Modification of Heat Exchanger Network Design by Considering Physical Properties Variation

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The temperature dependency of streams' physical properties can have a significant effect on heat exchanger networks (HENs) design. An average value can be utilized during each temperature interval in order to determine the physical properties of the streams. Another method is the use of the physical properties' values, which vary with regard to temperature along each stream.

In this paper, the energy targeting for an ammonia plant has already been done before using both methods, with and without stream segmentation. Pinch temperature, ΔT_{min}, and the values of the hot and cold utilities in both cases are different and so the HEN has to be changed. The results demonstrates that when splitting streams into two or more segments within the existing ammonia plant, the pinch point increases by about 3 °C, and hot and cold utilities consumption increases by approximately 23 % and 11 %, respectively. The area of the heat exchanger network also is increased by about 50 %. Finally, an aggregation diagram is introduced for the evaluation of specific heat capacity distribution along the whole streams of the network.

Key words:
Heat exchanger networks, heat integration, pinch technology, physical properties variation, aggregation diagram

Introduction

Energy integration technology is a remarkable approach for decreasing energy consumption and improving profitability throughout the chemical process industries. Pinch analysis is an efficient method for developing better-integrated process designs during process heat integration, these advances being achieved as pinch technology by Linnhoff and Vredeveld.[1] The main objective of this method is to save expenses by maximizing process-to-process heat recovery. The concept of "target before design" was introduced by Linnhoff and Hindmarsh,[2] for designing those of individual processes which consider pinch rules. The first step in the targeting phase is to calculate the minimum heating and cooling requirements for the heat exchanger network. Well-designed HENs can significantly contribute to a decrease in energy consumption and, therefore, energy expenses.[3] This is accomplished by minimizing the use of utilities and maximizing heat recovery between existing hot and cold streams.

Several techniques and analyses have been developed recently for the heat exchanger network design problem: tree searching algorithm method,[4] neural networks,[5] mixed integer nonlinear programming,[6] genetic algorithms,[3,7] R-curve and Site Source Sink Profile (SSSP) analysis,[8] shortcut method,[9] graphical technique,[10] etc. Although pinch analysis relies on heuristic rules and does not guarantee a global optimal HEN solution, it is one of the most notable approaches to designing HENs and maximizing heat recovery.[3,10] Therefore, we used pinch analysis in this paper.

Energy management can be achieved along two routes; paying less per unit of energy, or reducing energy consumption per unit of product.[11] Co-generation of heat and power is an example of the first route, whilst energy integration of the process plant is an example of the second. In the theory of process integration, it is generally supposed that the values of the physical properties are constant. This consideration can achieve solutions very far from the industrial application point of view.[12] However, physical property variation can have a significant effect during the targeting phases. In the works of Panjeh Shahi,[13] Polley *et al.*,[14] and Polley and Panjeh Shahi,[15] a relationship between the pressure drop and the individual heat transfer coefficients was proposed.

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This paper presents energy integration and modification of heat exchanger network design for an ammonia plant, using recent advances in pinch technology in both cases. In the first case, targeting has been carried out and the physical properties over the whole of each stream are supposed to be constant. In the second case, various physical properties have to be considered as some streams have to be divided into several segments containing constant properties. On the other hand, the streams that have various physical properties within the range of their temperatures have to be segmented into several sub-streams using an approximation of their physical properties. Various specific heat capacities can lead to a shifting of the pinch point, and thereupon produce differences during utility targeting.

Energy targeting

Targets are theoretical values that illustrate an ideal or perfect situation. They are significant as examination tools as they provide a comparison of how close the current design is to the optimal design. Energy targets are the minimum amounts of utilities needed to satisfy the process streams' requirements.[16] During energy integration, extracting process streams is the first step when considering energy targets. Therefore, as CP is assumed to be constant for each cold or hot stream, from a supply temperature (T_s) to a target temperature (T_t), the total heat added or removed will be equal to the stream enthalpy change, eq. (1):

$$Q = \int_{T_s}^{T_t} CP\mathrm{d}T = CP(T_t - T_s) = \Delta H \qquad (1)$$

where, CP is the product of the specific heat capacity (C_P) and the mass flow rate of the process stream. On the other hand, differential heat flow dQ, when added to a process stream, will increase its enthalpy (H) by $CP\,\mathrm{d}T$.

