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Proactive Optimization and Control of Heat-Exchanger Super Networks

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Abstract: This paper presents an integrated approach for the optimization and control of heat-exchanger networks (HENs) that are managed proactively, where both renewable energy generation and time-varying electricity pricing are considered in calculating the utility cost and revenues. A real-time optimization strategy is carried out to deal with the resulting variability in energy resource availability and costs. The heat-exchanger super structures are first defined where transitions between the included HEN sub-structures are assumed to be instantaneous. The optimal configurations are sent to the local controllers as structural set points to be implemented. The explicit nonlinear models of heat exchangers built in Aspen Plus® are adopted to describe the dynamic behaviors of the HENs. The dynamic models are incorporated not only for simulating the local control scheme but also the supervisory level to account for the structural transitions that incur operational and possibly capital costs.

Keywords: Heat-exchanger networks, Optimization, Dynamics, Renewable energy, Economics

1. INTRODUCTION

Large-scale chemical or petrochemical processes are highly energy intensive and usually require energy recovery systems to guarantee high efficiency and low cost. A heat-exchanger network (HEN) aims at utilizing internal flow streams to satisfy outlet temperature targets so that operating costs can be minimized (Linnhoff (1978)). Attributed to the significance of determining energy cost in chemical processes, the HEN synthesis problem has been widely studied with the objective to minimize overall investment (e.g., Dipama et al. (2008); Gorji-Bandpy et al. (2011); Gundepsen et al. (1988); Yee and Grossmann (1990); Zamora and Grossmann (1998); Ciric and Floudas (1991)). Another category of studies deals with optimal operation of HENs following the synthesis step (e.g., Aguilera and Marchetti (1998); Glemmestad (1999); Lersbamrungsuk et al. (2008)).

A traditional HEN is expected to be operated under the condition of maximum heat integration and minimum utility consumption due to the high cost of utilities (González (2006)). With the emerging trend in energy management systems to integrate renewable generation, such as wind and solar resources, and to supply heat and power not only to residential users but also to process industries, the electricity can be "zero-cost" as well as "zero emission", making renewable energy a promising power alternative (Wang et al. (2014)). Furthermore, the time-varying electricity prices with respect to supply and load brings more opportunities for electricity users to manage their interaction with the power grid and optimize economic performance.

Despite the wide implementation of renewable resources, the discrete generation and inherent uncertainty in renewable resources continue to pose significant challenges. The time-varying electricity pricing also requires more comprehensive scheduling to lower the energy cost. Receding horizon optimization is thus a meaningful strategy that can incorporate future conditions, such as the energy generation and loads, and coordinate the real-time operation with as much information as possible. On the other hand, although the overall steady-state operating cost can be reduced by adjusting the operational states of the plant, frequent changes may cause safety issues and harm the equipment, and ultimately economic performance. To avoid infeasible solutions, it is necessary to take the dynamic models that describe the state transitions into consideration and look for reasonable control strategies as well.

In this paper, an innovative methodology of proactive reconfiguration of HENs is introduced. The methodology is aimed at realizing – at any given time - the optimal operational state of the HEN within an existing super network. Based on extensive research on HEN synthesis, a reconfiguration step is proposed to unite the simultaneous design, operation and control activities. Assuming, for simplicity, that the synthesis step is already carried out, which means that all necessary exchangers, utility units, and the connecting structure are completely defined, this work demonstrates a re-configuration step to realize the transitions between the possible sub-structures based on real-time generation, power load and cost. Both the steady-state optimization and dynamic control are considered to close the loop at the supervisory and local levels. We will first discuss the HEN reconfiguration problem statement and formulation in Section 2. Then the proactive supervisory optimizer is described in Section 3 to simultaneously decide the HEN sub-structure and operating states. In Section 4, several issues regarding the control of the target HEN are discussed. Conclusions, along with future research directions, are presented in Section 5.

2. HEAT EXCHANGER NETWORK

2.1 Problem Statement

Here, we focus on the optimal design, operation and control within a hierarchical framework as shown in Fig.1. Under market fluctuations, such as varying electricity pricing and supply of renewable resources, a steady-state optimization over a short time horizon is performed to generate the operating set-points for the heat flows and temperature targets, which are subsequently sent to the local controllers for tracking. The local controllers (PID or MPC) are adopted to realize optimal operation and effectively handle process disturbances.

