CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216 DOI: 10.3303/CET1545307

Rational Use of Cooling Water in Heat Exchanger Network on Industrial Site

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The parallel heat exchanger network (HEN) arrangement is typically used industrially for once-through cooling water systems of several hot streams. The studied systems are when the cooling water temperature increase is rather low and limited by environmental restrictions, e.g. temperature increase lower than 10 °C, and the cooling water is at a temperature much lower than the output temperature of the hot streams. In the parallel arrangement, the water is supplied to each exchanger at the lowest temperature available. The series HEN arrangement requires higher exchanger area because the increase of cooling water temperature in each exchanger is lower than the attainable for the parallel arrangement. Nevertheless, the present study shows using a MINLP optimisation that some configurations combining series and parallel arrangements of heat exchangers can be more advantageous than the parallel. The optimal arrangement is obtained when the heat exchangers with similar amount of heat exchanged are grouped in parallel in the same stage where the stages are in series.

1. Introduction

Most industrial processes have a significant amount of heat that must be removed effectively in the environment using usually water as coolant. When once-through cooling water systems are used for the rejection of wasted heat to the environment, the output cooling water temperature becomes limited to avoid thermal pollution of the aquatic media where it is discharged. A particular scenario is when only hot streams to refrigerate are present, the allowed increase of temperature of the cooling water is rather low, e.g. 10 °C, and the cooling water temperature is much lower than all process streams. Industrial HEN configuration for this scenario is mostly in a parallel combination and cooling water is supplied to each exchanger at the lowest temperature available. Methods to improve the parallel combination for this particular scenario have not been addressed in literature. However, there are many methods focused not only on capital cost or retrofitting (Pejpichestakul and Siemanond, 2013), but on heat recovery and minimisation of heating and cooling services and some other parameters that are fixed for the mentioned scenario. Some examples of these methods are the genetic algorithm and simulated annealing (Ravagnani, 2005) or Pinch Analysis combined with MINLP programing (Klemeš and Kravanja, 2013).

In this work a mixed-integer nonlinear programming (MINLP) algorithm for HEN synthesis is presented to solve the above mentioned particular scenario. The problem involves a stage-wise superstructure development, its modelling and solution as an MINLP problem to obtain a favourable operating window. The HEN topology consists of parallel and series arrangements of heat exchangers. Three study cases are presented: in the first example the superstructure contains three hot streams and one cold utility (cooling water - CW); in the second example the superstructure contains four hot streams and the CW stream; for the third example a set of five hot streams and the CW stream is given. All data needed are collected from datasheets and measurements from an industrial site.

Please cite this article as: Tohăneanu M., Pleşu V., Iancu P., Bonet-Ruiz A., Bonet-Ruiz J., Muchan B., 2015, Rational use of cooling water in heat exchanger network on industrial site, Chemical Engineering Transactions, 45, 1837-1842 DOI:10.3303/CET1545307

2. Method

Heat transfer coefficient (HTC), heat capacity flowrate (FCP), initial and final temperature for the hot streams (THIN and THOUT) are provided for each case study. All the streams must be cooled and no integration opportunities exist, then the energy to be eliminated from the system is a constant value and does not depend on the HEN configuration. The cooling water (CW) is available at an initial temperature of 28 °C and a maximum output temperature of 38 °C is assumed, therefore the increase of temperature for the cooling stream is of 10 °C. Cooling water specific heat used is 4.193 kJ/(kg·K) and the heat transfer coefficient is considered 2.5 kW/(m^2·K). The required cooling water flow rate becomes fixed by the overall energy mass balance because the energy to be eliminated, cooling water specific heat and temperature increment of the cooling water stream are constant. However, a general approach for Pinch optimisation is also used for threshold problems (Ibrić et al, 2013). A constant cooling water flow rate means that the utility cost is also constant. Therefore, the annualised capital cost determines which the optimal HEN configuration is. The function for heat exchangers capital cost (€/y) is:

$$C_{inv} = 1{,}000 + 700 \cdot A \tag{1}$$

Although, the utility cost is known to be constant, a general approach is implemented where it is also optimised. The number of heat exchangers situated sequentially in the cooling water defines the number of stages and in each stage can be several heat exchanges situated in parallel. Several assumptions are considered: heat transfer coefficients and heat capacity flow rates are constant, counter-current flow in each heat exchanger (more efficient); only one match is allowed between hot stream and cold stream in every stage. The program is structured in five sections: data input (data parameters definition and input, variable definitions, equation definitions); equations; model; initial starting point (variable bounds, dynamic parameter initialization, initial starting point) and steady state iterations (solve subproblems).
The equations for HEN retrofit design are presented below. Each match corresponds to one heat exchanger:

$$Q_{i,k} - \Omega_i \cdot z_{i,k} \le 0 \tag{2}$$

Energy balances for each hot process stream:

$$(T_{in,i} - T_{out,i}) \cdot CP_i = \sum_{k \in N} Q_{i,k} \tag{3}$$

Energy balances for each match (hot process stream - CW):

$$(T_{hi,k+1} - T_{hi,k}) \cdot CP_i = Q_{i,k} \tag{4}$$

$$(T_{couti,k} - T_{cin,k}) \cdot \dot{m}_{W\,ik} \cdot c_{pw} = Q_{i,k} \tag{5}$$

