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New Algorithms for Heat Exchanger Network Optimization

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Much works have been done regarding design and optimization of Heat Exchanger Networks (HEN). Amongst those, some methods are more conceptual and handle uncomplicated trade-offs between thermal aspects (such as energy, area, stream splitting ratio, etc.), whilst others are more mathematical and have almost no limitation to incorporate complicated features of a HEN (such as hydrodynamics, shell arrangement, etc.). However, a Pinch-based approach that simultaneously handles both thermal and hydrodynamic aspects of a HEN when optimizing an initial network was missing.

In previous works, we have shown how pressure drop can be optimized in targeting stage, by exploiting a three-way trade-off between energy, area and stream pressure drops. It has also been discussed that, in synthesis stage, these optimized values for stream pressure drops are used to determine surface area distribution amongst various process streams and also different matches on each individual stream.

Having synthesized the network in this fashion, an initial network is obtained that features loops and paths and hence is subject to another trade-off between energy consumption, surface area requirement, stream pressure drops and network complexity. Here, we need to re-optimize pressure drop values, as streams' overall pressure drops, and re-distribute them amongst various heat exchanger units/shells, whilst at the same time loop braking, stream split ratios and heat load distribution amongst heat exchangers should be re-examined.

In this research, a series of new algorithms have been developed that accommodate all these trade-offs and enable the designer to simultaneously optimize energy consumption, surface area requirement, stream splitting ratios, number of heat transfer units/shells and pumps/compressors capital and operating costs in a network, which has already been designed as grass-root or been modified as retrofit.

These new algorithms have also been applied to two case studies (Aromatics Plant as grass-root, and Crude Distillation Unit, as retrofit) and the results showed significant improvement compare to the networks, in which stream pressure drops had already been optimized in targeting stage. Having optimized the two initial networks, 8 percent improvement in Total Annual Cost of Aromatics Plant and 9 percent improvement in payback period of the CDU were identified.

1- Introduction

In design approaches that are based on streams' optimum pressure drops rather than assumed Heat Transfer Coefficients (HTC), design of Heat Exchanger Networks (HEN) is carried out based on the optimum values of HTC which are calculated in targeting stage. These HTC values are much more accurate than those of assumed values, because they are consistent with streams' optimum pressure drops. However, there are still reasons for the optimization of these networks. These reasons are as follows:

- The values of HTC's may be different in the heat exchanger units installed over a given stream;
- The total pressure drop of a given stream may not be optimally distributed amongst different heat exchangers;
- When loops are broken to reduce number of units, or stream splitting ratios are changed during network optimization, the heat loads and heat transfer areas of the exchangers are changed, and hence pressure drops need to be re-optimized on both sides of the exchangers;
- Even when loop braking is not economically justified, re-distribution of heat loads between heat exchangers necessitates the re-optimization of pressure drops.

Therefore, we need a very sophisticated method to take care of all the trade-off's and optimize the whole problem. In this research we have developed an efficient method in which the overall algorithm is shown in Figure 1.

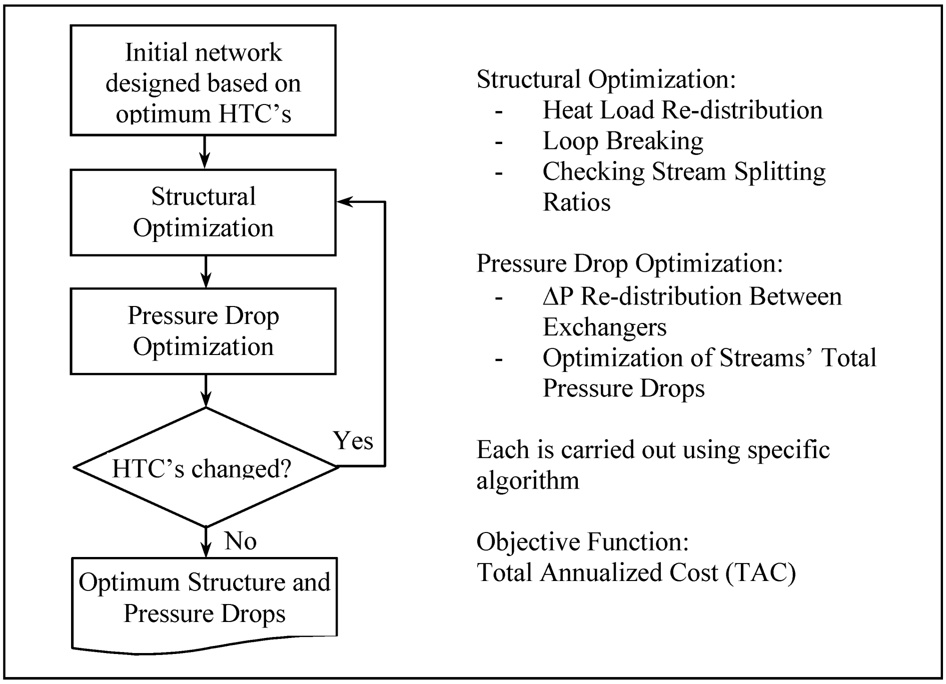

Figure 1. Overall Optimization Algorithm

2- Structural Optimization

In a heat exchanger network with a given structure, one can change the Heat load of the exchangers, coolers and heaters in such a way that the Total Annual Cost (TAC) is minimized. This optimization is done in the following stages:

1. Determination of the independent and dependent units;
2. Calculation of area, temperatures, and flow-rates of the exchangers with zero degree of freedom;
3. determination of minimum and maximum values of heat loads and also allowable range of variation for hot and cold temperature;
4. checking the minimum approach temperature to avoid violation;
5. repeating stages 2 to 4 until there is no changes on temperatures;
6. changing the independent variables (temperature) based on optimization algorithm;
7. iteration of the above stages to reach minimum TAC

Also, the number of heat transfer units may be reduced by loop breaking techniques and stream splitting ratios should be optimized using mathematical approaches, "Jezowski. J., Bochenek. R. & Jezowska A. (2001)".

3- Pressure Drop Optimization

Pressure drop values in a network should be addressed from two respects. First, we have to check the overall pressure drop of each individual stream and try to find the best values. Here, we face a tree-way trade-off between heat exchange area costs, pumps and compressor capital costs and network operating costs including hot and cold utilities and electricity. In other words, the higher the values of stream pressure drop the more capital and energy costs of the pump/compressor, but the smaller the heat exchanger areas. Also, network area cost trade-offs with network utility cost and we indeed have to explore a tree-way trade-off. Pressure Drop equations that applies to this trade-off are given below, "Bell K.J. (1963), Panjeshahi M.H. (1992).

$$\Delta P_T = K_T A h_T^{3.5}$$

$$\Delta P_S = K_S A h_S^{4.412}$$

Secondly, the total pressure drop of a given stream should optimally be distributed between two or more heat exchange units installed on that stream. In order to do so, three different criteria may be used, "Polley, G.T., Panjeshahi, M.H., (1991)".

1. Pressure drop distribution proportional to heat exchanger area

$$\Delta P_{ij} = \Delta P_j * \frac{A_i}{\sum_i A_i}$$

2. Pressure drop distribution based on kAh^m

$$\Delta P_j = \sum_i \Delta P_{ij} = \sum_i K_j A_i h_{ij}{}^m$$

$$\Delta P_{ij} = \Delta P_j * \frac{A_i h_{ij}{}^m}{\sum_i A_i h_{ij}{}^m}$$

3. Pressure drop distribution using Mathematical (Simplex) Method, "Spenley W., Hext G.R. & Hext F.R. (1962)".

In this research all three criteria have been investigated and the second one found to be more efficient in terms of accuracy and calculation time.

4- Case Study1 - Grass-roots

The algorithms and procedures have been incorporated into PILOT "PILOT 2.02 ©, (2005)"and applied to many case studies and results showed good improvement compare to initial networks. In Grass-roots, we applied the new optimization approach to Aromatics Plant, in which the initial network had been produced using HTC values based on optimized stream pressure drops, "Fallahi, Hamidreza (2000). Initial network is shown in Figure 2 and cost data is reported in Table 1.

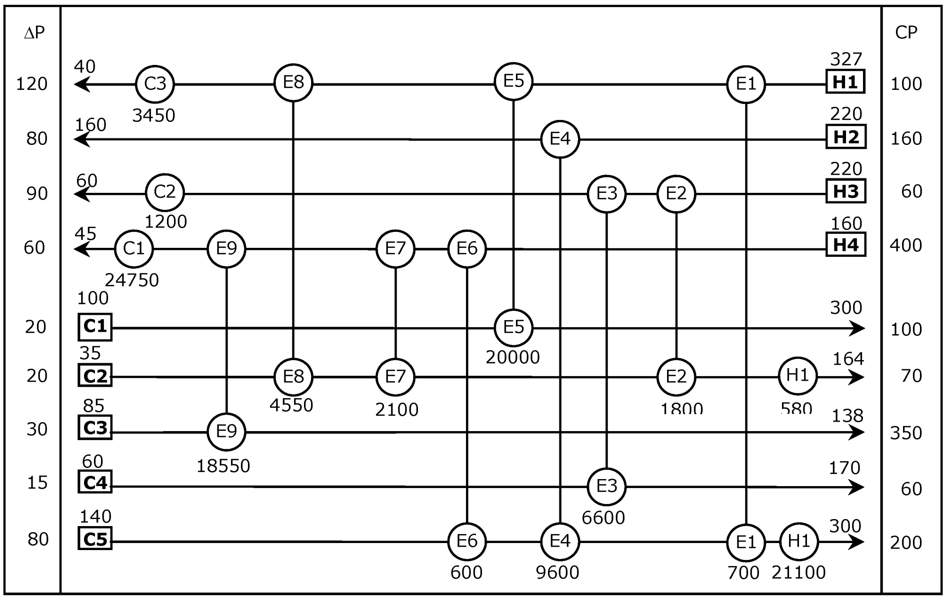

Figure 2. Initial design for Aromatics Plant (Duty: kW, ΔP: kPa, mCp: Kw/C)

Also, the cost data is given in Table 1.