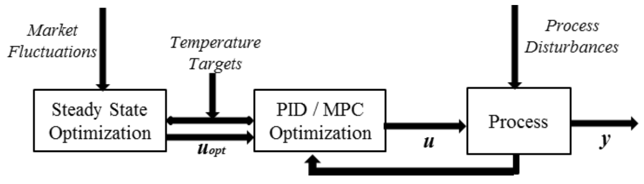


Fig. 1. Overview of the proactive optimization and control problem.

The synthesis problem for HENs is based on the idea of matching a set of hot process streams, H, to be cooled, and a set of cold streams, C, to be heated. Each stream has a specific heat capacity C_p and flow rate m, along with their inlet and target outlet temperature. Also, the hot and cold utilities, HU and CU, are available to guarantee the temperature requirements to be satisfied in spite of how much heat is recovered in network heat exchangers.

The objective of a traditional synthesis problem is to decide the HEN with the least total annualized cost which includes not only the energy cost, but also the capital cost for heat-exchangers corresponding to the equipment area required (Floudas (1995)). In our case, the starting point is an existing super structure that includes several potential HEN sub-structures (networks) so that the fixed cost can be neglected while emphasizing only the energy and operating costs. Fig. 2 shows an example of a super structure consisting of two hot process streams and two cold process streams with no bypassing or stream splitting.

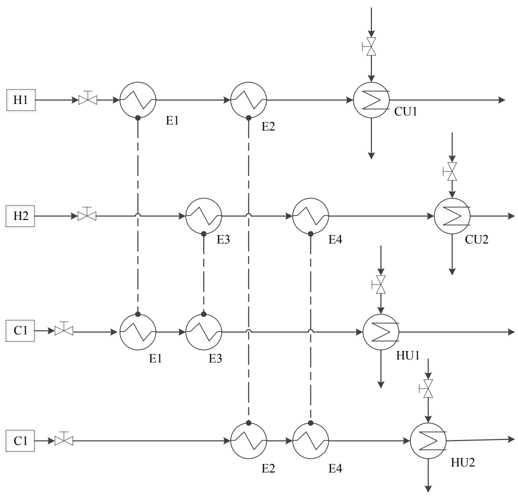


Fig. 2. A typical super structure for a heat-exchanger network comprised of two hot and two cold streams (no bypassing or stream splitting).

2.2 Problem Formulation

A key issue when designing a HEN structure is the pinch point, which acts as a thermodynamic bottleneck that limits the maximum energy integration and poses feasibility constraints (Floudas (1995)). Hence, a procedure of decomposition by the pinch temperature is always required to guarantee the feasibility of temperature and energy balance. However, instead of specifying the minimum approach temperature and the corresponding pinch point(s) a priori, these parameters can be optimized simultaneously with the matches and network (e.g., Yee and Grossmann (1990), Ciric and Floudas (1991)). In this work, a similar multi-stage optimization scheme is adopted and described as follows.

Given the simplification of the super structure by considering a number of stages, N_S, all possible matches are allowed within each stage. Also, the isothermal mixing assumption can assign the same temperature as a single variable to each stream after splitting at the end of every stage. Two other types of variables are defined which are continuous variables for the heat flow, and binary variables representing the existence of a process or utility match at each stage.

The objective, while searching within the super structure, is to find the sub-network that minimizes the cost for specific heat exchange requirements, i.e. satisfying temperature targets of cold and/or hot outlet streams. Three cost terms are considered which are the utilities cost, co-generation revenues from renewables and amortized depreciation cost for heat-exchangers:

$$\min J = \alpha\,(\sum_{i=1}^{N_H} C_{CU}C_i + \sum_{j=1}^{N_C} C_{HU}H_j) - \beta\,(C_{ele\_sell}P_{sell}) + \lambda\,(\sum_{k=1}^{N_E} C_{HE}Q_k + \sum_{i=1}^{N_H} C_{HEh}C_i + \sum_{j=1}^{N_C} C_{HEc}H_j) \quad (1)$$

