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Optimization by stage-wise model for complex industrial heat exchanger network

Anita Kovač Kralj and Peter Glavič

Faculty of Chemistry and Chemical Engineering
Smetanova 17, Maribor, Slovenia, E mail: anita.kovac@uni-mb.si

Abstract

The heat exchanger network (HEN) can be optimized using the stage–wise model of superstructure representation as proposed by Yee and Grossmann (1990). The model can be solved easily for trivial problems but for the nontrivial, complex and industrial plant the model becomes nonsolvable because the high number of streams increases the number of stages and with them the number of combinations. The number of stages must be reduced for a complex industrial plant. The complex retrofitted and new designed HEN can be solved easily and well enough with less stages than the maximum number of hot or cold streams.

Keywords: modification of the stage-wise, MINLP model and industrial plants

1. Introduction

Many efficient optimization methods for retrofitted and new designed heat exchanger network (HEN) are known. The stage-wise (Yee and Grossmann, 1990) optimization methods can be applied to optimize trivial HEN easily and well enough with nonvertical heat transfer but the nontrivial problems are not able to converge because of many binary variables. The heat exchanger network can be optimized using a transshipment model (Ciric and Floudas, 1990). The method can not enable nonvertical heat transfer, so it can not approach the global optimum. The pinch method (Tjoe and Linnhoff, 1986) can be used to integrate very well complex HEN.

2. Stage-wise model for complex heat exchanger network

Heat exchanger network is an important component of any plant since it determines to a large extent the energy efficiency of the process. The heat exchanger network can be optimized using a mixed integer nonlinear programming (MINLP) model which is based on the stage-wise (heat integration intervals between hot and cold process streams) superstructure representation as proposed by Yee and Grossmann (1990). Within each stage of the superstructure, potential exchanges between any pair of hot and cold streams can occur. In each stage, the corresponding process stream is split to be directed to an exchanger for a potential match between each hot stream and each cold stream. The outlets of the exchangers are isothermally mixed defining the stream for the next stage. The outlet temperatures of each stage are treated as variables in the optimization model. Utilities are located at the ends of the superstructure. The MINLP model is presented which can generate networks where utility cost, exchanger areas and selection of mathches are optimized simultaneously. Heat capacity flow rates, inlet and outlet tempeatures are treated as fixed. Process streams are divided into two sets, *HP* set for hot streams represented by index *i* and *CP* set for cold sreams represented by index *j*. Index *k* is used to denote the superstructure – stages of *ST* set or temperature locations. Indices *HU* and *CU* correspond to the heating and cooling utilities respectively. The network does not involve any stream splitting. The number of stages in the superstructure can be set for instance to the maximum number of hot or cold streams. The model can be solved easily for trivial problems but for a nontrivial, complex industrial plant the model becomes nonsolvable because the high number of streams increases the number of stages and with them the number of combinations. The number of stages must be reduced when dealing with complex industrial plants. The maximal number of stages can be calculated, than the minimum number of hot or cold streams is divided by two and rounded off. We must find the optimal number of stages for industrial process. Therefore, we made research about them in this paper. The model is including heat exchanger networks connection with the other part of process. The procedure was tested by a green–grass plant of the dimethylether production to reduce cost of the retrofitted process for the methanol production. Retrofit constraints can easily be included into the model.

2.1 Retrofit

A good approach optimization method the approaching to the global optimum for retrofitted, complex heat exchanger network (HEN) can easily be found. The stage-wise model can given a good solution. The stage-wise model was extended by additional equations of heat balances for the retrofitted exchangers, heaters and coolers:

$$A_{ijk} = \Phi_{ijk} /(K_{ij}\, LKTD_{ij}) \qquad i \in HP, j \in CP, \ k \in ST \qquad (1)$$

$$Ah_j = \Phi hot_j /(Kh_j\, LKTDh_j) \qquad j \in CP \qquad (2)$$

$$Ac_j = \Phi cold_j /(Kc_j\, LKTDc_j) \qquad i \in CP \qquad (3)$$

Equations 1, 2 and 3 present the new heat exchanger area of match (*i*, *j*) in stage *k* (A_{ijk}), with its heater area (Ah_j) and cooler area (Ac_j). The areas can be calculated with variables:

- Φ_{ijk} is the heat flow rate of match *ij* in stage *k*,
- Φhot_j is the heat flow rate of hot utility on stream *j*,
- $\Phi cold_j$ is the heat flow rate of cold utility on stream *i*,
- K_{ij} is the overall coeficient of heat transfer between streams *i* and *j*,
- Kc_j is the overall coeficient of heat transfer between streams *i* and cold utility,
- Kh_j is the overall coeficient of heat transfer between streams *j* and hot utility,
- $LKTD_{ij}$ is the driving force of match *ij* in stage *k* using Chen aproximation,
- $LKTDh_j$ is the driving force of streams *j* and hot utility using Chen aproximation,

- $LKTDc_j$ is the driving force of streams i and cold utility using Chen aproximation.

