Fuzzy Approach for Heat Exchanger Network

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ABSTRACT
A systematic method for synthesis of heat exchanger networks by using fuzzy approach is presented in this paper, the proposed method consists of three sequential steps to select the optimal approach temperature: i) estimation of minimum approach temperature, minimum hot utility and minimum cold utility. ii) Fuzzy approach. iii) Selection of the best weight index. The proposed method has been applied for two problems well-known in published literature. The results of these case studies show that the present strategy is simple and accurate in finding out global optimum in comparison with previous works, characterized by its simplicity and can be implemented by hand calculations.

Keywords
Process Synthesis, Fuzzy Approach, Energy saving, Heat Recovery, Heat Integration, Heat Exchanger Network.

1. INTRODUCTION
Chemical plants need efficient management of energy. For this purpose, an optimum integration of supply and removal of heat among the process streams is required. The most important equipment in energy integration is heat exchanger. A heat exchanger exchanges heat between a hot and a cold process stream: the hot stream cools down to the desired temperature and the cold stream becomes hot to the desired level. Based on the heat load, the heat exchange area is determined. The exchanger is fabricated based on this area. A network of heat exchangers is usually used in a process plant.

Design of the best heat exchanger network is an optimization problem where the total cost is to be minimized. The total cost comprises of the cost of the exchanger units and the cost of the utilities. Cost of the exchanger is directly related to the heat exchange area. The cost of hot and cold utilities is based on their unit cost and annual consumption. Masso and Rudd [1] first defined the network design problem in a rigorous manner. They proposed minimization of the total cost for designing an optimum heat exchanger network. Since then, more than 500 publications have appeared in the literature in search of the method, which can find the least-cost network. A recent article by Furman and Sahinidis [2] provides an excellent review on the subject.

In heat exchanger network design several heuristics are used. Some examples of these heuristics are minimization of number of exchangers, splitting of process streams, minimization of the consumption of utility and use of the cheapest utility. Although suitable for a particular problem, these heuristics do not provide any general guideline, which can ensure that following a particular set of them will ensure the best network. Although there have been many publications on the design of heat exchanger networks during the past three decades, the problem is still open for further research. Mainly two approaches are noted in these works: (a) pinch method and (b) optimization techniques. in process design The pinch method has been a landmark development Linnhoff & Hindmarsh, [3]. This method is based on the first and second laws of thermodynamics. The main objective of this method is to save expenses by maximizing process-to-process heat recovery. This also reduces the external utility (e.g., steam and cooling water) load.

Successful work has been done on heat exchanger network synthesis (HEN) using both pinch technology and MINLP techniques. Such developments have been reviewed in a number of publications Linnhoff & Flower, [4, 5]; Linnhoff & Ahmad, [6] Papoulias & Grossmann, [7, 8]; Yee & Grossmann, [9, 10].

According to Ravagnani *et al.* [11], several kinds of studies were done aiming to develop methodologies to obtain optimal HEN to reach these goals. Research was concentrated in three important areas, Pinch Analysis, which uses thermodynamic concepts, Heuristics and Mathematical Programming, such as (LP), (NLP), (MILP), and (MINLP). Recently, heuristic methods of optimization have also been used to solve linear and non-linear models Hussein [12]

Recent approaches with both techniques have shown to be capable of synthesizing near optimal networks for real industrial problems. However, not much has been done to ensure that the resulting networks are fully consistent with what is finally achieved in terms of industrial hardware. Although most of the current synthesis techniques are based on the assumption of constant film heat transfer coefficients

In this paper a new systematic method for synthesis of heat exchanger networks has been presented, the proposed method consists of three sequential steps to select the optimal approach temperature, the results of case studies show that Fuzzy approach is simple in finding out global optimum minimum approach temperature in comparison with previous works.

2. PROBLEM STATEMENT
The Heat exchanger network synthesis problem to be addressed in this paper can be stated as follows: A set of hot streams to be cooled and cold streams to be heated are given which include stream data with inlet and outlet stream temperatures, heat capacity flow rates and heat transfer coefficients. In addition, a set of hot and cold utilities are specified. The basic objective of the HENS problem is to synthesize a network of heat exchangers, which facilitate the desired heat exchange, while keeping the investment and operating costs to a minimum value. Fuzzy approach is employed in the present work to select the optimum minimum

approach temperature which accordingly leads to minimum total annual cost.