where α, β and λ are the weighting factors to weigh the significance of each cost term. N_H and N_C are the number of hot and cold streams. C_i and H_j are the load of cold and hot utilities located over the hot and cold streams of i and j respectively. C_{CU} and C_{HU} represent the price of the cold and hot utilities, respectively. We note here that C_{CU} and C_{HU} are not fixed but dependent on the utility sources. The prices may vary significantly according to whether the utilities are powered by the electricity from renewable generation or electricity purchased from the grid with varying pricing.

As an example, Fig. 3 shows at a fixed time instant when the renewable generation is $P_{renewable}$ associated with a power to utility ratio η_{re}, if the total demand is less than the current available renewable generation (see P_{demand_1} in Fig. 3), the unit cost of utility will be equal to C_{re} and the total cost is also reduced by the profits of selling extra electricity from renewable resources generation back to the grid. When the total demand is larger than the renewable generation (see P_{demand_2} in Fig. 3), the unit cost of utility will be a combination of two parts described as a step function:

$$C_{HU} = \begin{cases} C_{re}\ , when \sum_{j=1}^{N_C} H_j \le P_{renewable}\eta_{re} \\ C_{ele\_buy} / \eta_{ele}\ , when \sum_{i=1}^{N_H} H_j \ge P_{renewable}\eta_{re} \end{cases} \quad (2)$$

C_{ele_buy} is the price of electricity purchased from the grid as a raw source for utilities, while η_{ele} is the efficiency of electricity converted to required utilities. C_{ele_sell} and P_{sell} are the price and amount of electricity sold back to the grid, which is treated as a revenue term from the renewable energy co-generation. C_{HE}, C_{HEh}, and C_{HEc} are the unit operating costs of heat exchanged depending on the type of exchanger. N_E is the number of total exchangers actively in use excluding the utility powered heaters or coolers.

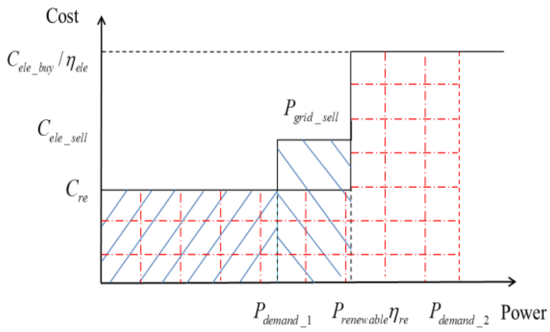


Fig. 3. Demonstration of the relation between utility cost and power.

The following set of constraints are considered:

a) Heat/ Energy balance

- Overall for each stream:

$$(mC_p)_i(T_i^{in} - T_i^{out}) = \sum_{j=1}^{N_C} Q_{i,j,1} + \sum_{j=1}^{N_C} Q_{i,j,2} \ldots + \sum_{j=1}^{N_C} Q_{i,j,Ns} + C_i, i \in N_H \quad (3)$$
$$(mC_p)_j(T_j^{out} - T_j^{in}) = \sum_{i=1}^{N_H} Q_{i,j,1} + \sum_{i=1}^{N_H} Q_{i,j,2} \ldots + \sum_{i=1}^{N_H} Q_{i,j,Ns} + H_j, j \in N_C$$

- For each stream at each stage:

$$for\ l = 1, 2, \ldots, N_S$$
$$(mC_p)_i(T_{i,l}^{in} - T_{i,l}^{out}) = \sum_{j=1}^{N_C} Q_{i,j,l}\ , i \in N_H \quad (4)$$
$$(mC_p)_j(T_{j,l}^{out} - T_{j,l}^{in}) = \sum_{i=1}^{N_H} Q_{i,j,1}\ , j \in N_C$$