In the conventional pinch method, CP is the mean heat capacity flow rate for each stream between the supply and target temperatures, which can be calculated by arithmetic or geometric means. The mean value theorem is another way of calculating mean heat capacity flow rate, as given by eq. (2):

$$CP_m = \frac{\int_{T_1}^{T_2} CP\mathrm{d}T}{\int_{T_1}^{T_2} \mathrm{d}T} \qquad (2)$$

The CP of a stream rarely varies when the temperature difference is satisfactory and the enthalpy of each stream with fixed heat capacity is constant throughout the temperature range. However, for greater temperature differences, the physical properties and, therefore, the amount of enthalpy are related to the temperature. In this condition, streams should be segmented into different ranges of temperature; in order to accurately portray the CP value of a stream as it is heated or cooled.

Segmenting streams

A constant specific heat capacity can provide a sound approximation for the behavior of a stream if any changes in heat capacity, C_P, are small. On the other hand, dividing a stream becomes indispensable when the heat capacity of a stream fluctuates over its temperature range across the heat exchanger network (HEN). Fig. 1 illustrates how to determine segmentation regarding hot and cold process streams. Hot process stream segments must always predict a lower temperature than the actual temperature in order to preserve a conservative approach. Likewise, cold process stream segments must always predict a temperature higher than the actual temperature.[17,18] Process streams can be segmented by defining different heat capacities and local heat transfer coefficients for different temperature ranges of the temperature-enthalpy plot.

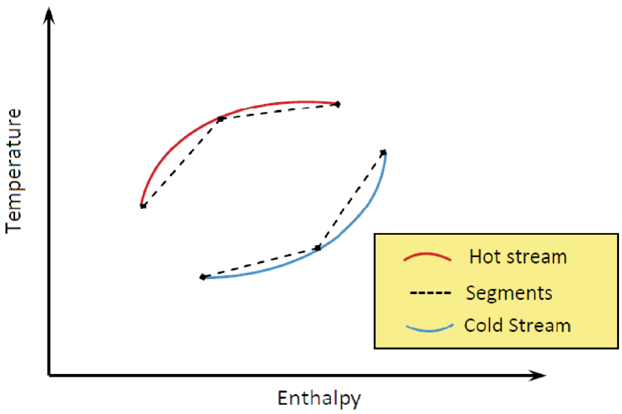


Fig. 1 – *Segmenting hot and cold process streams*

Heat transfer coefficient

The heat transfer coefficient (HTC) is used for calculating the area of the heat exchanger network. Within the targeted area, the effect of individual stream film heat transfer coefficients within the total area of the network can be represented by the following expression in eq. (3), as demonstrated by Linnhoff and Ahmad:[19]

$$A_{total} = \sum_{k=1}^{K} \frac{1}{\Delta T_{LM,k}} \left(\sum_{i=1}^{I} \frac{q_{i,k}}{h_{i,k}} + \sum_{j=1}^{J} \frac{q_{j,k}}{h_{j,k}} \right) \qquad (3)$$

Here $q_{i,k}$ and $q_{j,k}$ are the individual heat loads on the hot stream i or the cold stream j in the segment k; likewise $h_{i,k}$ and $h_{j,k}$ are the individual film heat transfer coefficients. Obtaining the total area of a heat exchanger network using this method requires knowledge of film heat transfer coefficients. For the shell and tube sides of the heat exchanger, the value of HTC relates to Reynolds and Prandtl numbers can be evaluated from eqs. (4) and (5) respectively:

For shell side:

$$\frac{h \cdot D}{k} = 0.36\,\mathrm{Re}^{0.55} \cdot \mathrm{Pr}^{\frac{1}{3}} \left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{4}$$

For tube side:

$$\frac{h \cdot D}{k} = 0.023\,\mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{\frac{1}{3}} \left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{5}$$

