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OPTIMAL SYNTHESIS AND DESIGN OF HEAT TRANSFER ENHANCEMENT ON HEAT EXCHANGER NETWORKES AND ITS APPLICATION

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Abstracts Synthesis for qualitative analysis in connection with quantitative analysis from the pinch design method, EVOP and Operations Research is proposed for the optimal synthesis of heat exchanger networks, that is through of the transportation model of the linear programming for synthesizing chemical processing systems, to determine the location of pinch points, the stream matches and the corresponding heat flowrate exchanged at each match. In the second place, according to the optimization, the optimal design of heat transfer enhancement is carried on a fixed optimum heat exchanger network structure, in which this design determines optimal operational parameters and the chosen type of heat exchangers as well. Finally, the method of this paper is applied to the study of the optimal synthetic design of heat exchanger network of constant-decompress distillation plants.

Keywords Energy system, System Engineering

1.NOMENCLATURE

- A Heat transfer area, m^2
- a the constant related the type of heat exchangers, reference valus is 1700
- a_i thermal energy flow to be removed from stream i, $kcal\cdot s^{-1}$
- b exponent factor related the type of heat exchangers, reference value is 0.75
- b_j thermal energy flow required by the cold stream j, $kcal\cdot s^{-1}$
- C number of cold process streams and cold utility streams
- C_p heat capacity, $kcal.kg^{-1}\cdot ℃^{-1}$
- C_k {j|cold stream j is present in interval k}
- C_t overall cost of a heat exchanger network, \$/a
- C_u the utility cost, $\$\cdot a^{-1}$
- C_{inv} the investment cost, $\$\cdot a^{-1}$
- C_f the operation cost, $\$\cdot a^{-1}$
- $C^u{}_t$ overall cost of the unit for thermal energy flow exchanged, $\$\cdot a^{-1}$
- $C^u{}_{inv}$ the investment cost of a match unit, $\$\cdot a^{-1}$
- $C^u{}_f$ the operation cost of a match unit, $\$\cdot a^{-1}$
- C_{fi} the power cost coefficient, $\$\cdot kw^{-1}$
- H number of hot process and hot utility streams
- H_k {i|hot stream i is present in interval k}
- $h_{s(or\ t)}$ the shell (or tube) -side film heat transfer coefficient, $kcal.m^{-2}.hr^{-1}\cdot ℃^{-1}$
- I_u the investment cost of the heat exchanger, $\$\cdot a^{-1}$
- N operation hours per annum, $hr\cdot a^{-1}$
- N_s number of shell bodies
- $Para_{s(or\ t)}$ structure parameter for the shell(or tube)-side of a heat exchanger
- $\Delta P_{1(or2)}$ pressure drop of shell(or tube)-side, $Kg\cdot m^{-2}$
- Q thermal energy flow exchanged in the unit, $kcal\cdot s^{-1}$
- Q_{ij} thermal energy flow exchanged in the match (i,j), $kcal\cdot s^{-1}$
- $Q^{s(or\ w)}{}_{m(or\ n)}$ the heat load of hot(or cold) utility m (or n), $kcal\cdot s^{-1}$
- $Q^H{}_{ik}$ the heat load of hot stream i entering temperature interval k, $kcal\cdot s^{-1}$
- $Q^c{}_{ik}$ the heat load flowing to cold stream j from temperature interval k, $kcal\cdot s^{-1}$
- $Q^s{}_{mk}$ the heat load of hot utility m entering temperature interval k, $kcal\cdot s^{-1}$
- $Q^w{}_{nk}$ the heat load flowing to cold utility n from temperature interval k, $kcal\cdot s^{-1}$
- R_k the residual heat load of each interval k, $kcal\cdot s^{-1}$
- $Re_{s(or\ t)}$ the shell(or tube)-side Reynolds number
- $r_{s(or\ t)}$ the heat resistance of the shell(or tube)-side borne filth, $m^2.hr.℃.kcal^{-1}$
- S_k {m| hot utility m is present in interval k}
- ΔT_{LM} temperature difference of logarithm average, ℃
- ΔT_{min} minimum temperature difference, ℃

$\Delta T_{min,opt}$ optimal minimum temperature difference, ℃

U overall heat transfer coefficient, $kcal.m^{-2}.hr^{-1}.℃^{-1}$

U_{opt} optimal overall heat transfer coefficient, $kcal.m^{-2}.hr^{-1}.℃^{-1}$

U_{ij} upper bound on the thermal energy flow exchanged in the match(i,j), $kcal.s^{-1}$

V_i the valume flowrate, $m^3.s^{-1}$

W_k {n| cold utility n is present in interval k}

Greek Symbols:

β_o the fundamental depreciation rate, a^{-1}

β_m the annual rate of maintenance, repairs and operation costs to premary investment, a^{-1}

γ Kinematic viscosity, cst

2. INTRODUCTION

Significant progress in understanding heat exchanger networks has been made in recent years, particularly, through the pinch design method [1], and automatic synthesis of optimum heat exchanger network configurations[2], in which the transshipment model from Operation Research are proposed for the optimal synthesis of heat exchanger networks, and the mixed-integer programming version yields minimum utility cost networks in which the number of units is minimized. Jaime Cerda's paper [3] has provided models P_1, P_2,P_3 and P_4 of linear transportation problems. This paper is based on above papers to do improvement.

