

# **DESIGN AND OPTIMIZATION OF CRYOGENIC PROCESS**

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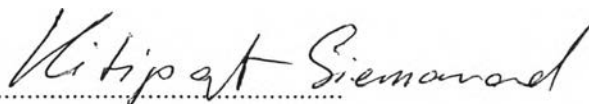
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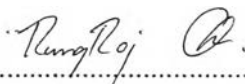
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## ABSTRACT

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Refrigeration system is widely used in the industry, especially in cryogenic process. The main problem of refrigeration system is high energy consumption from shaft work resulting in high operation cost. To minimize the amount of shaft work, it is accomplished by a combination of pinch and exergy analysis. The strength of pinch analysis is graphical representation by using simple diagrams of composite curves and grand composite curve for process modifications. However, limitation of pinch analysis is that it only deals with thermal system, not including power or shaft work. Exergy analysis is a tool to utilize power or shaft work and identify thermodynamic imperfection of process. Both strengths are combined to help improve process efficiency. In this study, this methodology is applied for case study of LNG to improve processes such as reducing shaft work and increasing the exergy efficiency. Furthermore, the cascade refrigeration system is designed by mathematical programming.

## บทคัดย่อ

จุฬาทิพย์ ทำทนาย : การออกแบบและหาค่าสถานะที่เหมาะสมที่สุดของกระบวนการที่  
 ดำเนินการภายใต้อุณหภูมิที่ต่ำ (Design and Optimization of Cryogenic Process ) อ. ที่ปรึกษา :  
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ในปัจจุบันระบบทำความเย็นใช้กันอย่างแพร่หลายในโรงงานอุตสาหกรรม โดยเฉพาะอย่างยิ่งกระบวนการที่ดำเนินการภายใต้อุณหภูมิต่ำ ปัญหาหลักที่พบในระบบทำความเย็นคือ ค่าดำเนินการของกระบวนการที่ดำเนินการภายใต้อุณหภูมิต่ำนั้นจะขึ้นกับงานที่เครื่องอัดอากาศต้องการ ดังนั้นการลดงานที่เครื่องอัดอากาศต้องการเป็นผลช่วยลดค่าดำเนินการได้ งานวิจัยนี้ได้เสนอวิธีการที่ใช้การออกแบบกระบวนการเพื่อลดความต้องการของงานโดยใช้ระบบอนุรักษ์พลังงาน (Pinch Analysis) และ เอ็กเซอร์จี (Exergy) ในการวิเคราะห์ ซึ่งข้อดีของการใช้ Pinch Analysis คือการแสดงผลที่เข้าใจได้ง่ายโดยการใช้เส้นโค้งคอมโพสิท (Composite Curve) ในการปรับปรุงกระบวนการ อย่างไรก็ตาม Pinch Analysis มีข้อจำกัดเนื่องจาก Pinch Analysis จะพิจารณาแค่ปริมาณความร้อน ซึ่งในกระบวนการดำเนินการภายใต้อุณหภูมิต่ำนั้นงานก็เป็นตัวแปรสำคัญเช่นกัน ดังนั้น Exergy Analysis จึงถูกใช้เป็นเครื่องมือในการออกแบบ เนื่องจาก เอ็กเซอร์จี้มีความสัมพันธ์กับงาน การนำจุดเด่นของทั้ง Pinch Analysis และ Exergy Analysis จึงช่วยกระบวนการมีประสิทธิภาพที่ดีขึ้นทั้งยังลดความต้องการของพลังงานและงาน ดังนั้นงานวิจัยนี้ได้ใช้หลักการดังกล่าวมาประยุกต์ใช้ในการออกแบบกับกรณีศึกษาของการเปลี่ยนสถานะก๊าซธรรมชาติให้กลายเป็นก๊าซธรรมชาติเหลว นอกจากนั้นได้นำโปรแกรมทางคณิตศาสตร์ (General Algebraic Modelling System; GAMS) มาใช้ในการออกแบบโครงสร้างเครือข่ายเครื่องแลกเปลี่ยนความร้อนอย่างมีประสิทธิภาพและลดความต้องการของงาน

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**LIST OF ABBREVIATIONS**

C	Cold streams
C1	Methane
C2	Ethylene
C3	Propane
CCs	Composite curve
CO <sub>2</sub>	Carbon dioxide
COP	Coefficient of performance
EA	Exergy analysis
ECCs	Exergy composite curve
EGCCs	Exergy grand composite curve
EMAT	Exchanger minimum approach temperature
ExPAnD	Extended Pinch Analysis and Design Methodology
GAMS	General Algebraic Modeling System
GCCs	Grand composite curve
H	Hot streams
H <sub>2</sub> S	Hydrogen sulfide
HCFC	Hydrochlorofluorocarbon
HEN	Heat exchanger network
Hg	Mercury
HRAT	Heat recovery approach temperature
HRS	Heat recovery system
iC4	Iso - butane
iC5	Iso - Pentane
LNG	Liquefied natural gas
MDEA	Methyldiethanolamine
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
N <sub>2</sub>	Nitrogen
nC4	Normal - butane

NG	Natural gas
NLP	Nonlinear programming
OPD	Ozone depletion potential
P	Absolute pressure
$P_0$	Ambient pressure
PA	Pinch analysis
T	Absolute temperature
$T_0$	Ambient temperature
TAC	Total cost associated in heat exchanger network
TEG	Triethylene glycol
$TH_{i,IN}$	Supply temperature of hot process stream i
$T_{min}$	Minimum temperature
W	Approximately shaft work