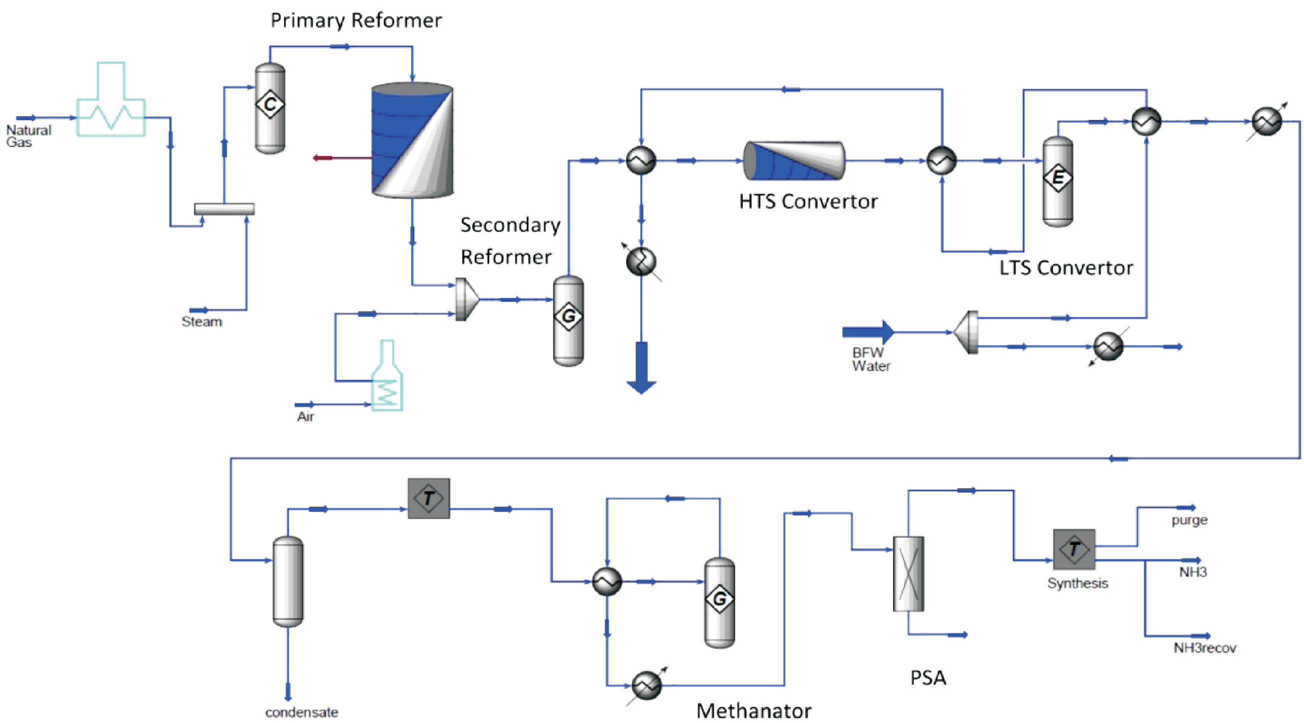
Which:

$$\mathrm{Re} = \frac{D \cdot \rho \cdot v}{\mu}, \qquad \mathrm{Pr} = \frac{C_P \cdot \mu}{k} \tag{6}$$

The eqs. (4) and (5) are used to calculate the HTC based on the specified physical properties values consisting of density, viscosity, heat capacity, and conductivity (according to eq. (6)); while these properties are also related to temperature.

Process description

A grass root design for an ammonia plant was applied as a case study in order to survey the effects of physical properties' variations within the heat exchanger network design. Natural gas was used as feedstock to produce 1000 tons of ammonia per day with purity of about 99.99 %. Firstly, the natural gas had been desulphurized in order to remove sulphur compositions from the feed stream. The natural gas was heated in the convection section of a primary reformer after mixing with steam, so that it would then react within the primary and secondary reformers. The nitrogen requirements for the ammonia reaction were obtained from preheated air introduced into the secondary reformer. The required heat for secondary reformer was provided from the reaction between O_2, H_2, and CH_4. The hot gases leaving the secondary reformer have high heat content and are primarily employed for the production of high-pressure steam in thermosiphon heat exchangers. In two stages consisting of high and low temperature shift converter, carbon monoxide was converted into carbon dioxide after mixing with H_2O, and then the CO_2 was absorbed by MEA. The residual CO and CO_2 were converted into CH_4 in the methanator, in order to prevent catalyst poisoning from the ammonia converter. H_2 and N_2 reacted in the ammonia converter to form the ammonia product after compression with steam turbines. The hot gases leaving the converter were cooled over a series of exchangers where the ammonia was condensed and the non-reactive gases were circulated back (Fig. 2).



