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Flexible and Operable Heat Exchanger Networks

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This paper presents the application of the proposed model-based methodology in solving integrated process design and control (IPDC) of heat exchanger networks (HENs). Many methods for HENs synthesis have been developed over the past decades, which aim to provide HENs designs that yield a reasonable trade-off between capital and operating costs. However, in most of HENs synthesis activities, the sole consideration in solution derivation is about design cost. Process operational issue especially controllability is frequently not a concern in the process design. As a result, the controllability of a designed HEN may be questionable. Industrial practice has made it clear that process controllability should be considered during process synthesis. The HENs design can be further improved to ensure that the design is more cost efficient and controllable. This can be achieved by developing a new model-based integrated process design and control methodology, which includes cost optimality and controllability aspects at the early HEN design stage.

The IPDC for HEN problem is decomposed into four hierarchical sequential stages: (i) target selection, (ii) HEN design analysis, (iii) controllability analysis, and (iv) optimal selection and verification. The set of constraint equations in the IPDC problem for HEN design is decomposed into four sub-problems which correspond to four hierarchical stages. The capability of the proposed methodology in solving IPDC of HEN problem was tested using biomethanol production plant. The results show that the proposed methodology was able to find the best solution which satisfied design, control and economic criteria in easy, efficient and systematic manner.

1. Introduction

There are many methods to synthesis heat exchanger networks (HENs) that has been developed over past decades. Several graphical tools such as Composite Curves (CCs) and Grid Diagram (GD) have been developed to determine the minimum energy targets as well as the Pinch points to design optimal HENs (Siemanond & Kosol, 2012; Pan et al., 2011; Klemeš et al., 2010). Wan Alwi and Manan (2010) have identified the limitations of CCs and GD, and suggested Stream Temperature versus Enthalpy Plot (STEP) as a new graphical tool for simultaneous targeting and designing of HENs that overcomes the some limitations of CCs and GD.

A HEN is considered optimally operated if the target temperatures are satisfied at steady state (main objective), the utility cost is minimized (secondary goal), and the dynamic behaviour and control aspects are satisfactory (tertiary goal). Another aspect that needs to be taking into consideration is the optimal HEN's controller structure (pairing of the controlled-manipulated variables). The best pairing will be selected based on the one where the effect of a given set of disturbances can be accommodated internally without requiring too much external utilities. While other optimization methods may not guarantee global optimum solutions, the proposed methodology uses reverse approach by decomposing the complex optimization problem into several sequential hierarchical sub-problems. Decomposition based solution strategy has been used to solve complex optimization problems in chemical processes (Hamid et al., 2010).

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and control solution (Wan Alwi and Manan, 2010). The design decision (target) is made at the pinch point at which also the minimum utility target for both external heat and cold utilities of the whole process plant. Then by using the reverse solution strategy, values of design-process variables that match the target are calculated in Stage 2. Using model analysis, controllability issues are incorporated in Stage 3 to calculate the process sensitivity and to identify the best manipulated-controlled variables pair. In Stage 4, the objective function is calculated to verify the best (optimal) solution (final selected design) that satisfies design, control and economic criteria. The final selected design is then verified through rigorous simulation.

The objective of this paper is to present the application of the proposed model-based methodology in solving the *IPDC* of *HEN* problem for a biomethanol production plant. In Section 2 the proposed methodology is briefly discussed. The application of the proposed methodology is discussed in details in Section 3. Finally, some conclusions are drawn in Section 4.

2. Methodology

2.1 Problem definition and formulation

The IPDC for HEN problem is typically formulated as a generic optimization problem in which a performance objective in terms of design, control and cost is optimized subject to a set of constraints: process (dynamic and steady state), constitutive (thermodynamic states) and conditional (process-control specifications)

$$\max \quad J = \sum_{i=1}^{m}\sum_{j=1}^{n} P_{i,j} w_j \tag{1}$$

subjected to:

Process (dynamic and/or steady state) constraints, $d\mathbf{x}/dt = f(\mathbf{u}, \mathbf{x}, \mathrm{y}, \mathbf{d}, \boldsymbol{\theta}, Y, t)$ (2)

