HEN RETROFIT OPTIONS: USING PROCESS INTEGRATION TECHNOLOGIES TO MAXIMISE THE BENEFITS OF TUBE INSERTS

By Sonia Farrokpanah, Process Integration Ltd and Tom Higley, CALGAVIN Ltd

Rapidly increasing energy prices and pressure for the process industries to develop in a more sustainable fashion demand significant improvements in process efficiency for both existing and new processes.

Typically, numerous retrofit projects might be carried out on a Heat Exchange Network (HEN) in an industrial plant over its lifetime. These may have different objectives such as increasing plant capacity, addressing changes in the performance of various equipment items, reducing energy consumption, or any combination of these. Compared to the design of a new HEN, retrofit projects are particularly challenging. The complexities are mainly caused by the limitations of the existing HEN and the background process. The current topology of the network, safety issues, maintenance constraints, and operational boundaries related to the background process are just some of the possible reasons why the number of feasible and economic retrofit projects for the plant may be limited and difficult to identify.

HEN retrofit options

The available modification strategies in a heat recovery network include changing the flowrates in the splitters, changing the bypass flows of the heat exchangers and/or optimising the background process. These options optimise the heat load distribution in the network and can bring benefits without requiring additional capital expenditure. However, often the associated benefits are small. Retrofit options that yield larger benefits typically require structural changes to the network such as re-piping and re-sequencing the existing heat exchangers, adding new exchangers and/or introducing stream splitting. The latter requires capital investment that will often be too large and unjustifiable, and moreover might be unreasonably difficult to implement (for instance, due to shortage of space and/or safety issues). Enhancing heat transfer in existing and new heat exchangers constitutes a retrofit approach that can address some of these problems. Intensification of the heat transfer in heat exchangers (via a range of enhancement techniques) provides a cheaper alternative for improving heat recovery in the network. Issues such as maximum available pressure drop or the viscosity of the process fluid may however limit the effect of the enhancement application.

Enhancement techniques can improve plant performance

Heat exchangers and more predominantly tubular heat exchangers are the ‘work horses’ of process plants in terms of consuming and dissipating energy. With increasing demand, throughput has to be maximised and heat exchangers sometimes act as a bottleneck. Replacing underperforming exchangers tends to involve high capital costs: typically, additional pipe work will be required, as well as increased plot space (which often in any event is not available).

PP83

In today's economic climate capital costs are under more scrutiny than ever and so there is a lot of incentive to investigate new technologies that enhance overall performance without requiring a large amount of capital expenditure.

Devices that increase heat transfer within the exchanger such that it can cope with larger duties are a good example of such technologies. Since the various enhancement devices all work on different principles they are however not universally applicable (i.e. different devices will be suited to different process fluids, temperatures and operating flows).

These varying technologies can be used on the shell side or tube side of the exchangers. They work either via promoting turbulence to increase heat transfer or extending the heat transfer surface area to achieve the same purpose. In the latter case, fins on both the outside of the tubes and the inside will improve heat transfer on both the shell and tube sides. In addition, a variety of baffles on the shell side can aid in improving heat transfer by changing flow and creating turbulence. Helical and 'EMBaffle'-style baffles will in many circumstances perform better than standard conventional baffles. Both can induce turbulence by changing the flow on the shell side. Helical baffles induce a spiral flow around the tube bundle whereas 'EMBaffle' send the flow longitudinally through the grid-like baffles, creating varying amounts of turbulence depending on the characteristics of the process fluid.

Turbulence-promoting devices have been demonstrated to increase the heat transfer coefficient by as much as 14 times on the tube side, though the benefit varies with different flow regimes. In laminar to transitional flow regimes static mixers, core tubes, wire matrix inserts and twisted tapes yield the best improvements. CalGavin's hiTRAN matrix elements have also been shown to enable increased duties when retrofitted within existing heat exchangers. When retrofitted into existing exchangers, this gain in heat transfer can be achieved at a relatively low capital cost. In new designs hiTRAN elements allow for a reduction in the size of the heat exchanger required.

