# HEAT EXCHANGER NETWORKS RETROFITTED WITH SIMULTANEOUS PRESSURE RECOVERY

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ABSTRACT – This paper introduces a new optimization model for the retrofit of heat exchanger networks (HENs), wherein the pressure recovery of process streams is used to enhance the heat integration. Especially important in cryogenic processes, the HEN retrofit with optimal integration between heat and work is mainly aimed at reducing the usage of the extremely expensive cooling services. In this approach, the conventional problem of HENs retrofit is extended to include streams subjected to a specific pressure manipulation route. Thus, the adjustment of pressure levels of process streams is performed simultaneously with the HEN synthesis, such that the streams pressure and temperature are optimization variables. The mathematical model based on a mixed-integer nonlinear programming (MINLP) formulation allows for the increment of the existing heat exchange area, and the use of new equipment for both heat exchange and pressure manipulation. Moreover, the proposed superstructure considers the coupling of turbine and compressor with a helper motor, in order to minimize the total annualized cost composed by additional capital and operational expenses. A case study is conducted to verify the accuracy of the proposed approach. The results indicate that the pressure recovery is essential for reducing the energy consumption in a sub-ambient process and, consequently, for decreasing the total cost of the HEN retrofitted.

## 1. INTRODUCTION

Reducing energy consumption through implementation of more efficient and innovative strategies is one of the major concerns in processing plants. In this context, the retrofit of heat exchanger networks (HENs) is an effective way to achieve the desired energy savings from an already established network (Wang and Smith, 2013; Wang et al., 2012). The HENs retrofit is aimed at reducing the consumption of thermal utilities, by minimizing changes needed to improve energy recovery in terms of restructuring the possibilities of heat exchange between streams (i.e., re-piping), and modifying or replacing existing heat exchangers, often translated as function of process costs (Pan et al., 2013; Polley et al., 2013). Despite the numerous attempts to optimize the heat recovery by synthesizing new HENs, only a reduced number of studies in the available literature propose solutions to the problem of optimal integration between heat and work. It is noteworthy that none of these studies considers the possibility to retrofit existing networks. Note that the pressure manipulation of process streams plays an especially important role in sub-ambient processes such as the production of liquefied natural gas (LNG), consuming excessive quantities of energy (Onishi et al., 2014a). It should be emphasized that the large consumption of cold utilities—extremely expensive in cryogenic processes—is responsible for high operational expenses.

Wechsung et al. (2011) proposed an optimization model for the HENs synthesis, enabling the adjustment of pressure levels of streams at sub-ambient conditions. In this work, it was verified through a real application related to LNG production that a specific route of expansion and compression of process streams may result in an optimal HEN with minimal irreversibilities. Onishi et al. (2014b) presented an mathematical programming model for the simultaneous HENs synthesis, considering the handling pressure of process streams to enhance the heat recovery. The authors demonstrated through the study of various configuration possibilities involving compressors, turbines and valves that the pressure recovery of streams can decrease the need for thermal utilities, reducing the total cost of the process. Although these works represent important contributions to the process synthesis field, they do not contain any assessment concerning the retrofit of existing networks.

This paper introduces a new mathematical model for the HENs retrofit, wherein the pressure recovery of process streams is used to improve the heat integration. A multi-stage superstructure is proposed for solving the problem. Thus, the pressure recovery of process streams is performed simultaneously with the HENs retrofit, through pressure manipulation stages connected to the network. Consequently, the process conditions (streams pressure and temperature) should be treated as optimization variables. The developed approach allows for increasing the existing heat exchange area and the use of new equipment for both heat exchange and pressure manipulation. Furthermore, the superstructure considers the coupling of the turbine and compressor with a helper motor for energy savings. The resulting MINLP-based model is optimized with the goal of minimizing the total annualized cost, composed by additional capital and operational expenses. A case study considering streams at sub-ambient conditions is conducted to verify the accuracy of the proposed model. The results indicate that the pressure recovery of streams decreases the cost of the HEN retrofitted, as a consequence of reduced expenses related mainly to cold utilities.