3. SIMPLE DESCRIPTION OF TRANSPORTATION MODELS FOR OPTIMAL SYNTHESIS ON HEAT EXCHANGER NETWORKS

The paper[2] has given that several formulations of the transshipment model from Operations Research are proposed for the optimal synthesis heat exchanger networks, in which the linear programming versions are used for predicting the minimum utility cost, and the mixed-integer programming version yields minimum utility cost networks in which the number of units is minimized. The linear programming model(LP) for minimum utility thermal energy flowrates is given by

$$\text{minimize} \sum_{m\in s} Q^s_m + \sum_{n\in w} Q^w_n \qquad \text{(LP)}$$

S.T.

$$R_k-R_{k-1}-\sum_{m\in S_k} Q^s_{mk}+\sum_{m\in W_k} Q^w_{nk}= \sum_{i\in H_k} Q^H_{ik}-\sum_{j\in C_k} Q^c_{jk},\ k=1,\ldots,k$$

$$Q^s_m \geq 0,\ Q^w_n \geq 0,\quad m\in s,\quad n\in w,$$

$$R_0 = R_k = 0,\quad R_k > 0,\ k=1,2,\ldots,k-1$$

The optimal value of the hot and cold utility flowrates and the residual heat load R_k of each interval k can easily be determined by solving the linear programming. The occurrence of any pinch points takes place between the temperature intervals with no residual heat flow, or equivalently at the point where the residual heat load R_k is equal to zero

According to the pinch point, the network is divided to some sub-networks. This paper offers the linear programming(LP*) model for the optimal synthesis design of each sub-network as follows:

$$\text{minimize} \sum_{i=1}^{H}\sum_{j=1}^{C} \frac{1}{U_{ij}}.Q_{ij} \qquad \text{(LP*)}$$

s.t.

$$\sum_{j=1}^{C} Q_{ij}=a_i,\ i=1,2,\ldots,H;\ \sum_{i=1}^{H} Q_{ij}=b_j,\ j=1,2,\ldots,C$$

$$Q_{ij}\geq 0,\ i=1,2,\ldots,H;\ \ j=1,2,\ldots,C;$$

$$Q_{ij}\leq U_{ij},\quad \text{for all } (i,\ j)\in \pi$$

where

$$\pi= \{(i,\ j)|\ u_{ij}\leq \min\ (a_i,\ b_j)\}$$

This model(LP*) appears similar to model(P_4) of the paper[3].

4. THE OPTIMAL DESIGN FOR A FIXED NETWORK

The total cost C_t of a heat exchanger network is the sum of the utility cost C_u, the investment cost C_{inv} and the operation cost C_f,that is

$$C_t = C_u + C_{inv} + C_f$$

According to optimization, this paper offers the optimal design for a fixed network. Optimized model for a exchanger of shell-tube type may be written by the following formulation:

$$\text{minimize } C^u_t = \text{minimize } \{ C^u_f + C^u_{inv} \}$$

$$= \text{minimize } \{\sum_{i=1}^{2} C_{fi}(V_i\Delta P_i)3600N+(\beta_o+\beta_m)I_u\}$$

where

$$\Delta P_1 = f1\ (Res,\ Paras)$$

$$\Delta P_2 = f2\ (Ret,\ Parat)$$

$$I_u = N_s.a.(A/N_s)b$$

$$A = Q/(U.\Delta T_{LM})$$

$$U = f_3 (h_s, r_s, h_t, r_t)$$
$$h_s = f_4 (Res, Paras)$$
$$h_t = f_5 (Ret, Parat)$$

5. THE OPTIMAL SYNTHETIC DESIGN OF HEAT EXCHANGER NETWORK OF CONSTANT-DECOMPRESS DISTILLATION PLANTS

Problem 1. The data of constant-decompress distillation for a refining factory of oil are given by Table 1. Processing quanlities and working times are 270 ten thousend ton per annum (or 337500 $kg.hr^{-1}$) and 8000 hours, respectively.