If the existing flow regime is already turbulent then the heat transfer enhancement is more limited but the pressure drop increase remains at a similar level to that of laminar/transitional flows. Helically-coiled inserts and twisted tapes generally work best for such regimes. Helical coils improve heat transfer by disrupting the fluid and increasing turbulence. Twisted tapes induce the flow to 'swirl' down the tube causing shear on the tube wall, which in turn creates turbulence. If pressure drop is available hiTRAN matrix elements are also an option for this type of flow regime.

hiTRAN matrix elements work by changing the mode of heat transfer across the tube wall. Normally, frictional forces give rise to a laminar boundary layer at the tube wall and heat is transferred via conduction. By installing hiTRAN elements, the laminar boundary layer is disrupted and convection becomes a more important contributor to heat transfer – improving thermal performance since this is both faster and more efficient than a conduction-mediated process.

In Industry, hiTRAN matrix elements have been used to good effect worldwide for the past 30 years in both new and retrofit exchangers. A good example of a retrofit installation relates to a Texas tower at the Ruhr Oil Refinery operated by BP America Inc. in Gelsenkirchen, Germany, where a TEMA type AET feed/effluent exchanger for P-Xylol production was installed. The refinery sought to increase its throughput and, as such, required a 15% increase in heat input from the fired heater. Conventionally, this would have required installing a new fired heater (implying a high level of capital cost) and, in addition, there were existing problems of superheating of the vapour, film boiling and mist flow which were limiting the heat transfer in the top region of the exchanger.

With the introduction of hiTRAN Matrix Elements a 15% increase in heat and increased throughput were achieved using the existing fired heater – meaning substantial savings were made since a new unit was no longer required. An additional 0.8 MW was recovered from the effluent stream, which equated to a direct reduction in energy input of 25 TJoule/year (in turn equating to a saving of ~€50,000/year) and a reduction of 1,700 tonnes/year in carbon emissions.

Revamping the heat exchanger network

Retrofit studies are by their nature challenging to undertake. Energy intensive processes usually feature large and complex HENs with different sections interacting with one another. It is frequently the case that the best way to remove a bottleneck involves modifying the network at a location far from where the limitations are observed. In other words, studying only the limiting heat exchanger may not lead to the identification of the cheapest and most profitable retrofit project. Therefore, identifying an optimal solution requires a holistic approach.

This involves considering the existing structure of the network in its entirety and, using accurate thermal data from the process streams, considering potential interactions within the network in order to compare a range of retrofit approaches. It is thus possible to capture the trade-offs implicit to different approaches and select an optimal strategy. Robust methodologies such as these however result in large Mixed Integer Nonlinear Programming (MINLP) problems that require sophisticated optimisation engines in order to generate a global optimal solution.

HEAT-int is a specialised software suite that Process Integration Ltd (PIL) has designed to help optimise HENs, and provides a robust platform for optimisation work at both design and retrofit stages – the software can be used to simulate highly complex networks. It takes into account the detail geometries of shell and tube heat exchangers and use these to calculate an overall heat transfer coefficient, as well as associated pressure drops. Once the network is built, further insight can be gained by using analytical tools incorporating network targeting techniques and UA sensitivity studies, both of which are available within HEAT-int. The software also represents the HEN as a grid diagram – providing a simple platform for visually observing and studying trends – with the engineer easily able to move exchangers around in the grid diagram (drag and drop), add or remove exchangers, change the geometry of the exchangers, change the stream splitter specifications and/or perform duty or area based simulations of the network in order to understand its behaviour better. In addition, HEAT-int tool employs methodologies that account for temperature-related changes to the physical properties of streams. For instance, streams that cover a wide temperature range in operation can be divided into multiple segments and the variations of their thermal capacity with temperature accounted for. Therefore, an accurate prediction of temperatures and hence the performance of the overall network can be achieved.

In optimisation mode, HEAT-int incorporates both deterministic and stochastic optimisation techniques in order to identify a global optimum. Both operational and structural changes to the network can be explored simultaneously or individually. The optimisation model can compare the option of enhancing heat exchangers against that of adding new area, all the while accounting for pressure drop. Once the optimisation results are available, the engineer can easily select to simulate any combination of the suggested modifications to further investigate the effect of the proposed retrofit projects. In the next section, a case study is presented to demonstrate how HEAT-int optimisation techniques may be applied in practice.

Crude distillation unit optimised Crude distillation units (CDUs) in oil refineries are a good example of plants associated with energy intensive processes. Large volumes of crude oil, which include heavy hydrocarbons, are partially vaporised before being fed to the atmospheric distillation column. The products of distillation leave the column at elevated temperatures and there is therefore a good opportunity to heat the feed by using these products to reduce the load on the furnace serving the CDU preheat train. Shrinking profit margins have in recent years forced refiners to carry out numerous retrofit projects in order to maximise CDU heat recovery. In turn, this means that further optimisation measures are becoming increasingly challenging both to identify and to implement in practice (especially so if they are to remain financially justifiable).