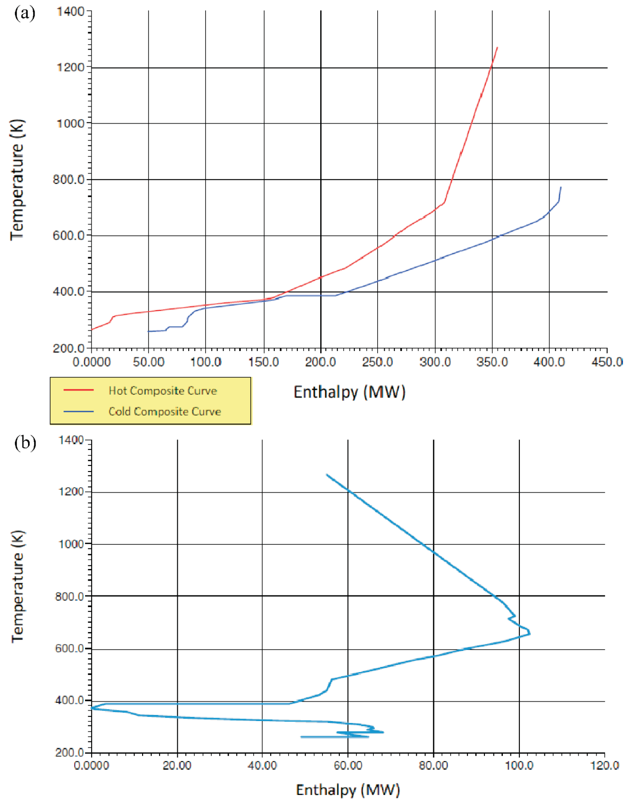
F i g . 2 – *Schematic diagram of ammonia plant*

Results and discussion

The crucial part of the pinch analysis is the stream data extraction from the process flowsheet that is required for the pinch analysis.[20] The process streams are those streams that contain the fluid that should change in heat load but not in composition. The stream data extracted for the current ammonia unit consists of 11 hot streams that required cooling and 12 cold streams to be heated, as shown in Table 1. There is a trade-off between energy and capital cost, and an economical amount of energy recovery when choosing optimum ΔT_{min}.[21] The composite and grand composite curves when considering the optimum ΔT_{min} for constant heat capacity are shown in Fig. 3. Required are 55.10 MW of hot utility and 49.03 MW of cold utility that are not serviced by heat recovery and should be provided by external utilities.

The heat exchanger network for the existing ammonia unit is presented in Fig. 4, and consists of 21 process-to-process heat exchangers that exchange approximately 305 MW duties between hot and cold process streams.

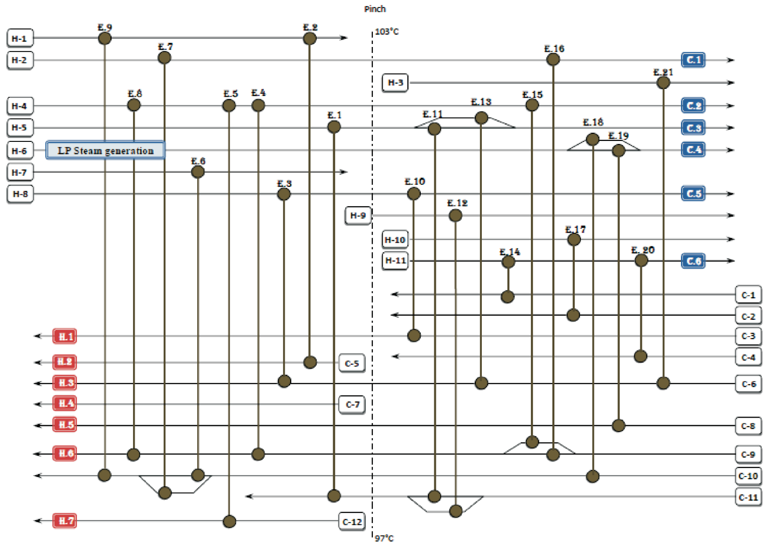
Using the basic problem table method, streams were approximated using constant *CP* and independent temperatures. However, heat capacities are apparently always related to temperature and will tend to vary according to temperature. If it is ignored it may lead to serious targeting errors. Thus, in the second considered streams with sensible temperature dependency, the variations of physical properties are segmented into certain sub-streams, as shown in Tables 2, 3. For example, stream H-3 has been divided into 3 segments within its temperature range (Fig. 5), whereas stream H-6 has greater fluctuation within its temperature range and is divided into 4 segments (Fig. 6). On the other hand, stream C-12 as a cold stream is segmented into 2 sections that modify the heat capacity value for this



F i g . 3 – *(a) Composite curve, and (b) grand composite curve, without considering the segmenting streams*