- Utility matches:

$$(mC_p)_i(T_i^{Ns} - T_i^{out}) = C_i, i \in N_H \quad (5)$$
$$(mC_p)_j(T_j^{out} - T_j^{Ns}) = H_j, j \in N_C$$

b) Temperature

- Assignment of inlet temperatures:

$$T_{i,0} = T_i^{in}, i \in N_H \quad (6)$$
$$T_{j,0} = T_j^{in}, j \in N_C$$

- Targets of outlet temperatures:

$$T_i^{out} = T_i^{target}, i \in N_H$$
$$T_j^{out} = T_j^{target}, j \in N_C \quad (7)$$

- Feasibility of temperatures:

$$T_i^{out} \le T_{i,Ns} \le \ldots \le T_{i,1} \le T_{i,0}, i \in N_H$$
$$T_j^{out} \ge T_{j,Ns} \ge \ldots \ge T_{j,1} \ge T_{j,0}, j \in N_C \quad (8)$$

(Also guaranteed by the assumption of isothermal mixing.)

c) Capacity

- Availability from all utility resources:

The utilities are assumed unlimited since the power can be purchased from the grid. However, the price varies when the sources are different, as previously shown in Fig. 3.

- Maximum and Minimum heat exchanger capacity limits ($y_{i,j,l}$ are 0-1 binary variables):

$$0 \le Q_{i,j,l} \le y_{i,j,l} Q_{i,j,l,\max}, i \in N_H, j \in N_C, l \in N_S \quad (9)$$

d) Logical constraints

- Matches that take place denoted by $y_{i,j,l}$ binary variables.

The topology or structure of the HEN can then be decided according to active matches and heat duties with respect to each stage.

3. SUPERVISORY OPTIMIZATION

A MILP model is developed to formulate the potential matches between the hot and cold process streams and generate optimal set-points from the supervisory level optimization. The data used to illustrate this model is listed in Table 1.

Table 1. Process stream data

Stream	mC_p (kW/K)	T_{in} (K)	T_{out} (K)	*Enthalpy* (kW)
H1	0.7	443	333	77
H2	1.0	423	313	110
C1	1.7	293	353	-102
C2	1.3	278	348	-91

Before demonstrating the proposed methodology, a pinch point and first-law analysis for the specific HEN is conducted as shown in Fig. 4 to assist understanding of the problem. The minimum approach temperature between hot and cold streams ΔT_{min} is set as 20K. As a result, the pinch temperatures are at 313K for hot streams and 292K for cold streams, and the minimum utility targets are 4.1 kW hot utilities in total with 0 kW cold utilities required.

In order to decide the optimal ΔT_{min} simultaneously with the network configuration, two stages are considered in this formulation that equals the minimum number of hot streams or cold streams in this case (Ciric and Floudas (1991)).

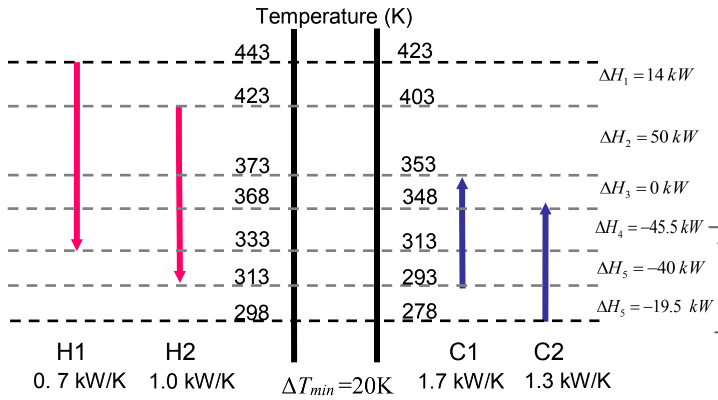


Fig. 4. Pinch point and first-law analysis for the given streams.

A receding horizon optimization can repeatedly optimize the control inputs and plan actions over a finite time-span into the future to deal with uncertainties. Here, we adopt a one-hour horizon length so that the weather information and electricity pricing are updated on an hourly basis. The electricity generated from renewables bears the priority of utility placement due to the low cost of wind and solar energy. Using the actual weather data and time-varying pricing information to purchase electricity from the grid (see Fig. 5), the reliability of applying a hybrid cogeneration system can be improved through hourly forecasting and update of available solar and wind energy, as well as the cost of purchasing electricity.

