal Water Allocation. *Chemical Engineering Communication*, 178: 67-101.

Briones, V. and Kokossis, A. (1996). A New Approach for the Optimal Retrofit of Heat Exchanger Networks. *Com. Chem. Eng.* 20: S43-S48.

Briones, V. and Kokossis, A. (1999). Hypertargets: A Conceptual Programming Approach for the Optimisation of Industrial Heat Exchanger Networks – II. Retrofit Design. *Chemical Engineering Science.* 54: 541-561.

Byers, W., W. Doerr, R. Krishnan, and D. Peters (1995) How to Implement Industrial Water Reuse: A Systematic Approach, Center for Waste Reduction Technologies (CWRT), American Institute of Chemical Engineers (AIChE), New York.

Carlsson, A., Franck, P. A. and Berntsson, T. (1993). Design Better Heat Exchanger Network Retrofit. *Chem. Eng. Sci*. 54: 541-561.

Castro, P., Matos, H., Fernandes, M. C., Nunes, C. P. (1999). Improvements for Mass-exchange Networks Design. *Chemical Engineering Science*, 54: 1649-1665.

Ciric, A. R. and Floudas, C. A. (1989). A Retrofit Approach for Heat Exchanger Networks. *Com. Chem. Eng.* 13 (6): 703-715.

Coulson, J. M., Richardson, J. F. and Sinnott, R. K. (1993). *Chemical Engineering. Vol. 6*, 2nd ed. U. K.: Pergamon Press.

Dhole, V. R., Ramachandi, N., Tainsh, R. A. and Wasileski, M. (1996). Make Your Process Water Pay for Itself. *Chem. Eng*. 103 (1): 100-103.

Dunn, R. F., and Wenzel, H. (2001). Process Integration Design Methods for Water Conservation and Wastewater Reduction in Industry. Part 1: Design for Single Contaminant. *Cleaner Production Processes,* 3: 307-318.

Eckenfelder, W. W. (2000). *Industrial Water and Pollution Control.* 3rd ed. New York: McGraw Hill.

El-Halwagi, M. M. (1997). Pollution Prevention through Process Integration: Systematic Design Tools. San Diego: Academic Press.

El-Halwagi, M. M. and Manousiouthakis, V. (1989). Synthesis of Mass Exchange Networks. *AIChE Journal.* 35 (8). 1233-1244.

El-Halwagi, M. M. and Manousiouthakis, V. (1990a). Automatic Synthesis of Mass Exchange Networks with Single Component Targets. *Chemical Engineering Science*. 45 (9). 2813-2831.

El-Halwagi, M. M. and Manousiouthakis, V. (1990b). Simultaneous Synthesis of Mass Exchange and Regeneration Networks. *AIChE Journal*. 36 (8). 1209-1219.

El-Halwagi, M. M. and Srinivas, B. K. (1992). Synthesis of Reactive Mass Exchange Networks. *Chemical Engineering Science*. 47 (8): 2113-2119.

Feng, X. and Chu, K. H. (2004). Cost Optimisation of Industrial Wastewater Reuse Systems. *Trans IChemE, Part B, Process Safety and Environment Protection*. 82 (B3): 249-255.

Feng, X. and Seider, W. D. (2001). New Structure and Design Method for Water Networks. *Industrial and Engineering Chemistry Research*. 40: 6140-6146.

Fraser, D. N. and Halale, N. (2000). Retrofit of Mass Exchange Network Using Pinch Technology. *AIChE Journal*. 46 (10): 2112-2117.

Hallale, N. (1998). *Capital Cost Targets for the Optimum Synthesis of Mass Exchange Networks*. Department of Chemical Engineering, University of Cape Town, South Africa: PhD Thesis.

Hallale, N. (2002). A New Graphical Targeting Method for Water Minimisation. *Advances in Environmental Research*. 6 (3): 377-390.

Hallale, N. and Fraser, D.M. (1998). Capital Cost Targets for Mass Exchange Networks A Special Case: Water Minimisation. *Chemical Engineering Science*. 53 (2): 293-313.

Huang, C.-H., Chang, C.-T., Ling, H.-C., and Chang, C.-C. (1999). A Mathematical Programming Model for Water Usage and Treatment Network Design. *Industrial and Engineering Chemistry Research*, 38: 2666-2679.

Intelligen, Inc. (1991). *SuperPro Designer*® (Academic Site Ed.). Version 5, Build 9.

Jacob, J., Kaipe, H. Couderc, F., and Paris, J. (2002). Water Network Analysis in Pulp and Paper Processes by Pinch and Linear Programming Techniques. *Chemical Engineering Communication*. 189(2): 184-206.