Mass and energy balances for splitters and mixers for each stage:

$$\sum_i \dot{m}_{W\,ik} + FF_{k+1} = FO_k + \sum_i \dot{m}_{W\,ik+1}, \ k \in \{1,\dots,N-1\} \tag{6}$$

$$\left(\sum_i \dot{m}_{wi,k}\right) \cdot TO_k = \sum_i (\dot{m}_{wi,k} \cdot T_{couti,k}) \tag{7}$$

$$\left(\sum_i \dot{m}_{wi,k}\right) \cdot TO_k + FF_{k+1} \cdot T_{wi} = \left(\sum_i \dot{m}_{wi,k}\right) \cdot T_{cin,k+1} + FO_k \cdot TO_k \tag{8}$$

Fresh utility requirements for the first stage:

$$FF_k = \sum_i \dot{m}_{W\,ik}, \ k=1 \tag{9}$$

Inlet and outlet temperatures for the superstructure:

$$T_{in,i} = T_{hi,N}$$
$$Tout,i = T_{hi,1} \qquad (10)$$
$$T_{cin,1} = T_{wi}$$

Hot process streams temperatures restrictions on every stage:

$$T_{hi,k} \le T_{hi,k+1}$$
$$T_{cin,k} \le T_{couti,k}$$
$$T_{wi} \le T_{cin,k} \qquad (11)$$
$$T_{couti,k} \le T_{couti,k+1}$$

Logical constraints regarding temperature differences:

$$dtcold_{i,k} \le T_{hi,k} - T_{couti,k} + \Gamma_i \cdot (1 - z_{i,k})$$
$$dthot_{i,k} \le T_{hi,k} - T_{cin,k} + \Gamma_i \cdot (1 - z_{i,k})$$
$$dtcold_{i,k} \ge \Delta T_{min} \cdot z_{i,k} \qquad (12)$$
$$dthot_{i,k} \ge \Delta T_{min} \cdot z_{i,k}$$

The objective function is the annualised total cost, which should be minimised:

$$\min F = \min C_T = \min(C_{inv} + C_{op}) \qquad (13)$$

The superstructure used for a HEN with three hot process streams is shown in Figure 1.

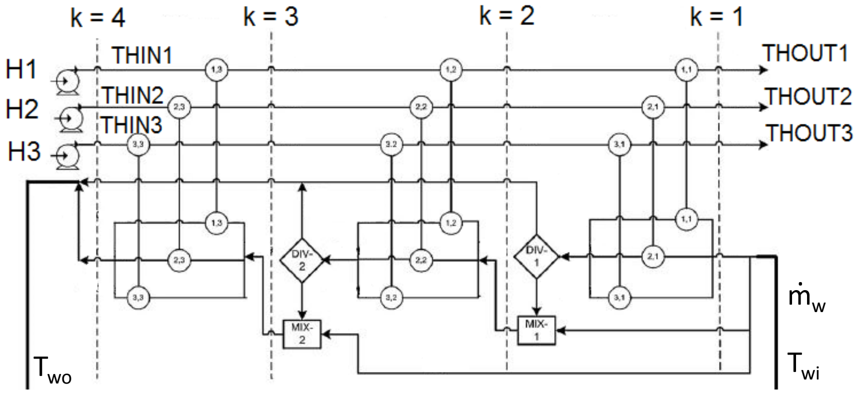

Figure 1: Superstructure proposed for a HEN with three hot streams (Ponce-Ortega, 2007)

3. Results

3.1 Case study A

Data input for first example with three hot streams are shown in Table 1. The structure industrially used is a single stage where all the heat exchangers are in parallel (Figure 2). The maximum number of stages with the minimum number of heat exchangers is when all the heat exchangers are arranged in series (Figure 3). The superstructure optimised has three stages (k = 3) and the number of parallel heat exchangers in each stage is optimised (Figure 4). The MINLP problem includes 2 binary variables, 6 positive variables, 31 parameters and 20 equations and the optimised variables are presented in Table 2. The required cooling water flow rate is 240 kg/s although the converged optimised value using MINLP is a bit lower, 233 kg/h. The parallel HEN arrangement provides a lower annualised capital cost, 74,000 €/y, than the series HEN arrangement, 78,000 €/y, or any other three stages arrangement, 80,000 €/y. The reason is that for any other three stages arrangement than the series HEN the number of heat exchangers increases and the exchanger cost expression has a fixed cost independent of the area that makes it not viable.

