SEQUENTIAL APPROACH FOR WATER–AND–HEAT EXCHANGER NETWORK DESIGN

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ABSTRACT

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Keywords: Water Network/Fixed-Flowrate Problem/Heat Exchanger Networks (HENs)/Stage model/Mixed Integer Nonlinear Programming

A water network (WN) is designed to reduce the amount of freshwater usage in industrial processes by reuse, recycle and regeneration methods. Source is indicated as waste stream from industrial process. Sink is indicated as the feed stream of process that usually requires freshwater catagorized as fixed–flow rate problem. The way to reduce freshwater required from sink is by maximizing source reuse. Mathematical programming by the general algebraic modeling system (GAMS) is used to simultaneously identify the minimum amounts of freshwater needed and design an optimal network. Mixed integer linear programming (MILP) is used to design an optimal WN where the objective is to minimize the amount of freshwater and wastewater with a minimum number of reuse, freshwater and wastewater streams. WN with regeneration unit and treating unit is studied to futher reduce freshwater consumption. The water–and–heat exchanger network (WHEN) is designed to reduce both frehwater consumption and heat and cold utilities in fixed–flowrate process with desired temperature using mixed integer nonlinear programming (MINLP), consists of mass balance for WN and heat balance for the heat exchanger network (HEN). The sequential step design, has two–step and four–step calculation procedures. Both two calculation methods are compared with based process consumption and other scenarios. WHEN by four–step calculation procedure give a best designed result by lowest total annual cost.

บทคัดย่อ

ศรุต ทองปรีชา : การออกแบบเครือข่ายแลกเปลี่ยนน้ำและพลังงานอย่างเป็นขั้นตอน 309 หน้า

ระบบหมุนเวียนนำเสีย (Water network) ถูกออกแบบเพื่อลดปริมาณน้ำสะอาดที่ใช้ในกระบวนการผลิตและ ลดปริมาณน้ำเสียที่ผ่านกระบวนการผลิตในโรงงานโดยวิธีการ นำน้ำเสียกลับมาใช้ใหม่โดยกระบวนการอื่น นำมาใช้ใหม่โดยกระบวนการเดิม และการบำบัดเสียพื่อนำกลับมาใช้ใหม่ สำหรับวิธีการคำนวณแบบระบบอัตราการใหลคงที่ (Fixed-flowrate problem) น้ำเสียจะถูกจัดเป็นประเภท ซอร์ส (Source) ซึ่งก็คือปริมาณที่มีอยู่เพื่อนำกลับมาใช้ใหม่ และน้ำดีที่ใช้ในกระบวนการจะถูกจัดเป็นประเท ซิงค์ (Sink) หรือปริมาณที่ต้องการเพื่อป้อนให้กระบวนการผลิต ซึ่งปกติจะใช้น้ำสะอาดทั้งหมดซึ่งเป็นวิธีที่สิ้นเปลือง วิธีที่จะลดน้ำสะอาดที่ใช้ในสายซิงค์ทำได้โดยการออกแบบระบบหมุนเวียนเพื่อนำปริมาณซอร์สกลับมาใช้ให้เยอะที่สุด กำหนดการเชิงคณิตศาสตร์ (Mathematical programming) ซึ่งคำนวณโดยโปรแกรม General Agebraic Modeling System (GAMS) ถูกนำมาใช้ เพื่อสร้างระบบหมุนเวียนน้ำที่ดีที่สุดโดยใช้ปริมาณน้ำสะอาดน้อยที่สุด ซึ่งเป็นระบบสมการแบบ Mixed integer linear programming (MILP) โดยมีสมการเป้าหมายคือ ลดค่าใช้จ่ายต่อปีของค่าปริมาณน้ำสะอาด และ ค่าจัดเรียงท่อน้ำสะอาด น้ำที่นำมาใช้ใหม่ และน้ำเสีย ในระบบหมุนเวียน นอกจากนี้ ยังได้ศึกษาการออกแบบระบบหมุนเวียนน้ำเสียที่มีกระบวนการลดของเสียเพื่อนำกลับมาใช้ใหม่ และบำบัดก่อนปล่อยทิ้ง ระบบเครือข่ายแลกเปลี่ยนน้ำและพลังงาน (water–and–heat exchanger network) ถูกออกแบบเพื่อลดทั้งปริมาณน้ำสะอาดและพลังงานในการลด และเพิ่มอุณหภูมิของ ซอร์ส และซิงค์ ของระบบอัตราการใหลคงที่ ที่มีอุณหภูมิกำหนดของแต่ละสาย โดยระบบสมการแบบ Mixed integer nonlinear programming (MINLP) ประกอบด้วย สมการสมดุลมวลของระบบหมุนเวียนน้ำ และสมการสมดุลพลังงานของเครือข่ายแลกเปลี่ยนพลังงาน (Heat exchanger network) ซึ่งรูปแบบหรือวิธีการคำนวณที่ใช้ เป็นแบบการคำนวณเป็นขั้นตอน แบ่งเป็น 2 วิธีคือ การคำนวณแบบ 2 ขั้นตอน และ 4 ขั้นตอน ซึ่งจะนำไปเปรียบเทียบกับ ระบบเครือข่ายแลกเปลี่ยนน้ำและพลังงาน โดยไม่ใช้การคำนวณแบบเป็นขั้นตอน ในรูปแบบต่างๆ ซึ่ง การคำนวณแบบ 4 ขั้นตอนสามารถออกแบบระบบเครือข่ายแลกเปลี่ยนน้ำและพลังงาน ที่มีค่าใช้จ่ายต่อปี น้อยที่สุด