Partition the entire temperature range of all streams into 14 temperature intervals to taking T_{min} = 20℃ which may be shown by Figure 1.

The pinch point and minimun utility consumption can easily be determined by solving the Linear Programming (LP). Therefore, its optimal solution is given by

Q^s=1879.4	Q^w=2684.78	R_1=91.6	R_2=0
R_3=3417.7	R_4=4033.34	R_5=4337.88	R_6=5072.42
R_7=5694.05	R_8=5697.9	R_9=6935.78	R_{10}=6978.24
R_{11}=6804.28	R_{12}=4517.18	R_{13}=2201.62	

Hence, We obtain that the temperature range of the pinch point is 375~355 (℃). The minimun thermal energy flowrates of hot and cold utility are 1879.4 and 2684.78($kcal.s^{-1}$), respectively.

According to the linear programming model (LP*), We obtain an optimal solution for synthesis design of heat exchanger networks. The matches on left at the pinch point can be found obviously. The matches on right at the pinch point may be found by the linear programming(LP*), that its optimal solution is given by

Q_{11}=0	Q_{12}=285.1	Q_{21}=0	Q_{22}=813.08
Q_{31}=2795.36	Q_{32}=0	Q_{41}=303.94	Q_{42}=1184.68
Q_{51}=24942	Q_{52}=402.05	Q_{61}=3260.3	Q_{62}=0
Q_{71}=3362.2	Q_{72}=0	Q_{81}=13485	Q_{82}=0
Q_{91}=7195.5	Q_{92}=0	$Q_{10,1}$=11232.5	$Q_{10,2}$=0
$Q_{11,1}$=981.77	$Q_{11,2}$=0.		

Hence, optimal heat recovery network of problem 1 for heat exchanger network synthesis of constant-decompress distillation plants may be shown as Figure 2.

Finally, according to optimization, the optimal design of heat transfer enhancement is carried on a fixed optimum heat exchanger network struture (Figure 2), and its optimized parameters may be by Table 2.

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Table 1. The data of constant-decompress distillation for a refining factory

Stream	T_{in}[℃]	T_{out}[℃]	Weight Flowrate[Kg/hr]	20℃ to Specific gravity of water[g/cm³]	Kinematic Viscosity γ_{t1}, γ_{t2} (cst)
C	45	370	337500	0.9078	γ_{80}=92.31 γ_{100}=18.74
H_1	95	60	24869.53	0.7080	γ_{20}=0.81 γ_{50}=0.5
H_2	182	80	20825	0.7883	γ_{50}=2.88 γ_{80}=1.68
H_3	280	150	34782	0.8385	γ_{50}=8.94 γ_{80}=3.22
H_4	320	150	13500	0.8607	γ_{50}=5.63 γ_{80}=2.22
H_5	375	80	148512	0.9708	γ_{50}=880 γ_{100}=30
H_6	195	130	97804	0.8094	γ_{50}=2.15 γ_{100}=0.88
H_7	300	232	65584	0.8485	γ_{80}=4.53 γ_{100}=1.82
H_8	200	100	28500	0.8718	γ_{80}=8.86 γ_{100}=2.85
H_9	300	170	88018	0.9020	γ_{80}=33.31 γ_{100}=8.72
H_{10}	380	305	175584	0.8881	γ_{80}=11.5 γ_{100}=4.61
H_{11}	150	85	38754	0.7888	γ_{20}=0.74 γ_{50}=0.8