T a b l e 1 – *Process streams with constant physical properties*

Hot streams					Cold streams				
Stream	T_S (°C)	T_t (°C)	CP (MW °C^{-1})	Enthalpy (MW)	Stream	T_S (°C)	T_t (°C)	CP (MW °C^{-1})	Enthalpy (MW)
H-1	998	360	0.084	53.6	C-1	4.1	4.6	22.00	11
H-2	325	40	0.042	11.9	C-2	–12	–11.4	27.17	16.3
H-3	89	40	0.116	5.7	C-3	50	300	0.041	10.2
H-4	445	26	0.241	101	C-4	–6	25	0.235	7.3
H-5	106	50	1.211	67.8	C-5	150	400	0.142	35.5
H-6	214	38	0.234	41.2	C-6	33	150	0.235	27.5
H-7	414	173	0.079	19	C-7	100	500	0.013	5.2
H-8	288	26	0.041	10.7	C-8	38	500	0.015	7
H-9	103	89	0.581	8.1	C-9	60	380	0.254	81.3
H-10	20	–6	0.627	16.3	C-10	60	450	0.201	78.3
H-11	100	38	0.314	19.5	C-11	69	100	1.242	38.5
					C-12	114.5	115	85.2	42.6



F i g . 4 – *Grid diagram of existing ammonia unit with constant heat capacity*

T a b l e 2 – *Hot streams segmentation*

Streams	T_S (°C)	T_t (°C)	Viscosity (kg/m^{-1} s^{-1})	Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	C_P (kJ kg^{-1} °C^{-1})	Heat load (MW)	HTC (kJ h^{-1} m^{-2} °C^{-1})
H-2	325	60	0.000016	0.151	6.67	3.486	10.80	902
	60	40	0.000015	0.119	13.97	4.644	1.10	1292
H-3	89	79	0.000039	0.068	66.63	31.917	2.593	3253
	79	61	0.000092	0.138	184.07	13.926	2.075	5733
	61	40	0.000156	0.175	257.20	5.963	1.037	5416
H-4	445	364	0.000020	0.195	21.31	4.217	19.40	2053
	364	253	0.000018	0.174	24.95	4.137	25.76	2119
	253	33	0.000014	0.136	38.07	4.063	50.30	2377
	33	29	0.000014	0.118	58.65	12.780	3.068	4044
	29	26	0.000017	0.130	76.68	11.980	2.099	4675
H-6	214	178	0.000018	0.090	11.87	2.126	2.798	728
	178	126	0.000041	0.162	121.78	11.907	22.95	5748
	126	86	0.000086	0.252	264.92	6.142	9.027	8069
	86	39	0.000169	0.263	313.09	3.572	6.208	6575
H-9	103	102.8	0.000016	0.030	1.29	2.293	0.0043	109
	102.8	100.3	0.000025	0.047	30.66	51.101	1.466	2149
	100.3	95.1	0.000053	0.107	123.97	59.435	3.675	7107
	95.1	92.4	0.000082	0.167	213.63	47.012	1.470	10849
	92.4	89	0.000100	0.200	264.67	36.780	1.470	12149
H-10	20	7	0.000021	0.141	91.03	10.066	8.874	4866
	7	–6	0.000032	0.168	128.03	8.408	7.395	5710
H-11	100	43	0.000010	0.035	11.20	2.430	2.114	441
	43	42	0.000052	0.218	268.10	1137.74	15.60	46836
	42	38	0.000102	0.426	550.76	30.776	1.772	28303

Table 3 – *Cold streams segmentation*

Streams	T_S (°C)	T_t (°C)	Viscosity (kg/m^{-1} s^{-1})	Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	C_P (kJ kg^{-1} °C^{-1})	Heat load (MW)	HTC (kJ h^{-1} m^{-2} °C^{-1})
C-2	–12	–11.7	0.000190	0.564	647.26	4.937	0.0205	19421
	–11.7	–11.4	0.000098	0.293	324.59	4858.89	16.25	97712
C-8	38	277	0.000016	0.059	16.89	2.725	3.204	617
	277	500	0.000021	0.100	9.96	3.498	3.844	539
C-9	60	187	0.000303	0.663	926.09	4.202	14.77	21930
	187	247	0.000126	0.646	834.44	4.857	8.182	31363
	247	380	0.000066	0.338	404.61	15.808	58.30	22836
C-10	60	237	0.000288	0.642	897.09	4.368	21.52	21724
	237	374	0.000068	0.344	413.63	15.503	58.80	23018
	374	450	0.000026	0.064	13.32	2.286	4.833	395
C-12	114.50	114.54	0.000300	0.564	973.88	1634	25.34	150462
	114.54	115.0	0.000293	0.546	940.92	106	17.31	58082