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ABBREVIATIONS

WN	Water Network
WAP	Water/Wastewater Allocation Planning
HEN	Heat Exchanger Network
WHEN	Water-and-Heat Exchanger Network
LP	Linear Programming
MIP	Mixed Integer Programming
MILP	Mixed Integer Linear Programming
NLP	Nonlinear Programming
MINLP	Mixed Integer Nonlinear Programming
GAMS	General Agebraic Modeling System
WCA	Water Cascade Analysis
LCC	Limiting Composite Curve
WCC	Water Composite Curve
NNA	Nearest Neighbors Algorithm
DAF	Dissolve Air Floatation
TSS	Total Suspended Solids
CDU	Crude Distillation Unit

SYMBOLS

Water Network Model, Water Network with Several Freshwater Sources model

CS_i	Contaminant concentration of sources (ppm)
CK_j	Contaminant concentration of sinks (ppm)
CKL_j	Contaminant concentration of sinks in data (ppm)
CF_u	Contaminant concentration of freshwater source (ppm)
FS_i	Flowrate of sources (t/h)
FK_j	Flowrate of sinks (t/h)
FW_j	Freshwater usage for each sink (t/h)
$FW_{u,j}$	Freshwater usage for each sink j from freshwater source u (t/h)
WW_i	Wastewater generated from each source (t/h)
$x_{i,j}$	Flowrate splitting fraction from source i to sink j
$F_{i,j}$	Flowrate splitting from source i to sink j (t/h)
OFW	Overall freshwater (t/h)
OWW	Overall wastewater (t/h)
$CostF$	Freshwater cost (\$/t)
$CostF_u$	Freshwater cost of each source u (\$/t)
$CostW$	Wastewater cost (\$/t)
CP	Piping cost (\$/spliter)
$OFWC$	Overall freshwater cost
$OWWC$	Overall wastewater cost
$y_{i,j}$	Binary variable for Fi,j
z_j	Binary variable for FWj
ω	Single parameter for stream existing
Ns	Number of sources stream
Nk	Number of sink stream
Nr	Number of freshwater source

Index

i	Source index
j	Sink index
u	Freshwater source index

Water network with treatment and regeneration model

CS_i	Contaminant concentration of sources (ppm)
FS_i	Flowrate of sources (t/h)
CK_j	Contaminant concentration of sinks (ppm)
CKL_j	Maximum contaminant concentration limit of sink (ppm)
FK_j	Flowrate of sinks (t/h)
FW_j	Freshwater usage for each sink (t/h)
WW_i	Wastewater generated from each source (t/h)
$x_{i,j}$	Flowrate splitting fraction from source i to sink j
OFW	Overall freshwater (t/h)
OWW	Overall wastewater (t/h)
FR	Regeneration flowrate (t/h)
CR	Regeneration concentration (ppm)
y_j	Split fraction of regeneration flowrate
$FCost$	Freshwater operating annual cost (\$/t)
$RCost$	Regeneration operating annual cost (\$/t)
$TCost$	Treatment operating annual cost (\$/t)
FC	Freshwater operating cost (\$/t)
RC	Regeneration operating cost (\$/t)
TC	Treatment operating cost (\$/t)
$OptCost$	Total operation annual cost (\$/t)
HY	Operation hour per year (h)
INC	Initial operation annual cost (\$/y)
$Save$	Operation annual saving (\$/y)
$Rarea$	Regeneration area (m^2)
HL	Hydraulic loading rate (ton/m^2 h)