The existing areas of heat exchangers (A^{ex}_{ijk}), heaters (Ah^{ex}_j) and coolers (Ac^{ex}_i) can be used or can be extended by additional areas (A^{a}_{ijk}) into the existence of match ij in stage k with binary variable (z_{ijk}), extended heater (Ah^{a}_j) and for cooler areas (Ac^{a}_i) into the existence of cooling and heating with binary variables (zh_j, zc_i):

$$A^{a}_{ijk} \geq A_{ijk} - A^{ex}_{ijk}\, z_{ijk} \qquad i \in HP,\ j \in CP,\ k \in ST \qquad (4)$$

$$Ah^{a}_{j} \geq Ah_{j} - Ah^{ex}_{j}\, zh_{j} \qquad j \in CP \qquad (5)$$

$$Ac^{a}_{i} \geq Ac_{i} - Ac^{ex}_{i}\, zc_{i} \qquad i \in HP \qquad (6)$$

The consumption of existing hot and cold utility (Φhot^{ex}_j, $\Phi cold^{ex}_i$) can be increased (Φhot^{a}_j, $\Phi cold^{a}_i$):

$$\Phi hot^{a}_{j} \geq \Phi hot_{j} - \Phi hot^{ex}_{j}\, zh_{j} \qquad j \in CP \qquad (7)$$

$$\Phi cold^{a}_{i} \geq \Phi cold_{i} - \Phi cold^{ex}_{i}\, zc_{i} \qquad i \in HP \qquad (8)$$

The objective function (Eq. 9) of the retrofit is to minimize additional annual total cost (C_{OF}) which sums up the annual investment cost (C_i) and utility cost (C_{CW}, C_{steam}). It searches the best integration matches:

$$C_{OF} = \Big[\sum_{ijk} (C_{fix}\, z_{ijk} + C_{v}\, A^{a}_{ijk}{}^{ep}) + \sum_{j} (C_{fix}\, zh_{j} + C_{v}\, Ah^{a}_{j}{}^{ep}) + \sum_{i} (C_{fix}\, zc_{i} + C_{v}\, Ac^{a}_{i}{}^{ep}) \Big]\, r + \sum_{j} \Phi hot^{a}_{j}\, C_{steam} + \sum_{i} \Phi cold^{a}_{i}\, C_{CW} \qquad (9)$$

The model including the use of existing area and buy of new area but not displacement of the existing exchanger. For the retrofit, complex HEN can be solved easily and well enough with less stages than the maximum number of hot or cold streams.

The retrofit model can be extended with additional binary variables. The problem is more exact but it is difficult to solve.

The existance of heat exchanger match ij in stage k (z_{ijk}) can be divided between the existing (zo_{ijk}) or new match (zn_{ijk}) in stage k, but only one is chosen:

$$z_{ijk} = zo_{ijk} + zn_{ijk} \qquad i \in HP,\ j \in CP,\ k \in ST \qquad (10)$$

$$zo_{ijk} + zn_{ijk} \leq 1 \qquad i \in HP,\ j \in CP,\ k \in ST \qquad (11)$$

The existance of heater (zh_j) and cooler (zc_i) can be divided between the existance of existing (zoh_j, zoc_i) or new ones (znh_j, znc_i), but only one is chosen:

$$zh_{j} = zoh_{j} + znh_{j} \qquad j \in CP \qquad (12)$$

$$zoh_{j} + znh_{j} \leq 1 \qquad j \in CP \qquad (13)$$

$$zc_{i} = zoc_{i} + znc_{i} \qquad i \in HP \qquad (14)$$

$$zoc_{i} + znc_{i} \leq 1 \qquad i \in HP \qquad (15)$$

The retrofitted model of HEN can include additonal equations of heat integration between hot (i) and cold (j) stream only one time in stage k, because of the additional control, when the number of stage is reduced:

$\sum_k z_{ijk} \leq 1$ $\quad\quad i \in HP, j \in CP$ (16)

The equation 17 can be controled the only one exhanger in one stage.