Table 1: Hot process streams data for case study A

Stream	THIN (°C)	THOUT (°C)	FCP (kW/K)	HTC ($kW/m^2/K$)
H1	166	43	24	0.232
H2	116	54	80	0.698
H3	85	66	114	0.581

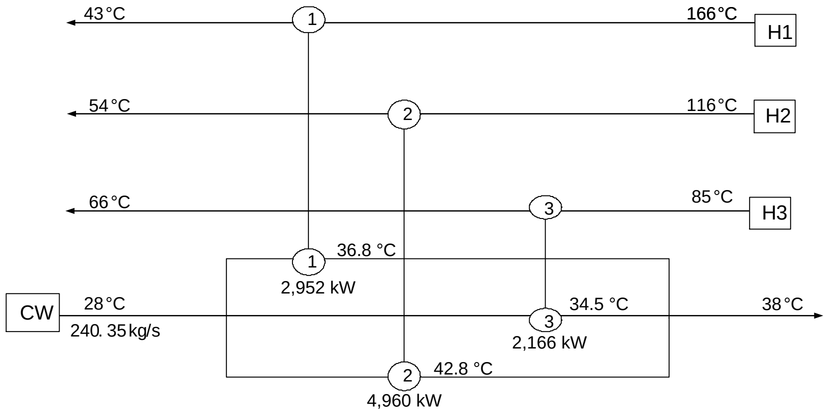

Figure 2: Grid Diagram for HEN with splitting for case study A

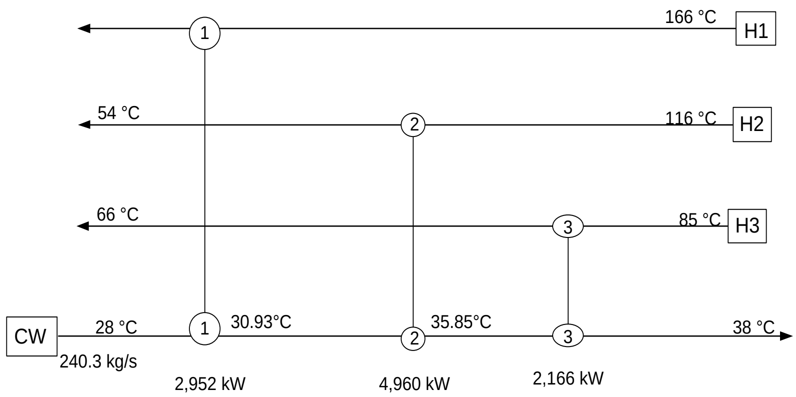

Figure 3: Grid Diagram for case A

Table 2: Heat exchangers characteristics for case study A

Exchanger	A (m^2)	Q (kW)	Cost (€/y)
1	115	2,640	42,895
2	84	1,464	34,952
3	26	2,166	18,484
4	76	2,320	32,885
5	104	1,488	40,188