RINV	Regeneration investment cost ($)
PINV	Piping investment cost ($)
INV	Total investment cost ($)
Pay	Payback period (y)
Ns	Number of sources stream
Nk	Number of sink stream

Index

i	Source index
j	Sink index

Water network with several treatment units model

CS_i	Contaminant concentration of sources
FS_i	Flowrate of sources
CK_j	Contaminant concentration of sinks
CKL_j	Maximum contaminant concentration limit of sink
FK_j	Flowrate of sinks
$FW_{r,j}$	Freshwater usage for each sink
$x_{i,j}$	Flowrate splitting fraction from source i to sink j
y_i	Flowrate splitting fraction from source i
$y_{i,u}$	Flowrate splitting fraction from source i to treatment u
$t_{u,w}$	Flowrate splitting fraction from treatment u to other w
$z_{w,j}$	Flowrate splitting fraction from treatment w to sink j
$xF_{i,j}$	Flowrate from source i to sink j
$yF_{i,u}$	Flowrate from source i to treatment u
$tF_{u,w}$	Flowrate from treatment u to other w
$zF_{w,j}$	Flowrate from treatment w to sink j
$WW1_i$	Wastewater generated from source
$WW2_w$	Wastewater generated from source after treated
OFW	Overall freshwater

OWW	Overall wastewater
CWL	Maximum contaminant concentration limit of waste
CW	Contaminant concentration limit of waste
FT_u	Combine source flowrate before treated
CT_u	Combine source concentration before treated
FTI_w	Treated flowrate
CTI_w	Treated contaminant concentration
α_u	Treatment efficiency
CFW_r	Freshwater contaminant concentration of each source r
$CostFW_r$	Freshwater cost
$TFC_{u,n}$	Treatment fixed cost
$TVC_{u,n}$	Treatment variable cost
$TFCI_u$	Treatment fixed cost to increase capacity
$TVCI_u$	Treatment variable cost to increase capacity
B_n	Flowrate bound of each treatment state n
OC_u	Treatment operation cost
$CPF1_{i,j}$	Piping fixed cost of source i to sink j
$CP1_{i,j}$	Piping variable cost of source i to sink j
$CPF2_{i,u}$	Piping fixed cost of source i to treatment u
$CP2_{i,u}$	Piping variable cost of source i to treatment u
$CPF3_{u,w}$	Piping fixed cost of treatment u to other treatment w
$CP3_{u,w}$	Piping variable cost of treatment u to other treatment w
$CPF4_{w,j}$	Piping fixed cost of treatment w to sink j
$CP4_{w,j}$	Piping variable cost of treatment w to sink j
$CPF5_{r,j}$	Piping fixed cost of freshwater source r to sink j
$CP5_{r,j}$	Piping variable cost of freshwater source r to sink j
$CPF6_i$	Piping fixed cost of source i to waste
$CP6_i$	Piping variable cost of source i to waste
$CPF7_w$	Piping fixed cost of treatment w to waste
$CP7_w$	Piping variable cost of treatment w to waste
FAC	Freshwater annual cost
TFC	Treatment annual fixed cost

$TFCI$	Increased capacity treatment annual fixed cost
TTC	Total treatment annual capital cost
TOC	Treatment operation cost
PAC	Piping annual capital cost
TAC	Total annual cost
HY	Operation hour per year
KY	Annualize factor of capital cost
$YT_{u,n}$	Binary variable of treatment unit
YTI_u	Binary variable of increase capacity treatment
$YT_{u,n}$	Binary variable of treatment unit
$zx_{i,j}$	Binary variable of flowrate i to j
$zy_{i,u}$	Binary variable of flowrate i to u
$zt_{w,u}$	Binary variable of flowrate w to u
$zz_{w,j}$	Binary variable of flowrate w to j
$zfr_{r,j}$	Binary variable of flowrate r to j
$zww1_i$	Binary variable of waste flowrate i
$zww2_w$	Binary variable of waste flowrate w

Fixed value parameter

FTP_u	Combine source flowrate before treated
CTP_u	Combine source concentration before treated
$FTIP_w$	Treated flowrate
$CTIP_w$	Treated contaminant concentration
$xFP_{i,j}$	Flowrate from source i to sink j
$yFP_{i,u}$	Flowrate from source i to treatment u
$tFP_{u,w}$	Flowrate from treatment u to other w
$zFP_{w,j}$	Flowrate from treatment w to sink j
$FW_{r,j}$	Freshwater usage for each sink
$WW1P_i$	Wastewater generated from source
$WW2P_w$	Wastewater generated from source after treated
CWP	Contaminant concentration limit of waste