## 2. PROBLEM STATEMENT

Given a set of hot and cold streams with a known supply state (inlet temperature and pressure), a target state (outlet temperature and pressure), and the heat capacities flow rates (i.e., product between heat capacity and flow rate). In addition, thermal utilities for heating and cooling, electricity, new equipment for pressure manipulation—namely turbines and compressors—and heat exchange, with their respective costs are also provided for solving the problem. The goal is to obtain an optimal design of HENs retrofitted considering the pressure recovery of process streams by minimizing the additional total annualized cost. The objective function is composed by the capital cost of investment in new equipment and related to the increment of the existing heat transfer area, as well as additional operating expenses associated to cooling and heating of streams and electricity. Moreover, it is also considered the revenues from power generation by stand-alone turbines.

In this approach, some cold streams must follow a specific route of pressure manipulation and heat exchange. As a result, a cold stream can potentially be heated, expanded, heated, compressed, cooled, expanded and heated. This route was proposed by Wechsung et al. (2011) based on the "plus-minus" principle for reducing the energy requirements of the system. Thus, the streams subject to handling pressure are connected to the HEN through compressors and turbines, so that the stream outlet conditions of the pressure manipulation equipment must match the inlet conditions in the HEN superstructure. Therefore, the streams pressure and temperature must be treated as unknown variables requiring optimization. The model allows for the increment of the available heat exchange area, and the coupling between turbines and compressors on a common shaft, in which the turbine is able to satisfy even 80% of the energy requirements of the compressor. In this case, a helper motor is used to supply the remaining energy demand of the compressor. The mathematical formulation for the HEN retrofit considering pressure recovery of process streams is presented in the next section.

## 3. MINLP-BASED MODEL

The proposed mathematical model is developed based on the superstructure by Onishi et al. (2014b), in which the model for the HENs synthesis proposed by Yee and Grossmann (1990) was extended to consider the simultaneous pressure recovery of process streams. The following indices definition is required for the development of the model:

$$I = \{ i \,/\, i = 1, 2, ..., I \text{ are hot streams} \}$$
$$J = \{ j \,/\, j = 1, 2, ..., J \text{ are cold streams} \}$$
$$K = \{ k \,/\, k = 1, 2, ..., K \text{ are the stages number of the HEN} \}$$
$$T = \{ t \,/\, t = 1, 2, ..., T \text{ are turbines} \}$$
$$V = \{ v \,/\, v = 1, 2, ..., V \text{ are compressors} \}$$

The thermal integration between the streams *i* and *j* must occur only once. Or, in other words, each heat exchanger should be used for only one possibility of heat exchange between the streams *i* and *j*, which is guaranteed by the following restriction:

$$\sum_{k=1}^{K} y_{i,j,k} \leq 1 \quad i \in I,\ j \in J \tag{1}$$

At each stage of the superstructure, the heat exchangers can be larger or smaller than the heat exchangers available in the existing network, but only one possibility can be chosen. If the heat exchange area is smaller or equal than the available area, the existing heat exchanger is reused. Otherwise, the additional heat exchange area required is calculated to be accounted in the total cost of the process.

$$y_{i,j,k}^{smaller} + y_{i,j,k}^{bigger} \leq 1 \quad i \in I,\ j \in J,\ k \in K \tag{2}$$

$$0 \cdot y_{i,j,k}^{smaller} \leq A_{i,j,k}^{smaller} \leq A_{i,j,k}^{ex} \cdot y_{i,j,k}^{smaller} \quad i \in I,\ j \in J,\ k \in K \tag{3}$$

$$A^{ex}_{i,j,k} \cdot y^{bigger}_{i,j,k} \leq A^{bigger}_{i,j,k} \leq A^{UP}_{i,j,k} \cdot y^{bigger}_{i,j,k} \quad i \in I,\ j \in J,\ k \in K \tag{4}$$

$$y_{i,j,k} = y^{smaller}_{i,j,k} + y^{bigger}_{i,j,k} \quad i \in I,\ j \in J,\ k \in K \tag{5}$$

$$A^{add}_{i,j,k} = A^{bigger}_{i,j,k} - A^{ex}_{i,j,k} \cdot y^{bigger}_{i,j,k} \quad i \in I,\ j \in J,\ k \in K \tag{6}$$