Table 1. Cost data

Cost of Hot Utility: 70 £/kw.yr	Plant Life Time (N): 5 yrs
Cost of Cold Utility: 7 £/kw.yr	Rate of Interest (i): 15%
Power Cost: 360 £/kw.yr	
Exchanger Capital Cost: 700 $(Area)^{0.83}$	
Pump Capital Cost: 2610 $(q\sqrt{H})^{0.2}$	
Pump Efficiency (%) : 70	
Compressor Capital Cost: 64.35 $W_c^{0.62}$	
Compressor Efficiency (%) : 70	
Annualization Factor: $i(i+1)^N/\{(i+1)^N-1\}$	

Final optimized network and summary of the results have been represented in Figure 3 and Table 2, respectively.

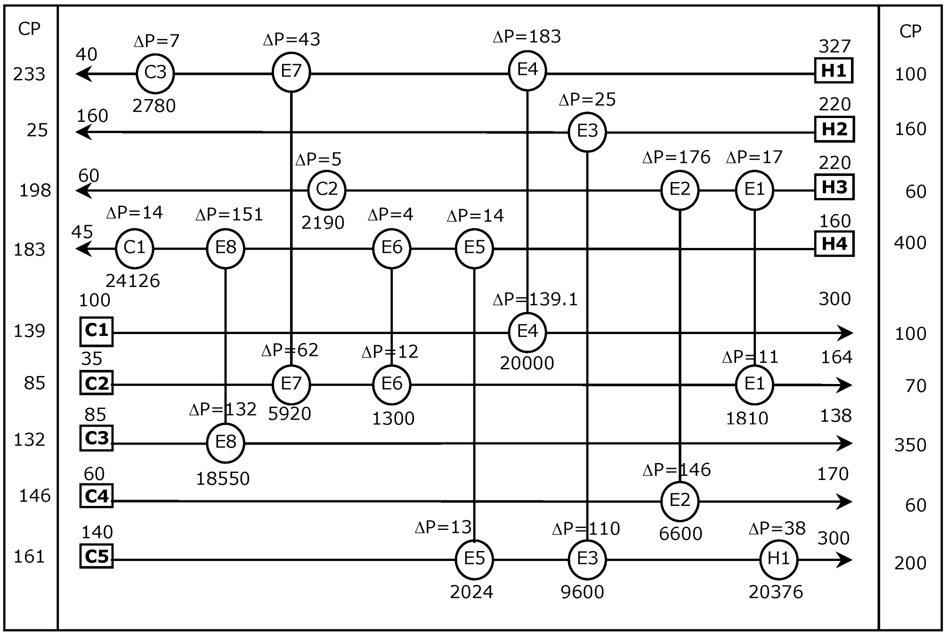

Figure 3. Final design for Aromatics Plant (Duty: kW, ΔP: kPa, mCp: Kw/C)

Table 2. Comparison between initial and final networks

	Initial Network Using HTC's based on Opt. Stream Pressure Drops	Final Optimized Network	Difference (%)
Energy (MW)	21.68	20.38	- 6
Area (m^2)	8263	7352	- 11
No. of Units	14	12	- 2 Units
No. of Shells	46	45	- 1 Shell
Energy Cost (£/yr)	1723403	1623008	- 5.8
Area Cost (£/yr)	713948	619508	- 13.2
ΔP Cost (£/yr)	135947	133831	- 1.6
Total Cost (£/yr)	2573298	2376347	- 7.7

5- Case Study2 - Retrofit

In second case study, a Crude pre-heat train was selected and studied using α-based retrofit method, whilst stream pressure drops were also optimized during targeting stage. The resulting network was then optimized by application of the procedure developed in this research. Although the optimization method of retrofitted network uses the same basics as for the grass-roots, but due to different constraints and limitations imposed by the existing heat exchangers and flow system, the algorithms are quite different.

Nevertheless, the corresponding algorithms and methodology were applied to this case study and results proved to be promising. Table 3 represents the comparison between initial retrofitted and final optimized networks.

Table 3. Comparison between initial and final networks

	Initial Network Using HTC's based on Opt. Stream Pressure Drops	Final Optimized Network	Difference (%)
Energy Reduction (MW)	26.84	28.83	+ 7.4
Additional Area (m^2)	8414	7828	- 7
Energy Saving (£/yr)	1825349	2017820	+ 9.5
Area Investment (£)	2060992	2007319	- 3
Pump Investment (£)	85420	149835	+ 75
Total Investment (£)	2146412	2157154	+ 0.5
Payback Period(yr)	1.175	1.07	- 8.9

6- Conclusions

A new conceptual approach has been developed for optimization of the networks which previously targeted and synthesized using Pinch concepts and pressure drop considerations. This approach investigates a three-way trade-off that exists between Heat Exchange Area, Utility Needs and Pumps/Compressor Size and consequently finds a solution that achieves minimum capital and operating costs.
Capabilities of this approach have also been checked by applying the techniques in real life case studies and the results found to be excellent. In Aromatics Plant, as grass-roots design, 8 percent and in Crude Distillation Unit, as retrofit modification, 9 percent improvement has been observed.

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