$\sum_j z_{ijk} \leq 1$ $\quad\quad i \in HP, k \in ST$ (17)

The objective function can be defined:

$$C_{OF} = [\sum_{ijk} (C_{fix}\, zn_{ijk} + C_v\, A^a{}_{ijk}{}^{ep}) + \sum_j (C_{fix}\, znh_j + C_v\, Ah^a{}_j{}^{ep}) + \sum_i (C_{fix}\, znc_i + C_v\, Ac^a{}_i{}^{ep})]\, r$$

$$+ \sum_j \Phi hot^a{}_j\, C_{steam} + \sum_i \Phi cold^a{}_i\, C_{CW} \quad (18)$$

We tested the model only in one part the retrofitted HEN (cooling of the synthesis gas) of the methanol production (Kovač Kralj et al., 2000) because of the convergence difficulties. The problem involves 5 hot streams and 3 cold streams along with hot and cold utility. The problem data of supply (T_s) and target (T_t) temperatures for the streams, the thermal conductance (G), the heat transfer coefficients (h) as well as the exchanger and utilities costs equations are presented in Table 1.

Table 1. Problem data for new designed plant example.

Stream	T_s/ °C	T_t / °C	G/(kW/K)	h/(kW/m^2 K)
H1	450,0	290,0	32,0	0,5
H2	140,0	35,0	21,0	0,7
H3	290,0	130,0	71,4	0,8
H4	120,0	55,0	99,8	0,7
H5	55,0	40,0	29,9	0,9
C1	0,5	400,0	8,0	0,5
C2	245,0	247,0	1340,0	2,5
C3	108,0	212,0	109,9	0,8

Installed heat exchanger cost, ($C_i = C_{fix} + C_v A^{ep}$) / EUR:
54 200 + 4220 $A^{0,83}$; A = m^2
Annual utility cost of cooling water (C_{CW}; Swaney, 1989) / EUR/(kW a): 6,3
Annual utility cost of 37 bar steam (C_{steam}; Swaney, 1989) / EUR/(kW a): 95,4
Payback multiplier (r; Ahmad, 1985): 0,216

The model was modificated for retrofit. After the stage-wise theory was used for the 5 fixed stages, the problem did not converge. So we used only 3 stages with good initial starting point and it converged to local optimum (see Figure 1).

The HEN was solved with the minimum approach temperature between hot and cold streams of 10 K. The model was solved by the DICOPT^{++} package using the program GAMS. One major iteration was required using a total CPU time of 15 s on the VAX-3100. The network involves 7 exchangers of which 3 are coolers. Process stream matches are the existing (H1, C1), (H3, C3) and new ones (H2, C1) and (H2, C1), they are selected amongst the 53 exchangers embedded in the superstructure. The total annual profit for the network is 230 000 EUR/a including the steam production (stream C2). The optimal by matches selected using the nonlinear programming model are the same as by all the optimized processes (Kovač Kralj et al., 2000).

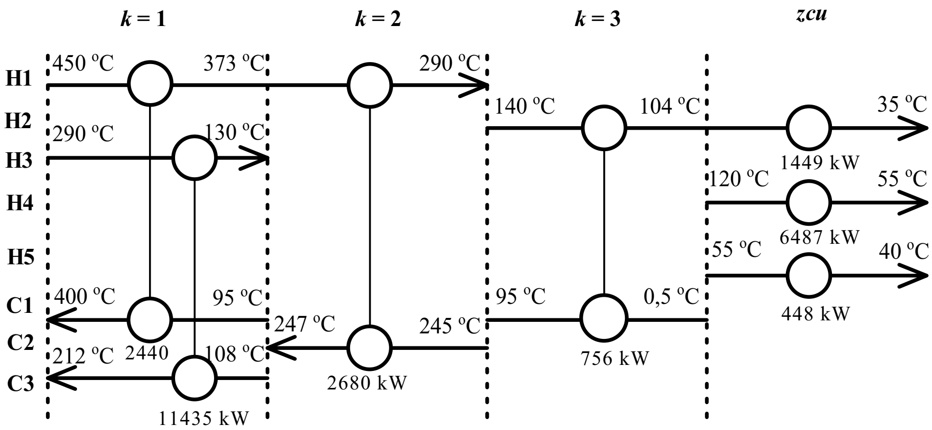

Figure 1. The optimal solution for the retrofitted problem.