An analogous formulation to Equations (2)–(6) is used to ensure that heaters and coolers larger or smaller than the existing heat transfer equipment can be used at the superstructure outlet streams. For this reason, these equations are omitted in this article. The amount of additional heat duty required to coolers and heaters must comply with the following restrictions:

$$Q^{add}_{i,n} \geq Q_{i,n} - Q^{ex}_{i,n} \cdot y_{i,n} \quad i \in I \tag{7}$$

$$Q^{add}_{m,j} \geq Q_{m,j} - Q^{ex}_{m,j} \cdot y_{m,j} \quad j \in J \tag{8}$$

The proposed model allows for the coupling of turbines and compressors with a helper motor, aimed at saving energy and reducing costs. However, if a turbine and/or compressor exist on the network, they may be allocated to the coupling shaft or act as stand-alone equipment. Of course, both possibilities cannot occur simultaneously. Thus, the following logical constraints are needed to ensure that decision.

$$y^a_t + y^s_t \leq 1 \quad t \in T \tag{9}$$

$$y^a_v + y^s_v \leq 1 \quad v \in V \tag{10}$$

In order to avoid very small and large equipment, the work of expansion and compression should be limited between a minimum and maximum value. Thus, if a stand-alone turbine exists in the network, it must carry out a minimum work. Otherwise, the expansion work should be zero.

$$We^s_t \geq We_{\min} - We^{UP}_t \cdot (1 - y^s_t) \quad t \in T \tag{11}$$

$$We^s_t \leq We^{UP}_t \cdot y^s_t \quad t \in T \tag{12}$$

The same should occur with turbines allocated on the shaft, as well as with stand-alone compressors and compressors allocated on the shaft. This fact is ensured through analogous formulation. As suggested by Couper et al. (2010), the work of compression and expansion should be restricted between a lower and an upper limit:

$$100 \leq We^s_t\,(\mathrm{kW}) \leq 1500,\ 100 \leq We^a_t\,(\mathrm{kW}) \leq 1500,\ 18 \leq Wc^s_v\,(\mathrm{kW}) \leq 950 \text{ and } 18 \leq Wc^a_v\,(\mathrm{kW}) \leq 950$$

The turbine allocated to the coupling shaft is able to satisfy 80% of the energy demand of the compressor on the same shaft, i.e.:

$$We^a_t \leq 0{,}8 \cdot Wc^a_v \cdot y^a_v \quad t \in T,\ v \in V \tag{13}$$

Consequently, a helper motor must be used to supply the remainder (i.e., 20%) of the energy requirements of the compressor. Thus, the global energy balance is needed to ensure that the expansion work is equal to the compression work in the shaft.