Constitutive (thermodynamic) constraints, $0 = g_1(\mathbf{x}, \mathbf{y}) - \boldsymbol{\theta}$ (3)

Conditional (process-control) constraints

$$0 = h_1(\mathbf{u}, \mathbf{x}, \mathbf{y}) \tag{4}$$

$$0 \le h_2(\mathbf{u}, \mathbf{x}, \mathbf{y}, \mathbf{d}) \tag{5}$$

$$CS = \mathbf{y} + \mathbf{u}Y \tag{6}$$

In the above equations (2-5), **x** and **y** are usually regarded as the set of process variables in the process design and as the set of state and/or controlled variables in the controller design; usually temperatures, pressures and compositions. **u** is the set of design (manipulated) variables. **d** is the set of disturbance variables, $\boldsymbol{\theta}$ is the set of constitutive variables (physical properties, heat capacities, etc.) and *t* is the independent variable (usually time).

The performance function in equation (1) includes design, control and cost, where *i* indicates the category of the objective function term and *j* indicates a specific term of each category. w_j is the weight factor assigned to each objective term $P_{i,j}$ (i=1,3; j=1,2). Eq (2) represents a generic process model from which the steady-state model is obtained by setting $d\mathbf{x}/dt$=0. Eq (3) represents constitutive equations which relate the constitutive variables to the process. Eqs (4)-(5) represent sets of equality and inequality constraints (such as heating utility, cooling utility, heat recovery, temperature interval, etc.) that has to be satisfied for feasible operation-they can be linear or non-linear. In equation (6), ***Y*** is the set of binary decision variables for the controller structure selection (corresponds to whether a controlled variable is paired with a particular manipulated variable or not).

2.2 Decomposition based solution strategy

The work flow and steps involved in the decomposition based solution strategy is shown in Figure 1.

Accordingly, the IPDC for HEN problem is decomposed into four hierarchical sequential stages: (i) target selection, (ii) HEN design analysis, (iii) controllability analysis, and (iv) optimal selection and verification. As shown in Figure 1, the set of constraint equations in the IPDC for HEN problem is decomposed into four sub-problems which correspond to four hierarchical stages. In this way, the solution of the decomposed set of sub-problems is equivalent to that of the original problem.

3. Application of Biomethanol Plant

This section presents the use of decomposition based solution strategy in solving *IPDC* for *HEN* problem of a biomethanol plant as illustrated in Figure 2.

Stage 1: Target selection

The objective of this stage is to select the target for design and control solution of *HEN* design problem by using *STEP* concept. This stage consists of four sequential steps.