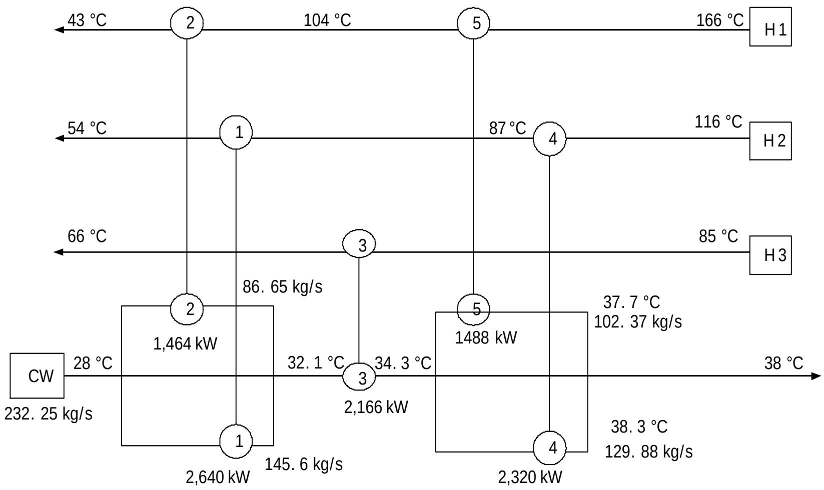

Figure 4: Grid Diagram of a cost-optimum HEN for case A with 3 stages

3.2 Case study B

Data input for the second example with four hot streams are shown in Table 3. Again the parallel HEN arrangement provides a lower total annualised capital cost, 98,000 €/y, than the series HEN arrangement, 105,000 €/y. Similar results are obtained in some other case studies analysed. Therefore, this fact is in agreement with the industrial practice to use the parallel HEN arrangement instead of the series HEN arrangement. Nevertheless, when three stages are used then a lower annualised capital cost is attained, 95,000 €/y. The novel HEN optimised arrangement is shown in Figure 5 and the results in Table 4. This result is very important because it shows that some HEN arrangements are more suitable than the default industrial parallel arrangement. According to several examples solved, it is stated that a HEN arrangement where heat exchangers with similar heat exchanged (Q) are grouped and placed together in stages in parallel can be more advantageous than the parallel HEN arrangement.

Table 3: Hot process streams data for case study B

Stream	THIN (°C)	THOUT (°C)	FCP (kW/K)	HTC (kW/m^2/K)
H1	80	39	59.2	0.508
H2	98	41	32.0	0.625
H3	105	40	25.8	0.416
H4	92	45	40.5	0.557

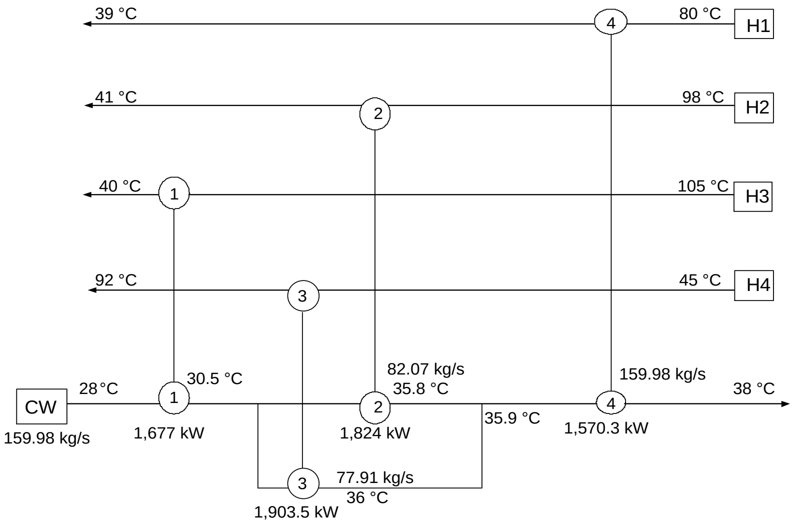

Figure 5: Cost-optimum HEN for case B with 3 stages

Table 4: Heat exchangers characteristics for case study B

Exchanger	A (m^2)	Q (kW)	Cost (€/y)
1	138	1,677	48,447
2	126	1,824	45,554
3	136	1,903	48,131
4	134	1,570	47,464

4. Conclusions

The study focused on once-through cooling water systems limiting the cooling output temperature used to cool several hot streams. A MINLP problem for HEN optimal design through a new superstructure has been proposed. The superstructure allows the combination of arrangements in series and in parallel of the heat exchangers. Based on the results obtained, it is stated that the heuristic rule that drives a design of HEN for minimum utility consumption in a parallel arrangement does not necessarily lead to an optimal solution. The optimal arrangement is obtained when heat exchangers with similar heat exchanged are grouped in parallel and each group (stage) with rather different heat exchanged are arranged in series.

Nomenclature

A - Heat transfer area, m^2
HTC - Total heat transfer coefficient, kW/(m^2·K)
c_p - specific heat, kJ/(kg·K)
C_{inv} – annualised investment cost, €/y
C_{op} – annualised operating cost, €/y
C_T - annualised total cost, €/y
dtcold - temperature difference for the cold side of match i-k
dthot - temperature difference for the hot side of match i-k
F - objective function
FF – water flow necessary for each level, kg/s
FCP - heat capacity flowrate, kW/K
ṁ - mass flow, kg/s
N - total number of stages
Q - heat flow exchanged between hot process stream i and cold utility in stage k, kW
TO – water temperature at the exit of the split, °C
T_{in} - hot process temperature at k level entrance, °C
T_{out} - hot process temperature at k level exit, °C
T_{cin} - water temperature at k level entrance, °C
T_{couti} - water temperature at k level exit, °C
T_{wi} - water temperature entering the cooling tower, °C
T_{wo} - water temperature leaving the cooling tower, °C
T_{wb} - wet bulb temperature, °C
ΔT_{min} – minimum approach temperature difference, K
z - binary variable for match i-k

Subscripts
i - hot process streams
k – superstructure level
w - cold utility

Symbol
Γ - upper bond for temperature difference
Ω - upper bond for heat exchanger duty

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