Here a subset of a HEN for an industrial crude unit is presented. For confidentiality reasons, several modifications and simplifications have been made to the actual (real-life) plant data. However, the case study nonetheless represents a good example of an industrial plant with large utility demands and some exchangers already operating at very low driving forces.

Table 1 and Table 2 present the stream data and the current network data, respectively. Figure 1 shows the grid diagram for the existing network. The study is comprised of two parts. First the network is optimised without the availability of an enhancement option. Later the enhancement option is introduced in order to evaluate if a more cost-effective scenario is feasible with it.

Table 1 Network stream data

Stream ID	Name	TS	TT	DH
		[°C]	[°C]	[MW]
1	Crude Oil	122.20	363.61	145.88
2	Residue	379.30	85.58	61.20
3	Heavy Gas Oil	345.10	51.00	1.70
4	Light Gas Oil	290.40	56.00	23.11
5	Recycle	279.10	227.32	28.00

Table 2 Current heat exchanger inlet/outlet temperatures

Exchanger	Hot In	Hot Out	Cold In	Cold Out	Minimum Approach Temperature
	[°C]	[°C]	[°C]	[°C]	[°C]
HE1	275.2	128.5	124.7	242.7	3.8
HE2	279.1	227.7	124.7	260.6	18.5
HE3	136.1	51.0	CW		-
HE4	128.5	85.6	CW		-
HE5	379.3	275.2	250.7	297.0	24.5
HE6	173.7	56.3	CW		-
HE7	290.4	173.7	124.7	275.9	14.5
HE8	Fuel Oil		294.4	363.6	-
HE9	345.1	136.1	122.2	124.7	13.9

Figure 1 Current network grid diagram

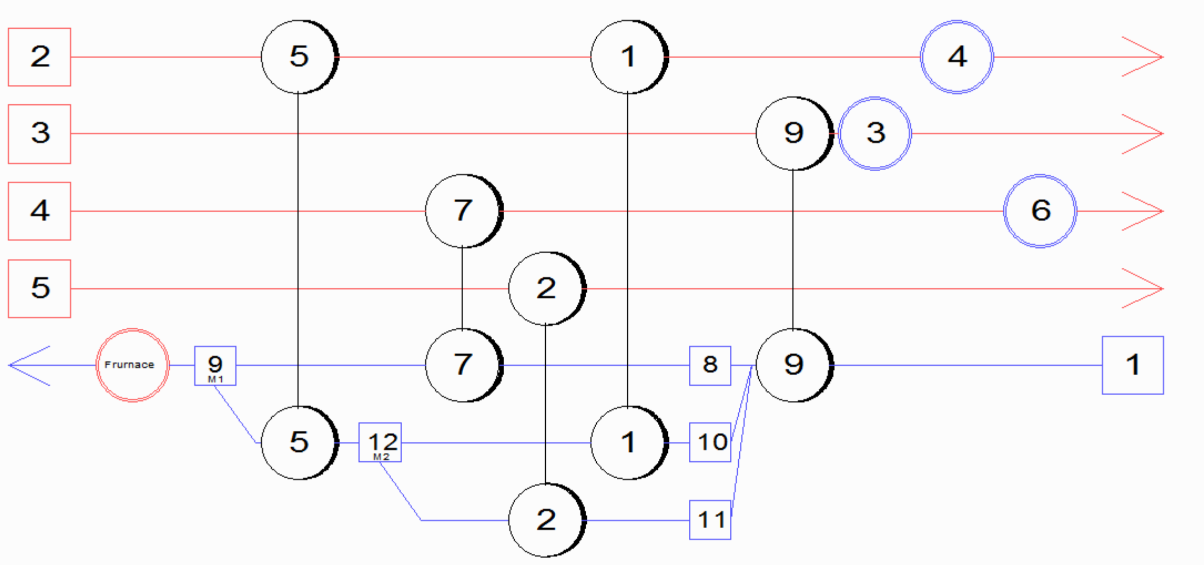

Figure 2 illustrates the proposed retrofit projects. Data relating to the utility requirement featuring both pre-optimisation and post-optimisation values are presented in Table 3. The optimisation process has suggested moving HE 5 onto the main branch of the crude oil stream in order to take advantage of better driving forces in the exchanger. It is also suggested that additional area is installed in HE 7 in order to recover further heat from light gas oil product. This methodology explores an energy-saving opportunity through the path that connects cooler HE 6 to the furnace. The split ratio of the branches on the crude oil unit is also optimised to allow more flow through HE 7 (this is up by 7%). This change has also improved the driving force in this exchanger. HE 2 is located on a stream with no coolers or heaters on it and is a constraint. Therefore, its flowrate has been kept constant.