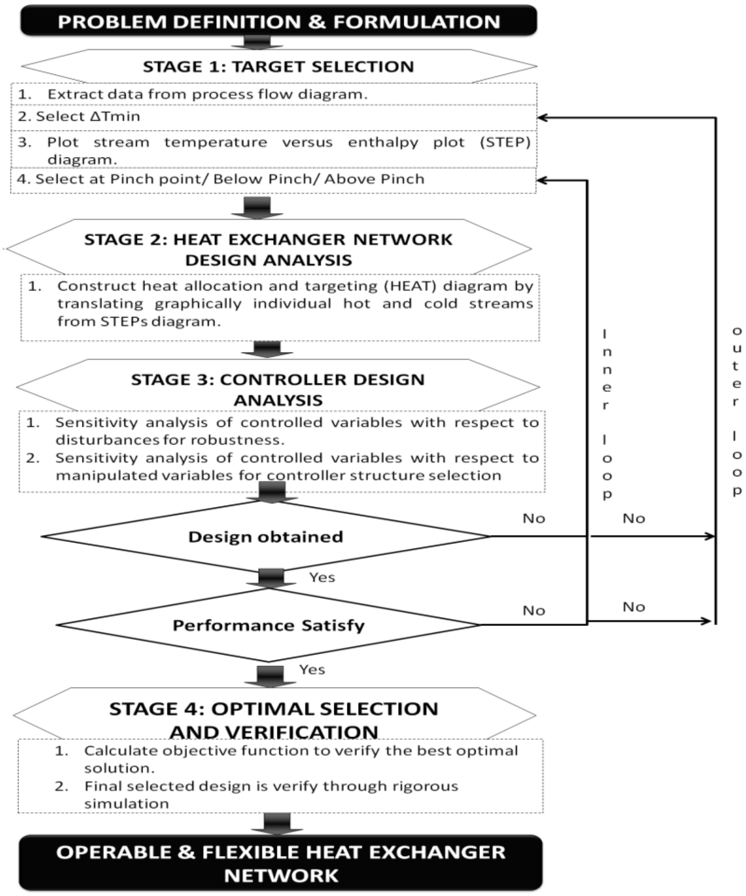

Figure 1: Decomposition method for IPDC of HENs problem (Abu Bakar et al., 2012).

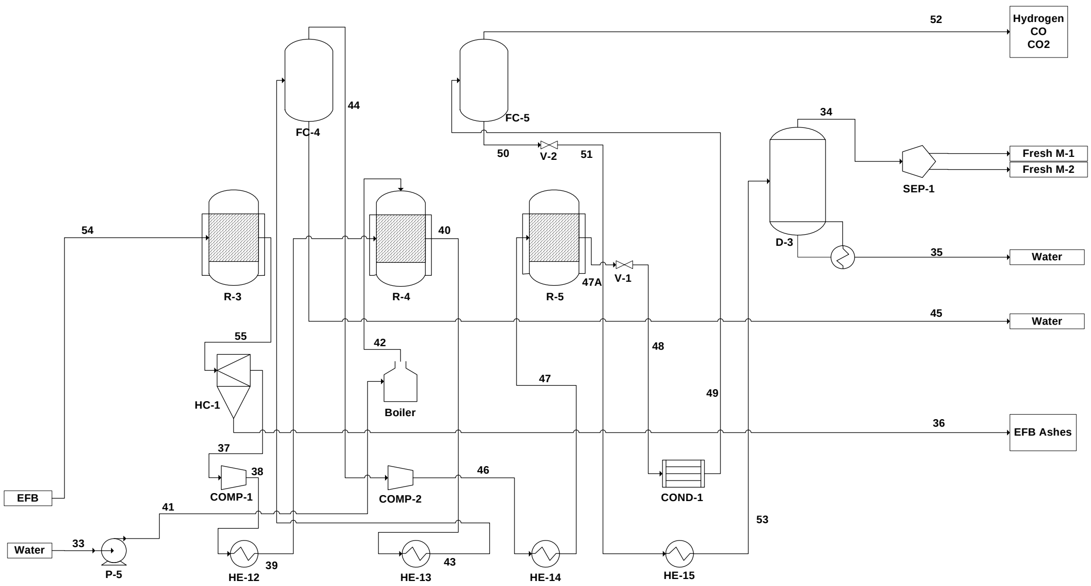

Figure 2: Process flow diagram of biomethanol production plant.

Step 1.1: Data Extraction - The objective of this step is to extract data from the process flow diagram. Data that need to be extracted from every single hot and cold streams are temperature, flowrate, and heat capacity, as shown in Table 1.

Table 1. Output data from Step 1.1 and Step 1.2

Stream Types	Equip.	Stream (in)	Supply Temp, T_s(°C)	Shifted Supply Temp, T'_s (°C)	Stream (out)	Target Temp., T_t(°C)	Shifted Target Temp., T'_t (°C)	*FCp* (kW/°C)
Hot 1	HE-13	40	870	860	43	60	50	2.838
Hot 2	COND1	48	250	240	49	50	40	1.929
Cold 1	HE-12	38	850	860	39	870	880	1.658
Cold 2	HE-14	46	60	70	47	250	260	1.703
Cold 3	HE-15	51	50	60	53	85	95	2.071

Step 1.2: Supply and Target Temperature to Shifted Supply Target Temperature Conversion - The objective of this step is to develop Problem Table Algorithm (*PTA*) (Klemeš *et al.*, 2010), as shown in Table 1.

Step 1.3: Continuous Hot and Cold STEPs Construction - In this step, continuous hot and cold *STEPs* are constructed based on Wan Alwi and Manan (2010) as shown in Figure 3 (top).