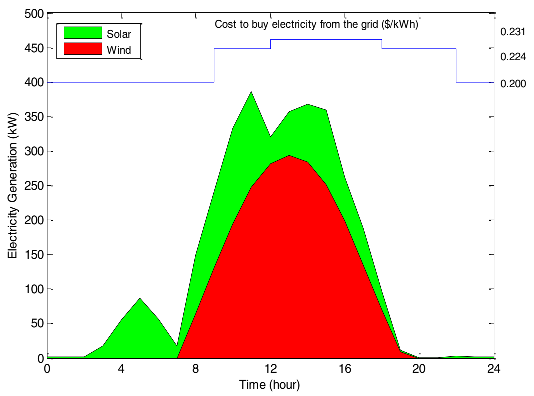


Fig. 5. Renewable generation and electricity price from the grid over a typical summer day in the Sacramento Valley.

By minimizing the total cost with the set of constraints stated in Section 2, the results of heat duties and temperature set-points according to the optimal solution can be achieved and are shown in Table 2 and Fig. 6, respectively.

Table 2. Results of MILP optimization

Heat duty (kW)	*0:00 – 11:00*	*11:00 – 14:00*	*14:00 – 17:00*	*17:00 – 24:00*
Q_H1_C1_1	0	78.8	78.8	0
Q_H1_C1_2	78.8	0	0	78.8
Q_H1_C2_1	0	0	0	0
Q_H1_C2_2	0	0	0	0
Q_H2_C1_1	0	23.4	20.5	0
Q_H2_C1_2	20.5	0	0	20.5
Q_H2_C2_1	0	88.5	91.5	0
Q_H2_C2_2	91.5	0	0	91.5
Q_H1_W	0	0	0	0
Q_H2_W	0	0	0	0
Q_C1_S	2.94	0	2.94	2.94
Q_C2_S	0	2.94	0	0

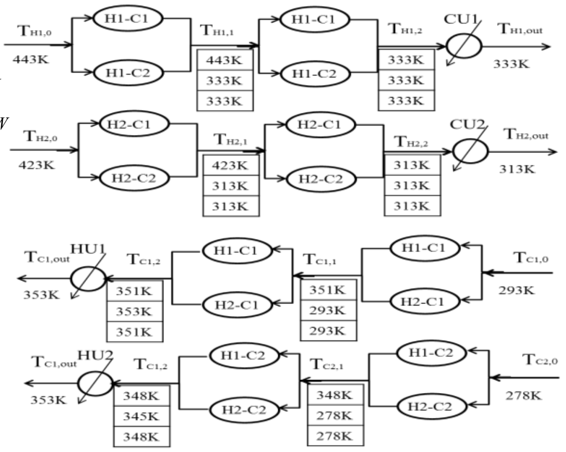
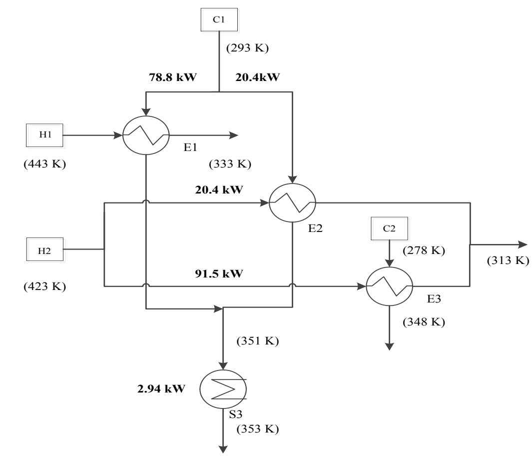
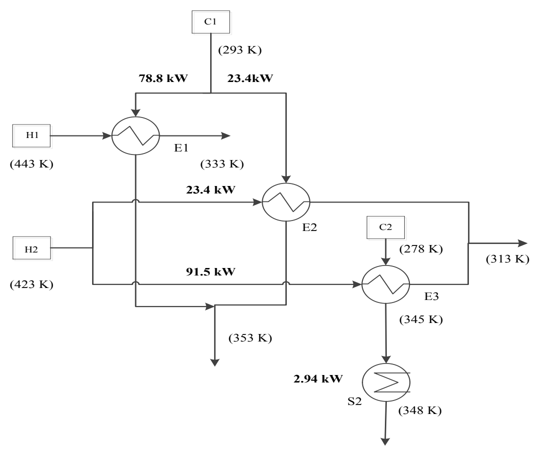


Fig. 6. Optimal heat-exchanger networks under real-time conditions over a day.