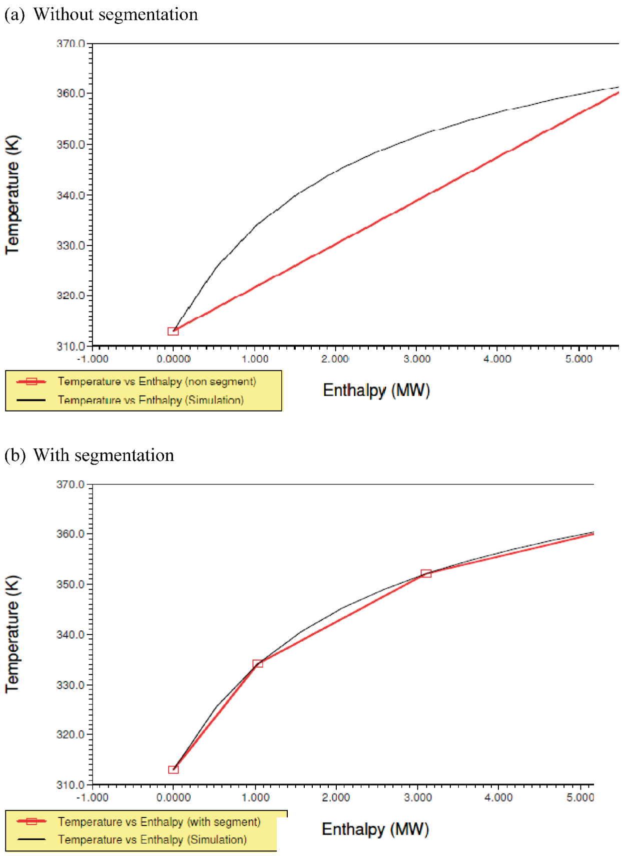


Fig. 5 – *Segmentation of stream H-3 into three sub-streams, (a): without segmentation and (b): with segmentation*

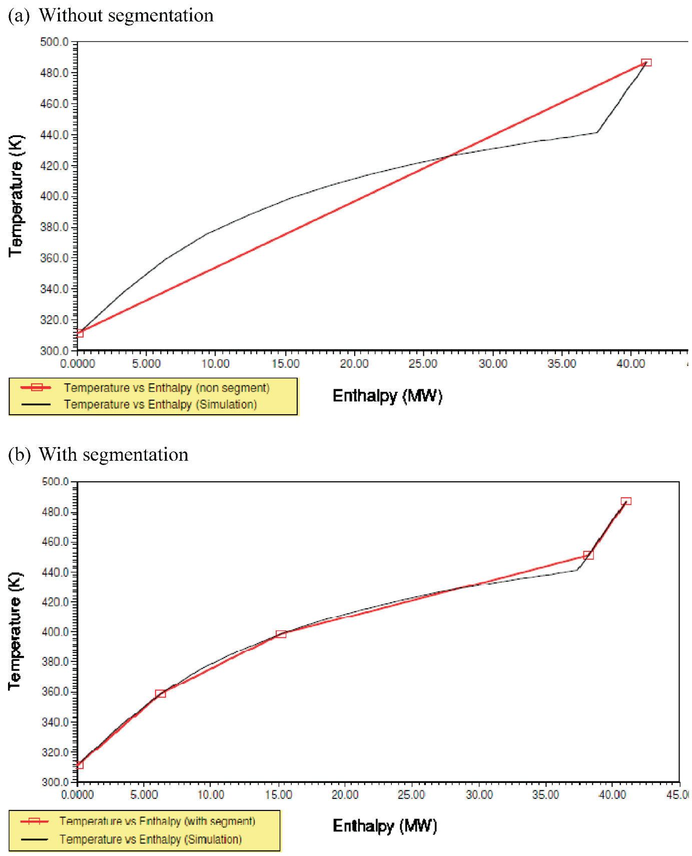


Fig. 6 – *Segmentation of stream H-6 into four sub-streams, (a): without segmentation and (b): with segmentation*