$$\sum_{t=1}^{T} We_t^a + Wh = \sum_{v=1}^{V} Wc_v^a \tag{14}$$

## 4. CASE STUDY

A case study related a cryogenic process is conducted to verify the applicability of the proposed model. In this example, a hot stream H1 and a cold stream C1 are at constant pressure, while a second stream C2 is subjected to pressure manipulation from an initial state of 3.0 MPa to a final state of 0.1 MPa. The route of pressure manipulation and heat integration of stream C2 includes the following consecutive steps: heating, expansion, heating, compression, cooling, expansion and heating. As a consequence, C2 behaves as C3 after the first expansion, as H2 after compression and, finally, as C4 after the last expansion. In addition, the unknown streams temperatures can vary between 103 K and 383 K, the pressure of stream C3 is restricted to 0.1–2.0 MPa, and the pressure of H2 is restricted to 2.0–3.0 MPa. The parameters $\Delta T_{\min}$ = 4 K, $T^{h}_{U}$ = 383 K, $T^{c}_{U}$ = 93 K, $\kappa$ = 1.352, $\eta_t = \eta_v$ = 0.7 are considered for the HEN retrofit. The process streams data, as well as the existing thermal equipment are shown in Table 1. Two different cases are conducted to evaluate the economic feasibility of the retrofit design. In the first case, the HEN retrofit is performed without pressure manipulation of stream C2. In the second case, the proposed MINLP-based model is used to design the HEN retrofitted, considering the use of all available heat transfer equipment, and a compressor and a turbine coupled with a helper motor. In all cases, the minimization of the total annualized cost of the HEN retrofit is considered to be the objective function.

In Case 1, the optimal configuration obtained for the HEN retrofitted consists of two heat exchangers with areas of 120.00 m$^2$ ($Q$ = 336.00 kW) and 161.51 m$^2$ ($Q$ = 277.12 kW), one heater with area of 8.32 m$^2$ ($Q$ = 59.48 kW) and, one cooler with area of 94.66 m$^2$ ($Q$ = 286.38 kW). Thus, all previous existing heat exchange equipment is reused in the HEN retrofit design. However, the cooler located in the stream H1 requires an additional heat exchange area of 14.66 m$^2$, with an additional heat duty of 186.38 kW. The total annualized cost of the HEN retrofitted with this configuration is 238,136 US$/year, composed by 23,795 US$/year associated to the capital cost of investment in equipment, and 214,341 US$/year related to additional operating expenses. In Case 2, the optimal configuration obtained for the HEN retrofitted with pressure recovery consists of four heat exchangers with areas of 120 m$^2$ ($Q$ = 336.00 kW), 180.00 m$^2$ ($Q$ = 119.11 kW), 81.47 m$^2$ ($Q$ = 97.35 kW) and 102.32 m$^2$ ($Q$ = 256.60 kW). Moreover, one heater with area equal to 10 m$^2$ ($Q$ = 80.00 kW), and one cooler of 80 m$^2$ ($Q$ = 90.45 kW) are used in the network. Thus, all existent heat equipment is again reutilized in the HEN retrofit design. However, two additional heat exchangers are needed in the process, corresponding to an additional heat exchange area of 183.79 m$^2$.

Table 1 – Stream data and existing heat transfer equipment for the Case Study

| Stream | *FCp* (kW/K) | *h* (kW/m$^2$K) | $T_{in}$ (K) | $T_{out}$ (K) | *P* (MPa) |
|---|---|---|---|---|---|
| H1 | 3.5 | 0.1 | 365 | 108 | 3.0 |
| C1 | 4.2 | 0.1 | 220 | 300 | 3.0 |
| C2 | 1.8 | 0.1 | 103 | - | 3.0 |
| C3 | 1.8 | 0.1 | - | - | - |
| H2 | 1.8 | 0.1 | - | - | - |
| C4 | 1.8 | 0.1 | - | 290 | 0.1 |
| *Existent network* | | *A* (m$^2$) | *Q* (kW) | *Cost data (*US$/year kW*):* | |
| H1.C1.k1 | | 120 | - | *CW* = 1150.00 | |
| H1.C2.k2 | | 180 | - | *CS* = 337.00 | |
| H1 | | 80 | 100 | *CE* = 455.04 | |
| C2 | | 10 | 80 | *CV* = 400.00 | |