(a) Configuration 1 (Off-peak hours)



(b) Configuration 2 (Peak-hours)

Fig. 7. Two different HEN sub-structures at different times of a day.

The optimal results for time periods 0:00 – 11:00 and 17:00 – 24:00 yield exactly the same HEN structure, which corresponds to configuration 1 in Fig. 7. The peak-hour (11:00 – 14:00) operation with high renewable energy output leads to a different strategy as demonstrated by configuration 2 in Fig. 7. Notice that although the numerical solution returns a different optimal set for the time period 14:00 – 17:00, the realized configuration of HEN substructure is actually the same as the one during 0:00 – 11:00 or 17:00 –24:00, considering the multi-stage formulation of Q and T as variables at the same time. As a result, there are only two operational states within a day, and the structural transitions occur at 11:00 and 14:00 hours.

With this switching scheme, the minimal cost of the system is shown is Fig. 8. During the mid-day when the renewable generation is high, the plant can even make a profit from selling electricity back to the grid.

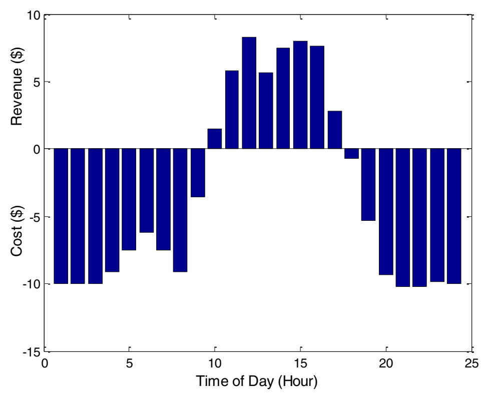


Fig. 8. Optimal real-time economic performance over a day.

4. DYNAMIC CONTROL

Although online optimization can provide the theoretical set-points to be implemented, it may lead to too frequent transitions during the dynamic operation, or the operation may even become infeasible. Dynamic models are necessary for further control and optimization if the transitions are not assumed instantaneous but incur some cost and expend energy. Heat-exchangers are complex devices for which the prediction of their operation from first principles is virtually impossible. As a result, process simulation tools such as Aspen Plus® can be utilized to demonstrate their potential especially when simulating dynamic behavior.

The control variables in a HEN system are of three kinds: (a) process stream bypasses around heat-exchangers, (b) utility stream flow rates in service units and (c) splits of process streams. The addition of the new splitters or bypasses can provide the HEN more flexibility so that some functionally uncontrollable problems can be solved. However, the bypasses or splits will change the configuration of the network, leading to transitions which may be time- and energy-consuming. Although in this two-hot-two-cold stream case study, the optimal configuration at each time step can be realized within reasonable time due to its simplicity, and justifies neglecting the transition-state cost, it is still necessary to study the transition process for further quantitative analysis. The flow diagram in Fig. 9 demonstrates the super HEN structure which uses valves and splitters to provide possibilities of bypasses and splitting and encompasses potential sub-structures.

In the absence of any control structures, the system will exhibit open-loop behaviour. For the first structural change, the outlet temperature of cold stream 1 increases from 351K to 353K, and cold stream 2 decreases from 348K to 345K. The required actions are setting the position of valve V3 from 50% to 62% opening, then V4 50% to 46% at the same time. As can be seen from the open-loop temperature profiles in Fig. 10 (black and blue lines), the system is able to meet the targets regardless of the performance. After the peak-hour periods, the temperatures can be reset to initial states. However, if some variations appear with respect to flow rates or temperature, the system can no longer keep operating at the optimal state. As also shown in Fig. 10, at time 19:00, the inlet temperature of hot stream 2 has a sudden increase by 10K caused by process variations, the open-loop system cannot meet the targets set by the optimal operation trajectory.