2.2 New designed plant

The heat exchanger network (HEN) of the complex, new designed of the plant can approach the global optimum. Several optimization methods for the complex HEN can be used but the easiest and the best is the stage-wise method, when the right number of stage *k* is found because the problem could not converge. The problem data are presented in Table 2.

Table 2. Problem data for new designed plant example.

Stream	T_s/ ºC	T_t/ ºC	G/(kW/K)	h/(kW/m^2 K)
H1	268,6	120,0	0,173	0,3
H2	232,8	158,0	0,182	0,3
H3	158,0	80,0	0,924	1,4
H4	73,4	60,0	0,495	1,4
H5	43,5	43,4	583,300	2,0
H6	80,3	74,3	15,100	1,5
H7	118,0	32,0	0,123	1,0
C1	36,2	57,0	0,341	0,6
C2	57,0	70,0	8,473	1,2
C3	85,4	125,0	0,142	0,1
C4	136,8	137,6	47,637	1,5
C5	117,3	118,4	85,545	1,7

Installed heat exchanger cost, ($C_i = C_{fix} + C_v A^{ep}$) / EUR:
25 000 + 900 $A^{0,285}$; A = m^2
Annual utility cost of cooling water (C_{CW}; Swaney, 1989) / EUR/(kW a): 6,3
Annual utility cost of 5 bar steam (C_{steam}; Swaney, 1989) / EUR/(kW a): 62,0
Payback multiplier (r; Ahmad, 1985): 0,264

After the stage-wise theory is used to the 7 fixed stages, the problem can not be converged. So we used only 2 stages with initial starting point and it converged to a local optimum (see Figure 2). The HEN was solved with the minimum approach temperature of 2,7 K between hot and cold streams. Two major iterations were required using a total CPU time of 21,4 s on the VAX-3100. The network involves 12 exchangers of which 4 are coolers and 3 are heaters. Process streams matches are (H1, C5), (H2, C4), (H3, C1), (H3, C2) and (H6, C2), which are selected amongst the 82 exchangers embedded in the superstructure. The total annual cost for the network is 90 000 EUR/a. Cost to be considered includes the utility cost and the annualized capital cost for the countercurrent heat exchangers.

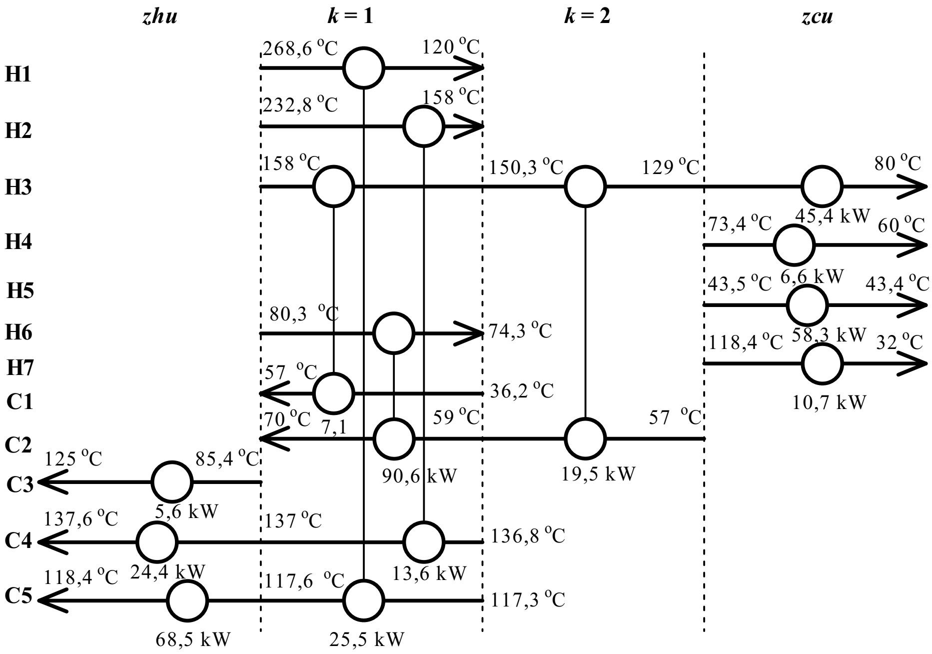

Figure 2. The optimal solution for the new designed problem.

3. Conclusions

We wanted to find the optimal number of stages in stage-wise method for industrial, retrofitted and newly designed process. Complex HEN can be solved easily and well enough with less stages than the maximum number of hot or cold streams.

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