Figure 2 Suggested network modifications in Scenario 1 (no enhancement option considered)

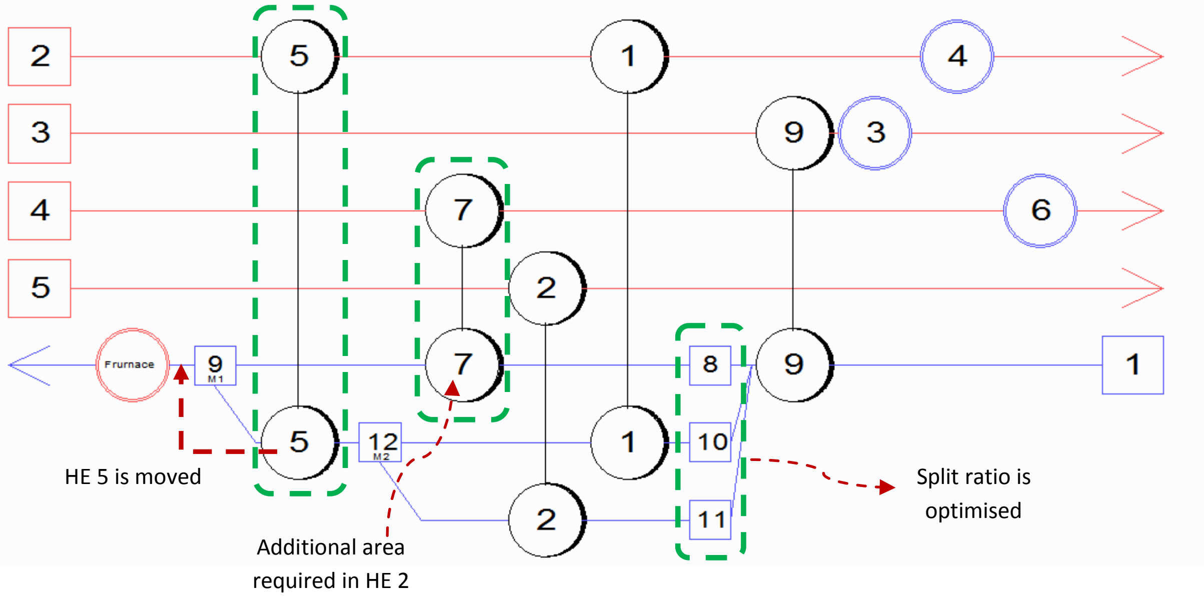

Figure 3 The optimised HEN in Scenario 1 (no enhancement option considered)