## LIST OF SYMBOLS

$(\sigma T_0)_{HEN}$	Exergy lose due to heat transfer equivalent to shaft work
$\dot{E}^P$	Pressure based exergy
$\dot{E}^Q$	Exergy of heat
$\dot{E}^T$	Temperature based exergy
$\dot{E}^{TM}$	Thermo – mechanical exergy
$\dot{W}_{rev}$	Work in reversible process
$\dot{W}_u$	Useful work
$\dot{Q}_0$	Heat rejected
$\dot{S}_{gen}$	Entropy generation
$\dot{E}_{in}$	Incoming exergy stream
$\dot{E}_{out}$	Outing exergy stream
$\dot{E}_{Deficit,min}$	Minimum exergy deficitt
$\dot{E}_{Destruction,min}$	Minimum exergy destruction
$\dot{E}_{Rejection,min}$	Minimum exergy rejection
$\dot{E}_{Requirement,min}$	Minimum exergy requirement
$\dot{E}_{Surplus,min}$	Minimum exergy surplus
$i_e$	Exergy destruction in ethane
$i_m$	Exergy destruction in methane
$i_n$	Exergy destruction in natural gas
$i_p$	Exergy destruction in propane
$\dot{m}_e$	Mass flowrate in ethane
$\dot{m}_m$	Mass flowrate in methane
$\dot{m}_n$	Mass flowrate in natural gas
$\dot{m}_p$	Mass flowrate in propane
$T^{ET}$	Temperature based exergetic temperature
$W_{1,2,3}$	Amount of power for supplying in each cycle namely 1,2 and 3
$W_{actual}$	Actual work
$W_{min}$	Minimum work

$\Omega_{i,j}$	Upper bound of heat content for heat exchanger
$CCU_i$	Cost of cooling utility $cu$
$CFHX_{i,j}$	Fixed charges for exchanger $i - j$
$CW_{i,j}$	Cost of work consumption of compressor
$C_p$	Average molar heat capacity
$FC_i$	Heat capacity of cold process stream $j$
$FH_i$	Heat capacity of hot process stream $i$
$FW_{i,j}$	Heat capacity of stream between compressor $i - j$
$\dot{Q}$	Heat absorbed
$T^{EP}$	Pressure based exergetic temperature
$TCU_{cu,IN}$	Inlet temperature of cooling utility $cu$
$TCU_{cu,OUT}$	Outlet temperature of cooling utility $cu$
$TC_{j,IN}$	Supply temperature of cold process stream $j$
$TH_{i,OUT}$	Target temperature of hot process stream $i$
$dthu_j$	Temperature approach for match of heating utility $hu$ and cold process stream $j$
$dtcu_{i,cu}$	Temperature approach for match between cooling utility $cu$ and hot process stream $i$
$dt_{i,j,k}$	Temperature approach for match $i - j$ at the left of heat exchanger
$qhu_j$	Heat exchanged between hot utility $hu$ and cold process stream $j$
$qcu_{i,cu}$	Heat exchanged between cold utility $cu$ and hot process stream $i$
$q_{i,j,k}$	Heat exchanged between hot process stream $i$ and cold process stream $j$ in stage $k$
$th_{i,k}$	Temperature of hot process stream $i$ at "hot end" of stage $k$
$tc_{j,k}$	Temperature of cold process stream $j$ at "hot end" of stage $k$
$zhu_j$	Existence of an exchanger for match between heating utility and cold process stream $j$
$zcu_{i,cu}$	Existence of an exchanger for match between cooling utility $cu$ and hot process



$z_{i,j,k}$	Existence of an exchanger for match $i - j$ in stage $k$
$\eta_c$	Carnot factor
$\Delta T_{lm}$	Log mean temperature difference
$\Delta e$	Change of exergy
$\Delta Ex_p$	Process receive exergy
$\Delta Ex_r$	Refrigeration system supply exergy
$\Delta W$	Reduction in shaft work
$A$	Area
$CHU_j$	Cost of heating utility
$e$	Exergy of process stream per unit mass
$E_{CV}$	Energy in control volume
$E_{destruction, i}$	Exergy destruction
$h$	Enthalpy per unit mass
$H$	Enthalpy
$h^*$	Enthalpy of ideal gas ( $P_0 = 0$ )
$h_0$	Enthalpy per unit mass at dead state
$m$	Mass flowrate
$P$	Absolute pressure
$P_0$	Ambient pressure
$P_C$	Critical pressure
$P^{vap}$	Vapor pressure
$Q$	Heat duty
$R$	Gas constant
$s$	Entropy per unit mass
$S$	Entropy
$s_0$	Enthalpy per unit mass at dead state
$S_{gen}$	Generated entropy
$T$	Absolute temperature
$T_0$	Ambient temperature
$T_C$	Critical temperature
$U$	Overall heat transfer coefficient

$W, W_c, W_{shaft}$	Shaft work
$\dot{W}_{min}$	Minimum work input to cycle
$Z$	Compressibility factor
$\varepsilon, \eta_{ex}$	Exergy efficiency
$\eta_i$	Compressor's isentropic efficiency
$\omega$	Acentric factor
$EMAT$	Minimum-approach temperature difference
$ST$	Number of stage (often chosen as maximum between number of hot and cold streams)
$k$	Specific heat ratio
$\Gamma$	Upper bound for temperature difference
$\kappa$	Dimensionless parameter