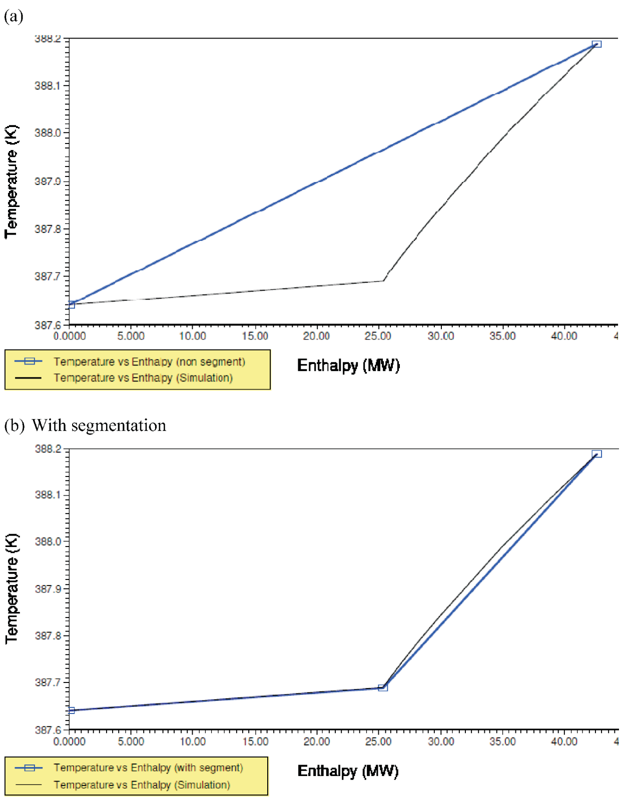


Fig. 7 – *Segmentation of stream C-12 into two sub-streams, (a): without segmentation and (b): with segmentation*

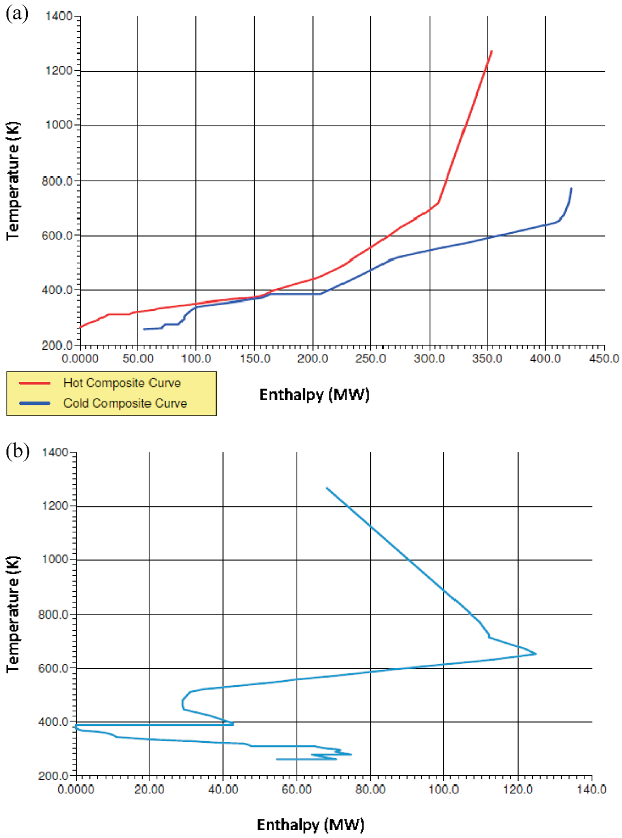


Fig. 8 – *(a) Composite curve and (b) grand composite curve, when considering the segmented streams*

stream (Fig. 7). Targeting by considering various physical properties and segmentation of the process streams has been repeated. The composite and grand composite curves then plotted again (Fig. 8). An aggregation diagram has been introduced for better understanding of the quality of heat capacity, and enthalpy distribution. For example, hot stream H-6, when reaching pinch temperature above the pinch, should exchange heat with a cold stream, which has a higher heat capacity flow rate, based on pinch technology rules. As shown in Fig. 9, none of the cold streams has this condition. The heat capacity accumulation for cold streams 9 and 10 are at higher temperatures than the pinch tem-