3. FUZZY SET THEORY

Zadeh [13] first formulated fuzzy set theory in 1965; the theoretical information are available in Dubois and Prade [14]. It will just explain the basic notions of such theory and the typical applications in chemical engineering. Fuzzy set theory is able to describe uncertainty that can arise in a lot of manners in chemical engineering. Following Kraslawski [15], distinguished two main kinds of uncertainty: ambiguity and imprecision. A proposition is ambiguity if its truth or its falsity cannot be definitely established. A proposition is imprecise if its value is not sufficiently determined with respect to a given scale. Both ambiguity and imprecision can be also divided into many uncertainty types. Here, the uncertainties of heuristic rules are on the latter type, because of the lack of precision of terms like “high” or “small”.

A fuzzy set A in the space $X = \{x\}$ can be defined as the set:

$$\mathbf{A} = \{x, \mu_A(X)\} \qquad \forall\, x \in X$$

$$\mu_A : X \to [0,1] \qquad X \to \mu_A(X) \tag{1}$$

$\mu_A(X)$: Expresses the grade of membership of x in A

$\mu_A(X) = 0$ Means that x is indefinitely a member of A

$\mu_A(X) = 1$ Means that x is definitely a member of A

The intermediate values of the membership function denote partial defined to some extent, membership of A.

The fuzzy set theory is, in effect, a step toward rapprochement between the precision of classical mathematics and the pervasive imprecision of the real world, a rapprochement born of the incessant human quest for a better understanding of mental process and cognition Zadeh [16].

Some algebraic operations can be defined on fuzzy set Dubois D. and Prade H. [14] like:

Union $$\mu_{A\cup B} = \max(\mu_A, \mu_B) \tag{2}$$

Intersection $$\mu_{A\cap B} = \min(\mu_A, \mu_B) \tag{3}$$

A decision is to be made by evaluating all the related rules at different levels in a knowledge base. The evaluations are carried out according to the MAX-MIN algorithm.

$$\mu_j(x) = \max\left\{\min_{k\in K}\left\{\mu_{j1,}(x_1), \mu_{j2,}(x_2), \ldots\ldots \mu_{jk,}(x_k)\right\}\right\} \tag{4}$$

Where:

$\mu_{jk,}(x) =$ Membership function of variable x in fuzzy set k representing the k[th] antecedent of the i[th] rule at the j[th] level.

The MIN operation yields a set truth values (τ_I) through evaluation of the membership functions of all the rules. Then, a single rule is selected by performing the MAX operation, i.e.

$$\tau = \max\{\tau_1, \tau_2, \tau_3, \ldots\ldots \tau_I\} \tag{5}$$

This selected rule is activated or fired. The same operation is repeated at the succeeding level based on the information received from the preceding level.

4. FUZZY APPROACH STRATEGY

Based on the strategy of Fuzzy set theory the following algorithm was developed to select optimal heat exchanger networks and it consists of four steps:

Step1. For different values of minimum approach temperature, get the minimum heating (Q_H) requirement & the minimum cooling (Q_C) requirement from the cascade diagram according to Linnhoff, B., and Hindmarsh [3], for each value of ΔT, normalized $[(Q_H)_{min}, (Q_C)_{min}]$ can be derived by application of a linear programming code, two bounds $(f)_{min}$ & $(f)_{max}$ can be computed, and the normalized variables can be estimated by:

$$\mu = \frac{(f - f_{max})}{(f_{min} - f_{max})}, \text{ Where} \tag{6}$$

$\mu = 0$ If $f = f_{max}$; $\mu = 1$ If $f = f_{min}$

Step2. Calculate the minimum value of parameters according to equation (4).

Step3. The final step corresponds to the choice of the best weight Index. The operation is carried out by comparing (τ) values for all minimum approach temperature and by choosing the greatest one according to equation 5.

Step4. Fuzzy approach strategy

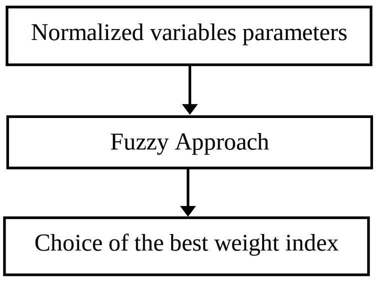

Fig.1. Fuzzy Approach Strategy

5. EXAMPLES

The proposed method will be tested using two case studies reported in the literature, for comparison.