Jödicke, G., Fisher, U., and Hungerbühler, K. (2001). Wastewater Reuse: A New Approach to Screen for Designs with Minimal Total Costs. *Computer and Chemical Engineering*. 25: 203-215.

Koppol, A.P.R., Bagajewicz, M.J., Dericks, B.J., and Savelski, M.J. (2003). On Zero Water Discharge Solutions in the Process Industry. *Advances in Environmental Research*. 8: 151-171.

Kuo, W. C. J., Smith, R. (1998). Design of Water-using Systems Involving Regeneration. *Transactions of the Institute of Chemical Engineers*. Part B, 76: 94-114.

Linnhoff, B., Townsend, D. W., Boland, D., Hewitt, G. F., Thomas, B. E. A., Guy, A. R. and Marshall, R. H. (1982). *A User Guide on Process Integration for the Efficient Use of Energy*. Rugby: IChemE.

Manan, Z. A., Foo, D. C. Y., Tan, Y. L. (2004a). Targeting the Minimum Water Flowrate Using Water Cascade Analysis Technique, *AIChE Journal*. 50(12): 3169-3183.

Manan, Z. A., Ooi, B. L., Lin, F. Y. and Foo, C. Y. (2003). Heat-MATRIX – A Computer Software For The Reduction Of Energy And Water In Process Plants. *31st Int. Exhibition of Invention, New Techniques and Products of Geneva*, Switzerland.

Manan, Z. A., Wan Alwi, S. R. and Ujang, Z. (2004b). Water Pinch Analysis for Urban Systems: A Paradigm for Water Minimisation. Water 21 (to be published in February 2005).

Mann, J. G. and Liu, Y. A. (1999). *Industrial Water Reuse and Wastewater Minimisation*. New York: McGraw-Hill.

Marcone, L. S. and Roger, J. Z. (2000). Retrofit of Pressure Drop Constrained Heat Exchanger Networks. *Applied Thermal Engineering*. 20: 1469-1480.

Nie X.R. and Zhu, X. X. (1999). Heat Exchanger Network Retrofit Considering Pressure Drop and Heat-Transfer Enhancement. *AIChE Journal*. 45 (6): 1239-1254.

Olesen, S. G., Polley, G. T. (1997). A Simple Methodology for the Design of Water Networks Handling Single Contaminants. *Transactions of the Institute of Chemical Engineers*. Part A, 75: 420-426.

Papalexandri, K. P., Pistikopoulos, E. N. and Floudas, A. (1994). Mass Exchange Networks for Waste Minimisation: A Simultaneous Approach. *TransIChemE*. 72: 279-294.

Parthasarathy, G., and Krishnagopalan, G. (2001). Systematic Reallocation of Aqueous Resources Using Mass Integration in A Typical Pulp Mill. *Advances in Environmental Research*. 5: 61-79.

Perry, R. H., and Green, D.W. (1997) *Perry's Chemical Engineer's Handbook*. 7th ed. New York: McGraw Hill.

Peter, M. S., and Timmerhaus, K.D. (1980). *Plant Design and Economics for Chemical Engineers*. 3rd. ed. New York: McGraw Hill.

Polley, G. T. and Heggs, P. J. (1999). Don't Let the Pinch Pinch You. *Chem. Eng. Prog.* December. 35-45.

Polley, G. T. and Majid A. (2000). Don't Let the Retrofit Pinch You. *Chem. Eng. Prog.* November. 43-48.

Polley, G. T. and Panjeh S. (1990). Process Integration Retrofit subject to Pressure Drop Constraint. Bussemaker, H. Th. and Iedema, P. D. ed. *Computer Application in Chemical Engineering*. May 7-9. The Hague, The Netherlands: Elsevier, 31-36.

Polley, G. T. Polley, H.L. (2000). Design Better Water Networks. *Chemical Engineering Progress*. 96: 47-52.

Polley, G. T., Van Reisen, J. L. B. and Verjeijen, P. J. T. (1998). Structural Trageting for Heat Integration Retrofit. *Applied Thermal Engineering*. 18 (5): 283-294.

Prakash, R. and Shenoy, U. V. (2005). Targeting and Design of Water Network for Fixed Flowrate and Fixed Contaminant Load Operations. *Chemical Engineering Science*. 60(1): 255-268.

Ramachandran, L. and Rene B. (1996). A Novel Visualization Tool for Heat Exchanger Network Retrofit. *Ind. Eng. Chem. Res.* 35: 4507-4522.

Reisen, V. J., Grievink, P. J. T. and Polley, G. T. (1995). The Placement of Two-stream and Multi-stream Heat Exchangers in an Existing Network through Path Analysis. *Com. Chem. Eng.* 19: S143-S148.