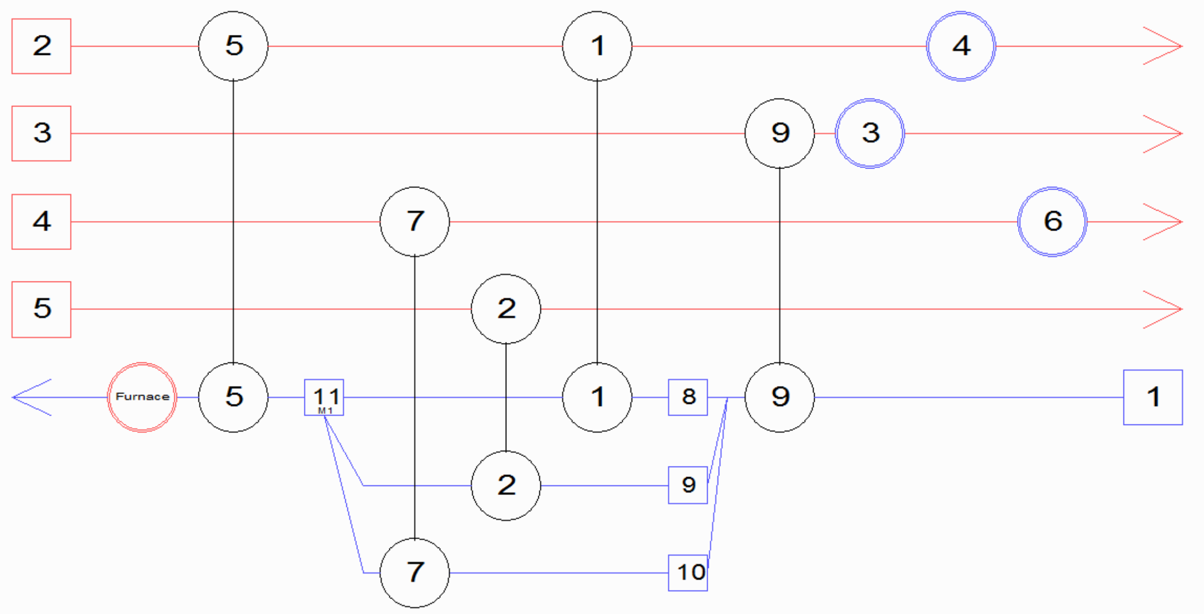

Table 3 Energy demand and cost comparison for different scenarios

	Existing HEN	Scenario 1 Without Enhancement	Scenario 2 With Enhancement
Coil Inlet Temperature (°C)	294.41	297.48	297.48
Hot Utility (MW)	51.84	49.5	49.5
Cold Utility (MW)	19.77	17.67	17.67
Operating Cost (MM$/yr)	12.78	12.2	12.2
Additional Area (m^2)	-	512	0
Capital Investment (MM$/yr)	-	0.699	0.105
Payback (years)	-	1.2	0.182

In a second scenario, CalGavin's hiTRAN matrix elements are used to enhance the overall heat transfer coefficient (OHTC) in HE 7. Details of the geometry for each shell of this exchanger are summarised in Table 4. The optimised results demonstrate that the value for the OHTC is improved such that no additional area is required after using hiTRAN matrix elements in HE 7. The required capital cost is reduced by 85%. As a result, the payback time is lowered to 0.182 years from 1.2 years in scenario 1. From a financial point of view, the installation of hiTRAN matrix elements is therefore likely to make the project considerably more attractive.

Table 4 Stream data and geometry for HE 7

HE 7					
	Shell side stream	Tube side stream			
Specific heat (kJ/kgK)	2.838	2.621			
Thermal Conductivity (kW/m K)	8.18E-05	1.02E-04			
Viscosity μ (Pa s)	4.88E-04	2.62E-04			
Density ρ (kg/m^3)	661	688			
Flow rate (kg/s)	36.01	45.11			
Fouling resistance (m^2 K/kW)	3.53E-01	3.53E-01			
Geometry of heat exchanger					
Tube pitch (m)	2.54E-02	Tube inner diameter (m)	1.49E-02	Outlet baffle spacing (m)	3.20E-01
Number of tubes	1399	Tube outer diameter (m)	1.91E-02	Baffle cut	0.2
Number of tube passes	2	Shell inner diameter (m)	1.15	Inlet nozzle diameter - tube side (m)	2.54E-01
Tube length (m)	6.1	Number of baffles	26	Outlet nozzle diameter - tube side (m)	2.54E-01
Tube conductivity (kW/m K)	7.72E-02	Baffle spacing (m)	2.18E-01	Inlet nozzle diameter - shell side (m)	1.52E-01
Tube pattern (Tube layout angle)	90°	Inlet baffle spacing (m)	3.20E-01	Outlet nozzle diameter - shell side (m)	1.52E-01
				shell-bundle diametric clearance (m)	2.00E-02

Identifying financially viable options

The retrofit of HENs is an inevitable part of the life cycle of most plants for several reasons, including not least in order to increase throughput. However, the most financially viable option is not necessarily achieved simply by modifying the exchanger that is most immediately identified as the restraining factor. Indeed, identifying an optimal solution within the context of a complex HEN is a challenging task that requires a much more holistic (and therefore robust) approach. It is necessary to investigate the operation of the plant in its entirety and take account of many structural degrees of freedom in the network efficiently and simultaneously.

In most retrofit projects additional area is added to the HEN. The case studies presented in this paper however demonstrate that using enhancement techniques can also improve the economics of a given project considerably and is an important consideration when evaluating retrofit options.