5.1. Example 1

Our problem here is H4SP1R, two hot and two cold streams, one cold utility and one hot utility stream taken from Shenoy [17]. The specifications for all streams, plant data are shown in Table 1and 2. The overall heat transfer coefficients for all matches are the same. The example was solved by Fuzzy approach method to minimize Total Annual Cost (TAC). The summary of results of the proposed method is shown in Table

5, which confirmed with results obtained, thus the optimum ΔT = 25°C which give a global cost of ($/Yr 287,875) and a weight index of (0.553), which ensures our strategy. The final optimum network is shown in Fig 4. The area requirement is 1886.8 m^2 and the total capital cost is ($/Yr 287,875). The solution obtained by the proposed method is lower than the solution produced by MINLP and Supertarget method as shown in Table 5.

5.2. Example 2

This problem involves finding a cost-optimal network of exchangers for six hot streams and four cold streams one cold utility and one hot utility stream having the same heat transfer coefficients. This case was studied first by Ahmed [18]. The input data for the problem is given in Table 6 and 7 The summary of results of the proposed method is shown in Table 8, which confirmed with results obtained, thus the optimum ΔT = 17.5°C with TAC ($/Yr 2,647,630) and a weight index of (0.500), which ensures our strategy. The final optimum network is shown in Fig 7. The annual cost of hot utility and cold utility is ($/Yr 2,104,705). The area requirement is 55,513 m^2 and the total capital cost is ($/Yr 3,330,832).

Table 1: Stream and cost data for Example 1

Stream	T_{in} (°C)	T_{out} (°C)	MCp kW/°C
H1	175	45	10
H2	125	65	40
C3	20	155	20
C4	40	112	15
HU	180	179	-
CU	15	25	-

Table 2: Plant Data for Example 1

Utility data	Fuel gas cost	120 ($/kW.yr)
	Cooling water cost	10 ($/kW.yr)
Plant Data	Rate of interest (i)	10 %
	Lifetime (n)	5 years
Capital cost data	A_f : *Annualization factor*	$(1+i)^n / n$
	Installed unit cost ($)	$30000 + 750(A)^{0.81}$
	U (overall heat transfer coefficients)	0.2 (kW/m^2°C)

Table 3: Results of Fuzzy Approach for Example 1

ΔT (°C)	μ_1	μ_2	μ_3	min	τ
15	0.375	0.926	0.926	0.375	
20	0.500	0.741	0.739	0.500	
25	0.625	0.556	0.553	0.553	**0.553**
30	0.750	0.370	0.367	0.367	
35	0.875	0.185	0.181	0.181	

Table 4: Cost Analysis of HEN at different ΔT_{min} for Example 1

ΔT_{min}	Q_H (kW)	Q_C (kW)	Area (m^2)	Annualized total cost ($/Yr)
15	430.0	350.0	3105	309,065
20	605.0	525.0	2360	292,357
25	780.0	700.0	1886	**287,875**
30	955.0	875.0	1555	290,250
35	1130	1050	1307	296,833

Table 5: Comparison of results for Example 1

	Shenoy [17]	Hojjati [19]	Present Work
Method	Supertarget	MINLP	F.A
ΔT (°C)	-	-	25
Hot Utility (kW)	400	400	780
Cold Utility (kW)	320	320	700
Total area (m^2)	2041	1590	1886.8
Global Cost ($/yr)	383,475	325,502	287,875

Table 6: Stream and cost data for Example 2

Stream	T_{in} (°C)	T_{out} (°C)	M Cp (kW/°K)
H1	85	45	156.3
H2	120	40	50
H3	125	35	23.9
H4	56	46	1250
H5	90	86	1500
H6	225	75	50
C1	40	55	466.7
C2	55	65	600
C3	65	165	180
C4	10	170	81.3
HU	200	198	-
CU	15	25	-

Table 7: Plant Data Example 2

Utility data	Fuel gas cost	100 ($/kW.yr)
	Cooling water cost	15 ($/kW.yr)
Plant Data	Rate of interest (i)	10 %
	Lifetime (n)	10 years
Capital cost data	A_f : *Annualization factor*	$\frac{i(1+i)^n}{(1+i)^n - 1}$
	Installed unit cost ($)	60 (A)
	U (overall heat transfer coefficients)	0.025 (kW/m^2K)