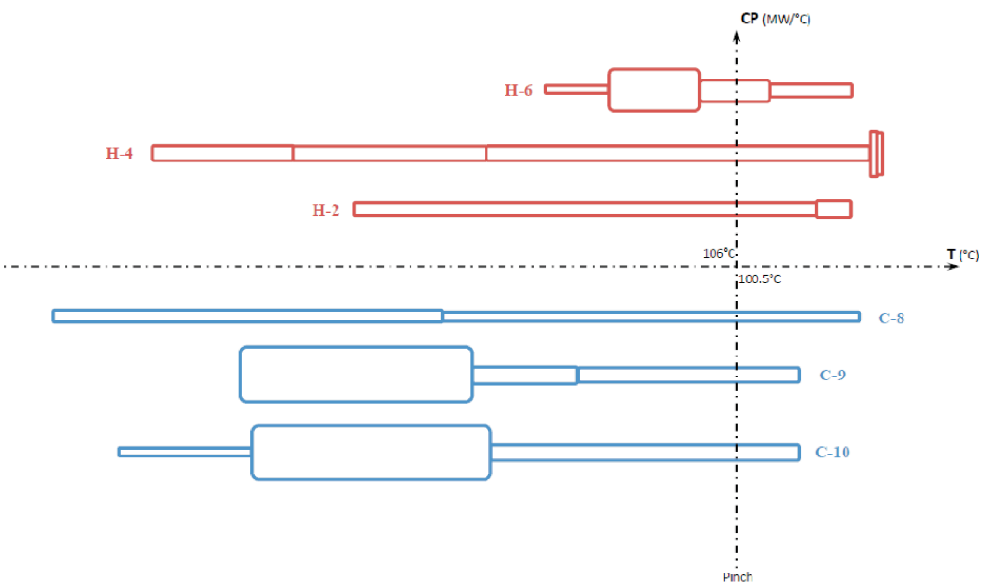


Fig. 9 – *Aggregation diagram for demonstrated CP distribution*

Table 4 – *Energy and area targeting with and without segmenting network*

	ΔT_{min} (°C)	Hot pinch temperature (°C)	Cold pinch temperature (°C)	$Q_{H,min}$ (MW)	$Q_{C,min}$ (MW)	Area (m^2)
Without segment	6	103	97	55.10	49.03	64.712
With segment	5.5	106	100.5	68.07	54.64	96.155

perature. There is no cold stream using the favored *CP* that is near enough to the pinch temperature to absorb the additional heat of hot stream H-6. If hot stream H-6 is connected to one of these cold streams, the heat exchanger will violate the ΔT_{min} condition; because the *CP* of the hot stream is higher than that of the cold streams. So, this stream is used for generation of the LP steam. Overall, the more *CP* accumulation of the hot streams above the pinch or the cold streams below the pinch, the less heat load of the utility streams would be obtained.

Summary of targeting results for both the cases of constant and varying physical properties, are shown in Table 4 as a demonstration of changing targeted values. These variations cause targeting correction and improvement in heat exchanger network design.

Conclusions

Against the fundamental problem table method for designing a heat exchanger network, in practical problems dependency of physical properties such as heat capacity according to temperature has been considered, and ignoring this dependence will often lead to serious targeting errors. Energy targeting for an ammonia plant has been investigated before using both methods, with and without stream segmentation. Pinch temperature, ΔT_{min}, and the values of the hot and cold utilities in both cases are different, and so the HEN has to be changed. When splitting streams into two or more segments within the existing ammonia plant, the pinch point increased by about 3 °C, and hot and cold utilities consumption increased by approximately 23 % and 11 %, respectively. The area of the heat exchanger network also is increased by about 50 %.

List of symbols

A_{total} – total area of the network, m^2
C_P – effective specific heat capacity, kJ kg^{-1} °C^{-1}
CP – heat capacity flowrate, kW °C^{-1}
CP_m – mean heat capacity flow rate, kJ kg^{-1} °C^{-1}
D – flow area diameter, m
ΔH – enthalpy difference, MW
$\Delta T_{LM,k}$ – log mean temperature difference in the segment ‘k’, °C
ΔT_{min} – minimum approach temperature, °C
$h_{i,k}$ – individual film heat transfer coefficients on the hot stream ‘i’ in segment ‘k’, W m^{-2} °C^{-1}
$h_{j,k}$ – individual film heat transfer coefficients on the cold stream ‘j’ in segment ‘k’, W m^{-2} °C^{-1}
K – thermal conductivity, W m^{-1} °C^{-1}
Pr – Prandtl number, –
$q_{i,k}$ – individual heat loads on the hot stream ‘i’ in segment ‘k’, kJ h^{-1}
$q_{j,k}$ – individual heat loads on the cold stream ‘j’ in segment ‘k’, kJ h^{-1}
Re – Reynolds number, –
T_s – supply temperature, °C
T_t – target temperature, °C

Greek symbols

ρ – stream density, kg m^{-3}
μ – stream viscosity, kg m^{-1} s^{-1}
μ_w – viscosity of water, kg m^{-1} s^{-1}
v – stream velocity, m s^{-1}

Abbreviations

CC – Composite Curve
GCC – Grand Composite Curve
HEN – Heat Exchanger Network

Indices

i – hot stream
j – cold stream
k – segment

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