Step 1.4: Design-Control Solution Target Identification - The objective of this step is to select the target for the optimal design-control solution at the pinch point (see Figure 3 - top).

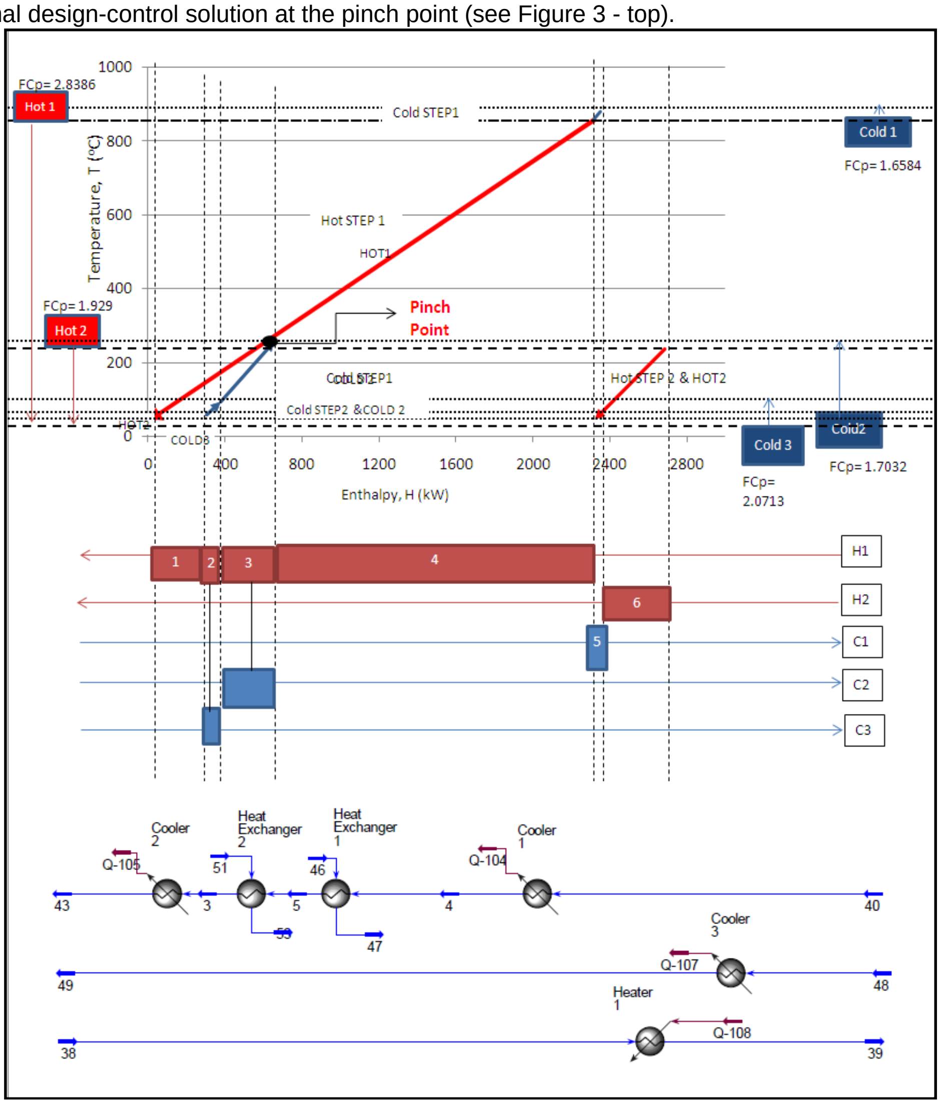

Figure 3: STEP and HEAT and HEN diagrams (output of Stage 1 and Stage 2)

Stage 2: Heat Exchanger Network Design Analysis
The objective of this stage is to design a *HEN* at the selected target.

Step 2.1: Construction of Heat Allocation and Targeting Diagram - The objective of this step is to design a *HEN* from the analysed data obtained in Stage 1. The Heat Allocation and Targeting (*HEAT*) diagram is constructed by transferring the *STEPs* diagram (from Stage 1) graphically into *HEAT* diagram as shown in Figure 3 (top and middle).