Figure 1 shows the optimal configuration obtained for the HEN retrofitted in this case, wherein the heat exchangers highlighted indicate the previous existing equipment that have been reused in the network. In this case, the heater allocated on stream C2 is replaced to the end of stream C4, due to pressure manipulation process. In addition to the heat exchange equipment, one stand-alone turbine with capacity of 241.46 kW and one compressor (125 kW) coupled to a turbine (100 kW), with one helper motor (25 kW) is used for the pressure manipulation process. As a consequence, no amount of additional heat duty is required to utilities. Therefore, no additional cost related to heating and cooling services of fluids is added to the process. The total annualized cost of the HEN retrofit is equal to 212,076 US$/year, composed by 297,282 US$/year related to the capital cost of investment, and 85,206 US$/year in revenue from the sale of electricity generated by the stand-alone turbine (already discounted the electricity cost spent by the helper motor). Thus, the total cost of the HEN retrofit with pressure recovery is 11% lower than the total cost obtained in Case 1, in which the HEN retrofit is performed without pressure manipulation of the stream C2. The CPU time for Case 1 is 15 s and for Case 2 is 6.48 min, both with the SBB solver under GAMS software (version 24.1.3).

## 5. CONCLUSIONS

A new MINLP model for the HENs retrofit is proposed, wherein the pressure recovery of process streams is used to improve the heat integration. In this proposed new approach, the pressure recovery of streams is performed simultaneously with the retrofit of the network by means of compression and expansion stages connected to the heat integration in the HEN. The process streams subject to compression and expansion are connected to the HEN through compressors and turbines, so that the state output stream of the handling equipment should match the pressure state of the superstructure of the HEN input. Thus, the process conditions (pressure and temperature of the streams) should be treated as unknown variables requiring optimization. It should be emphasized that this fact significantly increases the complexity of the model in comparison with the conventional approaches for HENs retrofit.

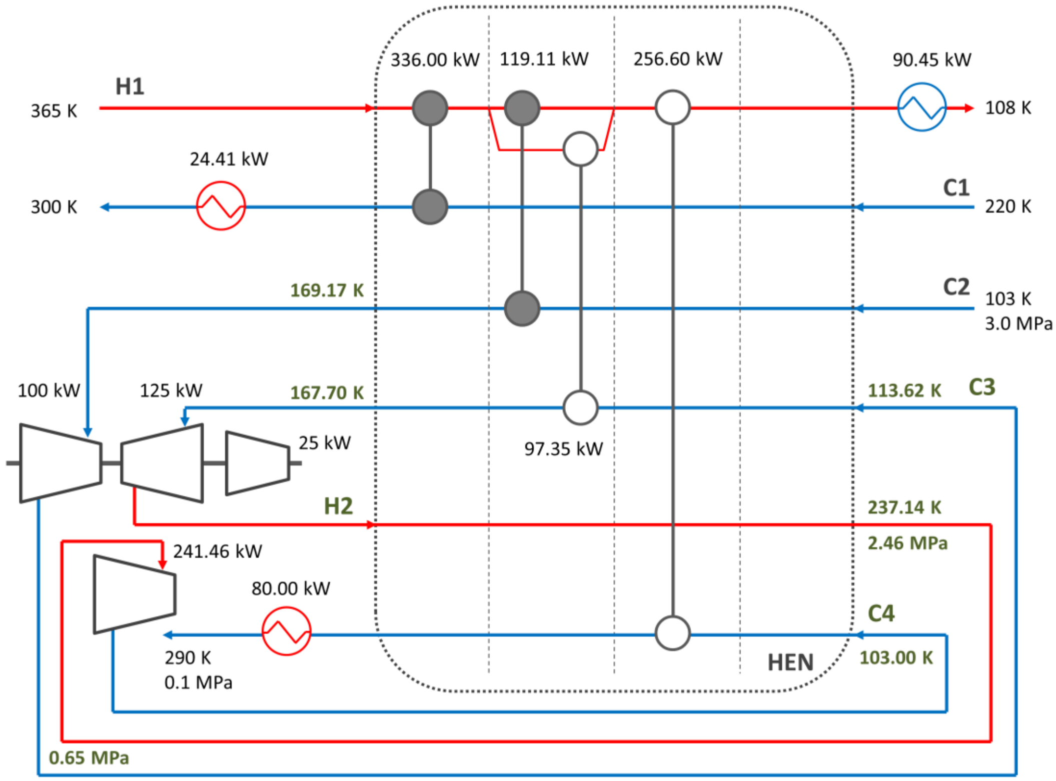


Figure 1 – Optimal configuration obtained for the HEN retrofitted for Case 2.