Ns	Number of sources stream
Nk	Number of sink stream
Nr	Number of freshwater source

Index

i	Source stream
j -	Sink stream
u	First treatment unit
w	Second treatment unit
n	Treatment stage
r	Freshwater source

Water-and-heat-exchanger network model for two-step design and four-step design

FS_i	Source flowrate (t/h)
CS_i	Source concentration (ppm)
FK_j	Sink flowrate (t/h)
CK_j	Sink concentration (ppm)
$x_{i,j}$	Transfer fraction i to j
$F_{i,j}$	Transfer flowrate i to j (t/h)
$F1_{i,j}$	Transfer flowrate i to j of section 1 (t/h)
$F1_{i,j}$	Transfer flowrate i to j of section 2 (t/h)
FW_j	Freshwater flowrate (t/h)
CFW	Fresh concentration (ppm)
TFW	Fresh temperature (°C)
WW_i	Waste flowrate (t/h)
TKL_j	Minimum desired sink temperature (°C)
TK_j	Sink temperature after WN design (°C)
$TK1_j$	Sink temperature after WN1 design (°C)
$TK2_j$	Sink temperature after WN2 design (°C)
FH_i	Hot stream flowrate (t/h)

FC_j	Cold stream flowrate (t/h)
$TH_i^{in}, TINH_i$	Inlet temperature of hot stream (°C)
$TH_i^{out}, TOUTH_i$	Outlet temperature of hot stream (°C)
$TOUTH1_i$	Outlet temperature of hot stream from section 1 (°C)
$TC_j^{in}, TINC_j$	Inlet temperature of cold stream (°C)
$TC_j^{out}, TOUTC_j$	Outlet temperature of cold stream (°C)
$TOUTC2_j$	Outlet temperature of cold stream from section 2 (°C)
CP	Heat capacity kJ/(kg·°C)
T_{cu}^{in}	Cooling water inlet temperature (°C)
T_{cu}^{out}	Cooling water outlet temperature (°C)
T_{hu}^{in}	Steam inlet temperature (°C)
T_{hu}^{out}	Steam outlet temperature (°C)
$q_{i,j,k}$	Heat transfer hot to cold stream (kW)
qcu_i	Cold utility heat transfer (kW)
qhu_j	Hot utility heat transfer (kW)
$TH_{i,k}$	Hot stream stage temperature (°C)
$TC_{j,k}$	Cold stream stage temperature (°C)
$dT_{i,j,k}$	Hot and cold temperature difference (°C)
$dTcu_i$	Cold utility temperature difference (°C)
$dThu_j$	Hotutility temperature difference (°C)
$LMTD_{i,j,k}$	Log mean temperature difference (°C)
$LMTDcu_i$	Cold utility log mean temperature difference (°C)
$LMTDhu_j$	Hot utility log mean temperature difference (°C)
$A_{i,j,k}$	Exchangers area (m^2)
Acu_i	Cold utility Exchangers area (m^2)
Ahu_j	Hot utility Exchangers area (m^2)
α	Single parameter for WN stream (100,000)
ω	Single parameter for exchangers (100,000)
γ	Single parameter for WN stream (100,000)

$EMAT$	Minimum temperature differece (°C)
$y_{i,j}$	Binary variable of WN steam existing
yfw_j	Binary variable of fresh steam existing
yww_i	Binary variable of waste steam existing
$z_{i,j,k}$	Binary variable of exchagers existing
zcu_i	Binary variable of cold utility existing
zhu_j	Binary variable of hot utility existing
WH	Working hour (h/y)
AF	Annualize factor (y^{-1})
FC	Piping fixd-cost ($/y) (1) source to sink, (2) fresh to sink, (3) source to waste
VC	Piping variable cost ($/t) (1) source to sink, (2) fresh to sink, (3) source to waste
CUC	Cold utility cost ($/kW y)
HUC	Hot utility cost ($/kW y)
$FRcost$	Freshwater annual cost ($/y)
$PIcost$	Piping annual cost ($/y)
$cuOP_i$	Cold utility annual cost ($/y)
$huOP_j$	Hot utility annual cost ($/y)
$Acost_{i,j,k}$	Exchangers area annual cost ($/y)
$Acucost_i$	Cold utility area annual cost ($/y)
$Ahucost_j$	Hot utility area annual cost ($/y)
TAC	Total annual cost ($/y)
Ns	Number of sources stream
Nk	Number of sink stream
Nhot	Number of hot stream
Ncold	Number of cold stream
Nstage	Number of stage

Index

i	Source or hot stream
j	Sink or cold stream
k	Stage of HEN model