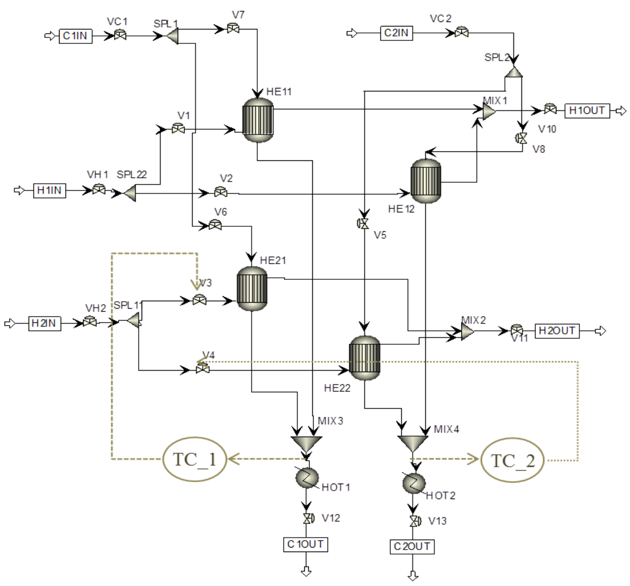


Fig. 9. The super HEN structure corresponding to the optimal results.

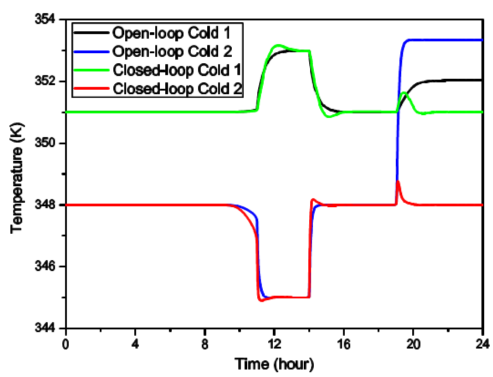


Fig. 10. Dynamic behaviours of the system switching between different states with open-loop and closed-loop structures.

To better deal with process disturbances, local controllers are necessary. Two key components in charge of the temperature transitions are the temperature controllers TC_1 and TC_2 for cold streams 1 and 2, respectively. In order to drive the outlet temperature of cold streams to the targets, the manipulated variables can be either the hot or cold stream inlet flow rates. By changing the valve positions (direct acting, air-to-open for cold stream inlet and reverse, air-to-close for hot stream), the outlet temperature of the cold streams will vary to meet the set-points. For the temperature control, properly-tuned Proportional-Integral (PI) controllers were designed to orchestrate the required sub-structure re-configuration. As indicated in Fig. 10 for the closed-loop temperature profiles (green and red lines), the settling time can be shortened compared with the open-loop system at the two switching times. And more importantly, when there are any disturbances, the set-points can always be tracked. Thus, the fast and effective substructure changes can be realized, and stable operation of the HEN can also be guaranteed when there are no configuration changes.

5. CONCLUSIONS AND FUTURE WORK

This paper introduced a proactive methodology to re-configure in real-time the optimal operation and control strategies of a HEN within a given super structure. In the proposed hierarchical approach, a steady-state optimization decides the real-time operation rules under varying renewable energy generation and electricity pricing, while local controllers orchestrate the required structural changes to realize the optimal strategy. Significant economic benefits with respect to plant energy cost can be achieved through the new operational scheme.

Based on this preliminary study, a number of future research directions remain to be explored. A more complex case study demonstrating how to handle additional streams in a complex HEN is under study to fully demonstrate the re-configuration process. Furthermore, the steady-state objective function can incorporate other important factors such as the explicit equipment cost at the design stage and the transition cost in the dynamic operation to yield a more comprehensive formulation. In addition, in lieu of simple PI controllers, model predictive control can add value to link the supervisory optimization and local tracking considering its strength in handle the necessary forecasting and model updates. Finally, energy storage can be considered as an integral part of the re-configuration strategy to manage the transition cost in a more realistic manner.

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