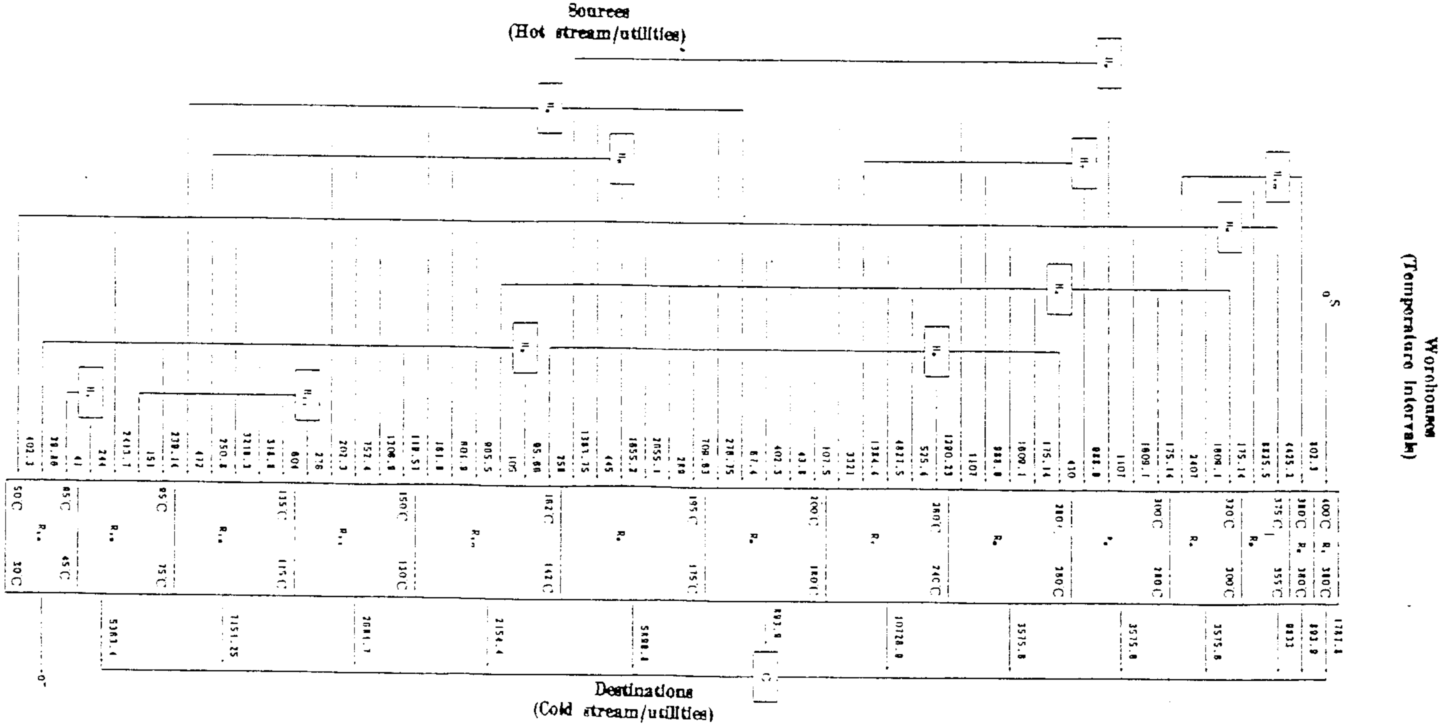

Figure 1. Analogy of heat recovery network with transportation model

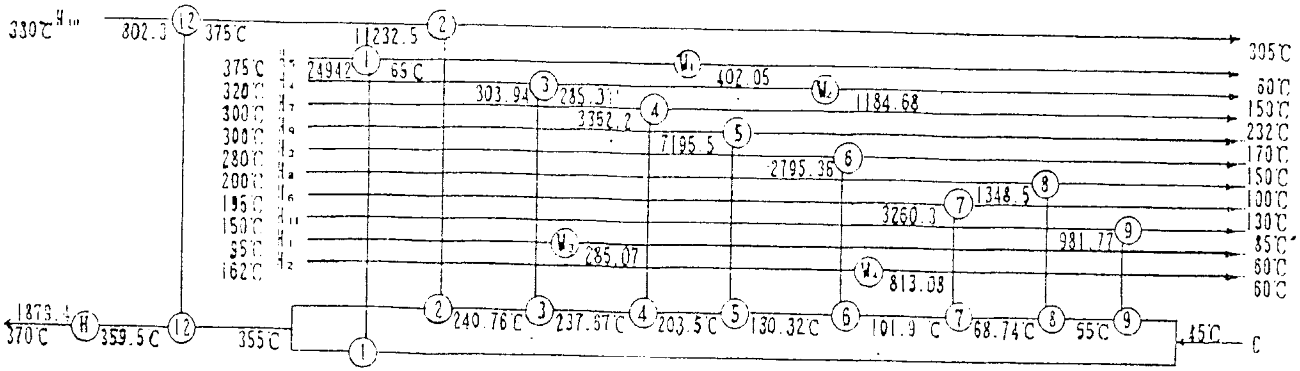

Figure 2. An optimal network design for constant-decompress distillation plants

Table 2. optimal parameters of a fixed optimum heat exchanger network structure

Number of Matching Unit	1	2	3	4	5	6	7	8	9	12	W_1	W_2	W_3	W_4	H
U (kcal/m² hr °C)	519.34	676.9	439.86	551.2	544.47	591.87	514.81	455.01	495.5	580.22	486.26	377.5	767	765.51	1050.9
A (m²)	3644.7	1572.08	40.05	507.98	743.4	193.23	223.13	132.4	114.5	245.81	137	30.7	62	74	192
Ns (Number)	11	3	1	2	2	1	1	1	1	1	1	1	2	2	1
Ct (\$/a)	36303.62	6653.55	6741.92	6745.31	9980.64	2723.67	3650.57	2117.12	1326.47	3070.91	2531.43	572.21	395.04	575.64	447.17