Rousseau, R. W. ed (1987). Handbook of Separation Process Technology. New York: John Wiley and Sons.

Saboo, A. K, Morari, M. And Colberg R. D. (1986). RESHEX: An Interactive Software Package for the Synthesis and Analysis of Resilient Heat Exchange Networks – I Programme Description and Application. *Computer and Chemical Engineering*. 10: 577-589.

Savelski, M., and Bagajewicz, M. (2001). Algorithmic Procedure to Design Water Utilization Systems Featuring A Single Contaminant in Process Plants. *Chemical Engineering Science*. 56: 1897-1911.

Shenoy, U. V. (1995) *Heat Exchanger Network Synthesis: Process Optimization by Energy and Resource Analysis*. Houston Gulf: Publishing Co.

Shiklomanov, I. A. (1999) State Hydrological Institute (SHI, St Peterburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris).

Silangwa, M. (1986) *Evaluation of Various Surface Area Efficiency Criteria in Heat Exchanger Network Retrofits*. University of Manchester Institute of Science and Technology: M.Sc. Dissertation.

Smith, R. (1995). *Chemical Process Design*. New York: McGraw Hill.

Sorin, M. and Bedard, S. (1999). The Global Pinch Point in Water Reuse Network. *TransIChemE.* 77 (B): 305-308.

Takama, N., Kuriyama, T., Shiroko, K., Umeda, T. (1980). Optimal Water Allocation in A Petroleum Refinery. *Computers and Chemical Engineering*. 4: 251-258.

Tan, Y. L, and Manan, Z. A. (2003). Retrofit of Water Network in a Paper Making Process based on Pinch Analysis Technique. *17th Symposium of Malaysia Chemical Engineers (SOMChE 2003).* December 29-30. Penang: Universiti Sains Malaysia, 61-66.

Tan, Y.L. and Manan, Z.A. (2004). Retrofit of Water Network for Mass Transfer based Processes, *18th Symposium of Malaysia Chemical Engineers (SOMChE 2004)*. December 13-14. Perak: Universiti Teknologi PETRONAS, 6:33-39.

Tan, Y. L., Manan Z. A., Foo, C. Y. (2002), Water Minimisation by Pinch Technology – Water Cascade Table for Minimum Water and Wastewater Targeting. *Proceeding of the 9th Asia Pacific Confederation of Chemical Engineering Congress (APCChE)*, New Zealand.

Tchobanoglaus, G., and Burton, F. L. (1991) *Wastewater Engineering: Treatment, Disposal and Reuse*. 3rd ed. New York: McGraw Hill.

Thevendiraraj, S., Klemes, J., Paz, D., Aso, G., Cardenas, G. J. (2003). Water and Wastewater Minimisation Study of A Citrus Plant. *Resources, Conservation and Recycling*. 37: 227-250.

Tjoe, T. N. and Linnhoff, B. (1986). Using Pinch Technology for Process Retrofit. *Chemical Engineering* April 28: 47-60.

Tripati, R. (1996). Pinch Technology Reduced Wastewater. *Chemical Engineering*. November, 87-90.

Ulrich, G. D. (1984). *A Guide to Chemical Engineering Process Design and Economics*. New York, U.S.A.: Wiley.

Wang, Y. P. and Smith, R. (1994). Wastewater Minimisation. *Chemical Engineering Science*. 49 (7): 981-1006.

Westerberg, A. W. (1987). *Process Synthesis: A Morphological View*. in Liu, Y. A., McGee, H. A. and Epperly, W. R. Recent Developments in Chemical Process and Plant Design. New York: John Wiley & Sons.

Wiseman, N., and Ogden, G. (1996). Zero Liquid Effluent Technologies for The Paper Industry. Paper Technology. 37: 31-38.

Xu, D., Hu, Y., Hua, B., Wang, X. (2003). Manimization of the Flowrate of Fresh Water and Corresponding Regenerated Water in Water-using System with Rregeneration Reuse. *Chinese Journal of Chemical Engineering*. 11(3): 257-263.

Yee, T. F. and Grossmann, I. E. (1991). A Screening and Optimisation Approach for the Retrofit of the Heat Exchanger Networks. *Ind. Eng. Chem. Res.* 30: 146-162.

Zhu, X. X. (1997). Automated Design Method for Heat Exchanger Network Using Block Decomposition and Heuristic Rules. *Com. Chem. Eng.* 21 (10): 1095-1104.

Zhu, X. X. and Asante, D. K. (1999). Diagnosis and Optimisation Approach for Heat Exchanger Network Retrofit. *AIChE Journal.* 45 (7): 1488-1503.