

TABLE OF CONTENTS

	Page
TABLE OF CONTENTS	i
LIST OF TABLES	ii
LIST OF FIGURES	iv
LIST OF ABBREVIATIONS	vi
INTRODUCTION	1
OBJECTIVES	4
LITERATURE REVIEW	5
MATERIALS AND METHODS	11
RESULTS AND DISCUSSION	52
CONCLUSION AND RECOMMENDATION	80
Conclusion	80
Recommendation	82
LITERATURE CITED	84
APPENDIX	89

LIST OF TABLES

Table		Page
1	The implication of $N_{DOF,U}$	6
2	Set of active constraints for example process	20
3	Structural system matrix of a process heat exchanger	37
4	Ranks of potential sets of manipulated variables	41
5	Square relative order matrix for each possible set of manipulated variables	44
6	The directional effect of manipulated variables and controlled variables in case study 1.1	53
7	The split-range signal in case study 1.1	55
8	Set of active constraints in case study 1.1	55
9	Optimization result of the HEN in case study 1.2	59
10	Active constraint regions of the HEN in case study 1.2	59
11	The directional effect of manipulated variables and controlled variables in case study 1.3	62
12	The split-range signal in case study 1.3	62
13	Set of active constraints in case study 1.3	64
14	The values of $x_{i,j}$ after solving Problem P1 ($J_I=3$)	65
15	The values of $x_{i,j}$ after solving Problem P1 with setting $x_{3,3} = 1 (J_I=3)$	65
16	Relative orders of the HEN in case study 1.3	66
17	The values of $x_{i,j}$ after solving Problem P2 ($J_I=3$)	66
18	The values of $z_{k,j}$ after solving Problem P2 ($J_{II}=5$)	66
19	Disturbances and active constraints for each period	68
20	$r_{k,j}$ of the HEN in case study 2.1	70
21	$p_{k,j}$ of the HEN in case study 2.1	70
22	$z_{k,j}$ of the HEN in case study 2.1	71

LIST OF TABLES (Continued)

Table		Page
23	$[r_{k,j}] \otimes [z_{k,j}]$ in case study 2.1	71
24	$[p_{k,j}] \otimes [z_{k,j}]$ in case study 2.1	71
25	Stream information for case study 3.1	74
26	Results from the original model with different values of DT_{min} and HU_{up}	75
27	Comparison of the solutions obtained from the model of Yee and Grossman (1990) with limiting the upper bound of the number of matches and the proposed model.	76
28	Stream information for case study 3.2	77
29	Results from the proposed model with different values of $N_{sub,min}$	78

LIST OF FIGURES

Figure		Page
1	A trivial HEN	15
2	Active constraint regions	20
3	Control system of the example process	23
4	Application of split-range control to a furnace system	23
5	(a) heat exchanger and (b) mixing tank model	36
6	Heat exchanger network in example 2.1	39
7	Digraph of the path from Q_I to T_{HI}	41
8	Steps of structural analysis for control system design	45
9	Implementation of structural controllability evaluation for screening the most controllable HEN	49
10	Implementation of the proposed modified MINLP model for HEN synthesis with a number of subnetworks	51
11	A simple HEN	52
12	The resulting control structure using approach 1 in case study 1.1	54
13	The resulting control structure using an inspection in case study 1.1	55
14	A simple HEN with a loop	56
15	A trivial HEN with an optimal split-range control structure	60
16	A HEN in case study 1.3	61
17	The resulting control structure using approach 1 in case study 1.3	63
18	The resulting control structure using approach 2 in case study 1.3	67
19	Dynamic simulation of the HEN in case study 1.3 with the resulting control structures from approach 2	69
20	Two possible HEN structures	72

LIST OF FIGURES (Continued)

Figure		Page
21	The resulting HEN structures in case study 3.2	79
Appendix Figure		
1	Stage-wise superstructure	90

LIST OF ABBREVIATIONS

CV	=	controlled variable
DOF(s)	=	degree(s) of freedom
HEN(s)	=	heat exchanger network(s)
ILP	=	integer linear programming
LMTD	=	logarithmic mean temperature difference
LP	=	linear programming
MINLP	=	mixed-integer linear programming
MV	=	manipulated variable
NLP	=	nonlinear programming
RHP-zero	=	right half plane zero
SISO	=	single-input single-output
TAC	=	total annual cost

Parameters

A	=	area of exchangers (m^2)
Ccu_i	=	cost of cold utility (\$/kW)
Chu_j	=	cost of hot utility (\$/kW)
C_p	=	heat capacity (kW/kg. $^{\circ}C$)
DI	=	decoupling index
DT_{min}	=	minimum allowable temperature difference ($^{\circ}C$)
HU_{up}	=	upper bound of total hot utility available (kW)
N_c	=	number of cold process streams
N_{CV}	=	number of controlled variables
N_{DOF}	=	number of degrees of freedom
$N_{DOF,U}$	=	number of degrees of freedom with respect to utility cost optimization
N_h	=	number of hot process streams
N_{MV}	=	number of manipulated variables
N_{POE}	=	number of parallel opposing effects

LIST OF ABBREVIATIONS (Continued)

N_s	=	number of process streams
N_{sub}	=	number of subnetworks
$N_{sub,min}$	=	minimum number of subnetworks
N_t	=	number of targets
N_U	=	number of utility types
N_{unit}	=	number of exchanger units (matches)
$N_{unit,min}$	=	minimum number of units (matches)
DS	=	dimension space spanned by the manipulated variables in the inner HEN to the outer HEN
RO	=	relative order
U	=	overall heat transfer coefficient (kW/°C.m ²)
$d_{k,i,j}$	=	$\frac{r_{k,i}}{r_{k,j}}$
m	=	mass flowrate (kg/s)
nok	=	number of stages
$p_{k,j}$	=	existence of parallel opposing effects from input j to output k ($p_{k,j} = 1$ if input j has parallel opposing effects to output k)
$r_{k,j}$	=	relative order between controlled variable k and manipulated variable j

Variables

Q_i	=	duty of heat exchanger i (kW)
$Q_{c,i}$	=	duty of cold utility exchanger i (kW)
$Q_{h,i}$	=	duty of hot utility exchanger i (kW)
T	=	temperature (°C)
Ph_i	=	thermal efficiency of exchanger i
ub_i	=	bypass fraction of exchanger i

LIST OF ABBREVIATIONS (Continued)**Binary variables**

$d_{k,i,j}$	=	existence of the term $\frac{r_{k,i}}{r_{k,j}}$ in the calculation of DI
$po_{i,j}$	=	existence of possibility for matching between hot stream i and cold stream j
$x_{i,j}$	=	existence of relationship between manipulated variable i and manipulated variable j
$y_{i,j,st}$	=	existence of match of hot stream i and cold stream j at stage st
$z_{k,j}$	=	existence of control pair between controlled variable k and manipulated variable j