A case study is conducted to verify the accuracy of the proposed model, in which the pressure manipulation of process streams at sub-ambient conditions is evaluated. It is noted that the pressure manipulation of process streams considerably increases the capital cost of investment related to new equipment. However, these turbines and compressors are also responsible for the reduction of costs of cooling of streams as a result of the significant decrease in the need for cold services. It should be highlighted that the streams cooling are extremely expensive in sub-ambient processes. In addition, the coupling of the turbine with the compressor and a helper motor reduces the electricity costs. This fact allied with the revenue from the sale of electricity generated by the stand-alone turbine used in the network make the process economically viable.

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## 7. NOMENCLATURE

| | |
|---|---|
| $A^{add}$ | additional heat exchange area |
| $A^{bigger}$ | heat exchange area bigger than the existing area |
| $A^{ex}$ | existing heat exchange area |
| $A^{smaller}$ | heat exchange area smaller than the existing area |
| $Q^{add}$ | additional heat duty |
| $Q^{ex}$ | existing heat duty |
| $We^{s}$ | stand-alone turbine work |
| $We^{a}$ | work of the turbine allocated on the shaft |
| $Wc^{s}$ | stand-alone compressor work |
| $Wc^{a}$ | work of the compressor allocated on the shaft |
| $Wh$ | helper motor work |
| $y^{bigger}$ | binary variable that define the use of heat exchangers larger than the existing equipment |
| $y^{smaller}$ | binary variable that defines the use of heat exchangers smaller than the existing equipment |
| $y^{a}$ | binary variable that defines the use of turbines and compressors coupled to the shaft |
| $y^{s}$ | binary variable that defines the use of stand-alone turbines and compressors |

## 8. REFERENCES

Couper, J.R., Penney, W.R., Fair, J.R., Walas, S.M. *Chemical Process Equipment, Selection and Design*. USA: Elsevier, 2010.

Onishi, V.C., Ravagnani, M.A.S.S., Caballero, J.A. Simultaneous synthesis of work exchange networks with heat integration. *Chem. Eng. Sci.*, v. 112, p. 87–107, 2014a.

Onishi, V.C., Ravagnani, M.A.S.S., Caballero, J.A. Simultaneous synthesis of heat exchanger networks with pressure recovery: optimal integration between heat and work. *AIChE J.*, v. 60, p. 893–908, 2014b.

Pan, M., Bulatov, I., Smith, R., Kim, J.-K. New MILP-based iterative approach for retrofitting heat exchanger networks with conventional network structure modifications. *Chem. Eng. Sci.*, v. 104, p. 498–524, 2013.

Polley, G.T., Tamakloe, E., Picon Nunez, M., Ishiyama, E.M., Wilson, D.I. Applying thermo-hydraulic simulation and heat exchanger analysis to the retrofit of heat recovery systems. *Appl. Therm. Eng.*, v. 51, p. 137–143, 2013.

Wang, Y., Smith, R. Retrofit of a heat-exchanger network by considering heat-transfer enhancement and fouling. *Ind. Eng. Chem. Res.*, v. 51, p. 8527–8537, 2013.

Wang, Y., Smith, R., Kim, J.-K. Heat exchanger network retrofit optimization involving heat transfer enhancement. *Appl. Therm. Eng.*, v. 43, p. 7–13, 2012.

Wechsung, A., Aspelund, A., Gundersen, T., Barton, P.I. Synthesis of heat exchanger networks at subambient conditions with compression and expansion of process streams. *AIChE J.*, v. 57, p. 2090–2108, 2011.

Yee, T.F., Grossmann, I.E. Simultaneous optimization models for heat integration. II. Heat exchanger network synthesis. *Comput. Chem. Eng.*, v. 14, p. 1165–1184, 1990.