Table 8: Results of Fuzzy Approach Example 2

ΔT	μ_1	μ_2	μ_3	min	τ
10	0.286	1.000	1.000	0.286	
12.5	0.357	0.845	0.845	0.357	
15	0.429	0.691	0.691	0.429	
17.5	0.500	0.590	0.590	**0.500**	**0.500**
20	0.571	0.425	0.425	0.425	
25	0.714	0.395	0.395	0.395	
30	0.857	0.265	0.265	0.265	

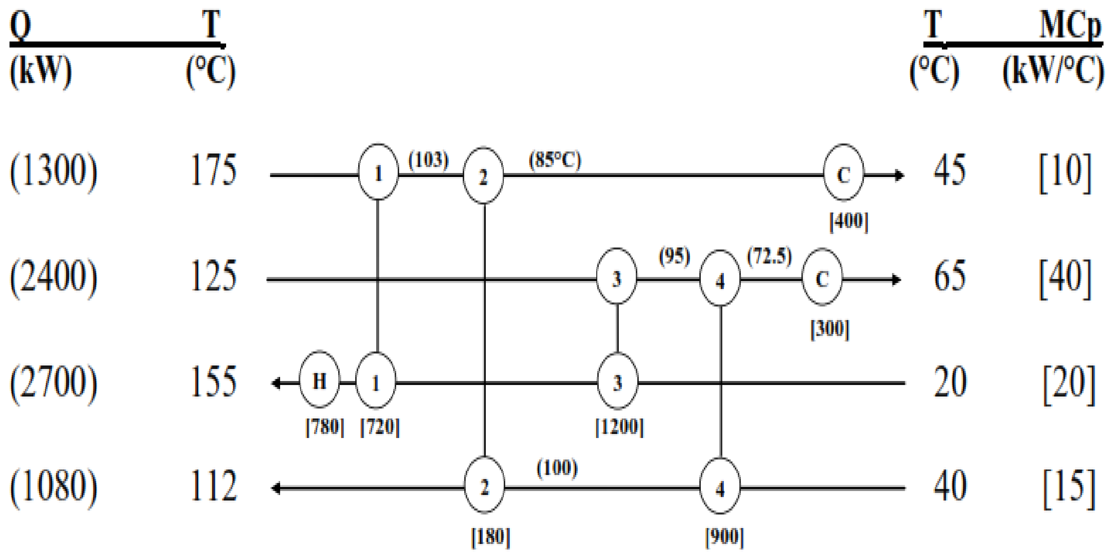

Fig.2. Optimum design for HEN synthesis problem H4SP1R at ΔTmin = 25°C

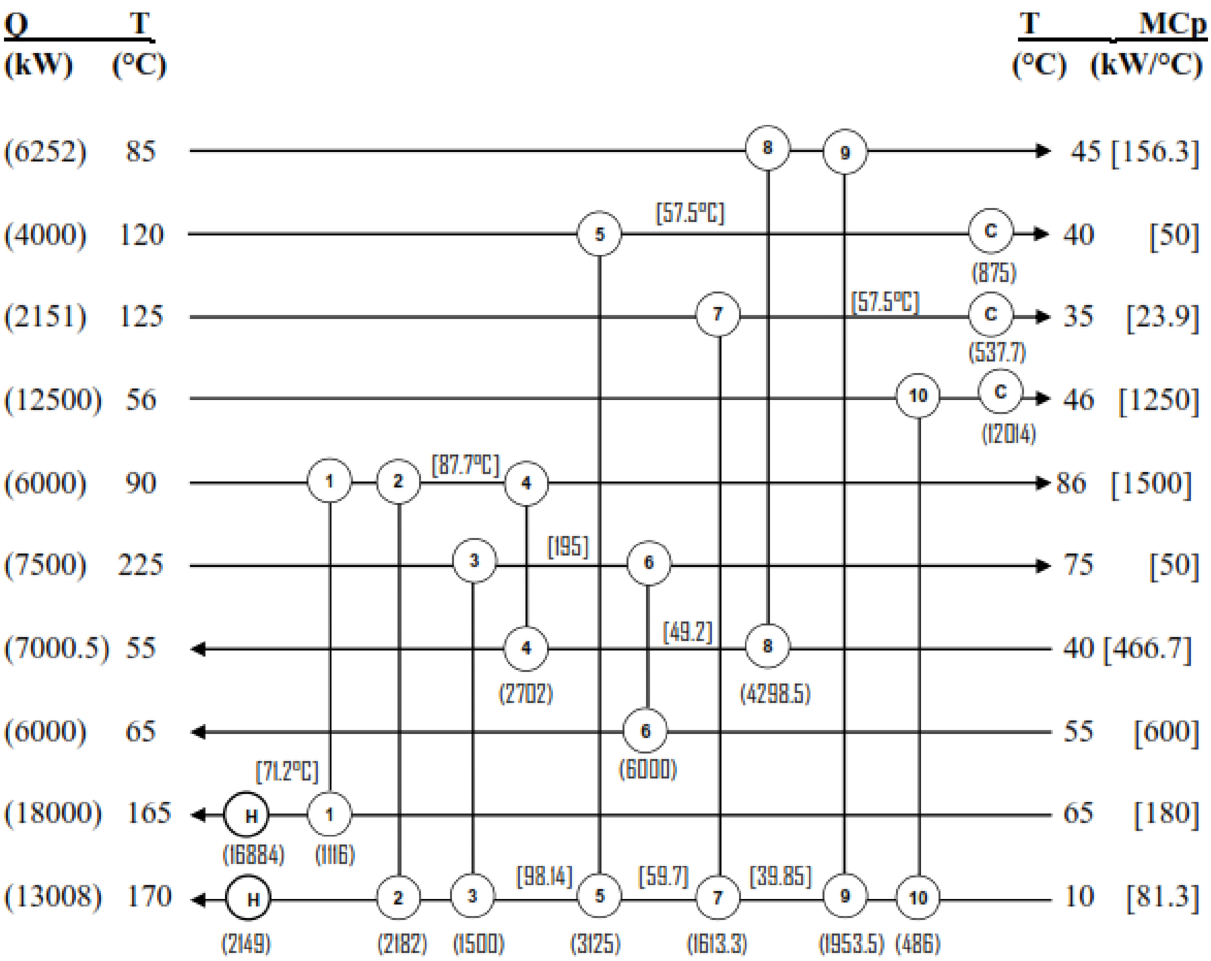

Fig.3. Grid diagram for HEN synthesis problem 10SP1 at ΔTmin = 17.5°C

Table 9: Cost Analysis of HEN at different ΔT_{min} for Example 2

ΔT_{min}	Q_{Hmin} (kW)	Q_{Cmin} (kW)	Area (m^2)	Annualized total cost ($/Yr)
10	15399	9795	122,634	2,886,189
12.5	16770	11166	88,711	2,712,060
15	18139	12534	72,979	2,715,645
17.5	19033	13429	55,513	**2,647,660**
20	19608	14004	55,070	2,709,499
25	20760	15156	47,936	2,772,104
30	21911	16307	29,669	2,725,819

Table 10: Comparison of results of HEN Example 2

	Ahmed [18]	Ravagnani [20]	Krishna [21]	This Work
Method	Super-target	Pinch + (GA)	(DEM)	F.A.
ΔT (°C)	10	24	19.46	17.5
Hot Utility (kW)	15,400	20,529	20,745	19,033
Cold Utility (kW)	9,796	14,923	15,139	13,427
Total area (m^2)	-	56,000	56,085	55,513
Global Cost (M$/yr)	**7.074**	**5.672**	**5.666**	**5.435**

6. CONCLUSIONS

The present study explores new systematic method for synthesis heat exchanger network. The proposed method when applied to problems previously reported in the literature yielded optimum solutions which are consistent with different approach. It is evident that the performance of the Fuzzy approach is quite encouraging, characterized by its simplicity and can be implemented by hand calculations.

The results of case studies show that the present strategy is both robust and accurate in finding out global optimum cost & optimum minimum approach temperature in comparison with previous works, which ensures its economic effectiveness

Nomenclature

LP	Linear Programming
NLP	Non Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
Max	Maximum
Min	Minimum
f_{min}	Minimum bound of linear programming
f_{max}	Maximum bound of linear programming
ΔTmin	Minimum approach temperature
T_{in}	Inlet Temperature (°C)
T_{out}	Outlet Temperature (°C)
MCp	Heat capacity flowrate
HU	Hot Utility
CU	Cold Utility
FA	Fuzzy Approach
W.I	Weight Index
TAC	Total Annualized Cost
GA	Genetic Algorithm
DEM	Differential Evolution Method
μ_1	Normalized ΔT
μ_2	Normalized Q_H
μ_3	Normalized Q_C

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