Step 2.2: HEN Model Construction in Aspen HYSYS Software - The objective of this step is to construct a *HEN* model using Aspen HYSYS to validate the *HEN* design obtained in the previous step. The Aspen HYSYS simulation model is shown in Figure 3 (bottom).

Stage 3: Control Design Analysis
The objective of this stage is to evaluate and validate the controllability performance of the feasible candidate (in this case only at the pinch point) in terms of their sensitivities with respect to disturbances and manipulates variables.

Step 3.1: Sensitivity Analysis - The process sensitivity is analyzed by calculating the derivative values of the controlled variables with respect to disturbances ($d\mathbf{y}/d\mathbf{d}$) with a constant step size using the steady-state process model developed in Aspen HYSYS. The results obtained shown that the designed *HEN* at the pinch point can accommodate the effect of disturbances up to ±5% without experiencing any temperature cross. This means that, the designed HEN is less sensitive and flexible to the effect of disturbances.

Step 3.2: Controller Structure Selection - The controller structure is selected by calculating the derivative values of controlled variables with respect to the manipulated variable ($d\mathbf{y}/d\mathbf{x}$) with a constant step size by using the steady-state process model developed in Aspen HYSYS. The objective if this step is to select the best controller structure (pairing of controlled-manipulated variables) which can satisfy the control objective (maintaining desired temperatures at their optimal set points in the presence of disturbances). The results are tabulated in Table 2. It can be seen that the derivative values of dT_{53}/dF_5, dT_3/dF_{51} and dT_{47}/dF_{46} are higher compared to other derivative values. Therefore, it can be clearly seen from Table 2 that the best pairing of controlled-manipulated variables that will be able to maintain the desired temperatures at their optimal set points values in the presence of disturbances are dT_{53}/dF_5, dT_3/dF_{51} and dT_{47}/dF_{46}. These controller structures are shown in Figure 4.

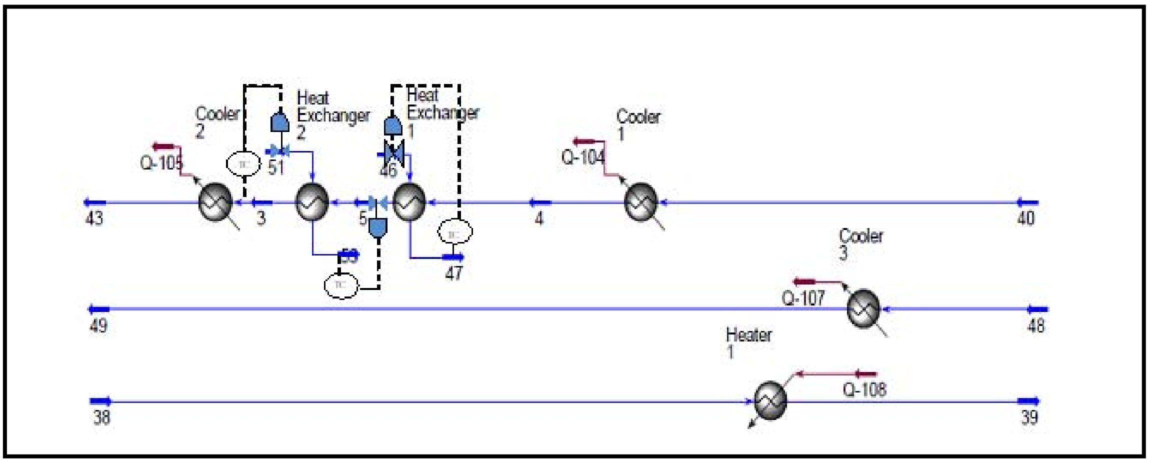

Figure 4: HEN with control loops (output of Stage 3)

It should be noted in this paper that Stage 4 – Optimal Selection and Verification is not analysed since there is only one design of HEN considered, which is at the Point point.

Table 2: Derivatives values of controlled variables (T_{53}, T_3, T_{47}) with respect to manipulated variables (F_{51}, F_{46}, F_4, F_3, F_5).

	dT_{53}	dT_3	dT_{47}
dF_{51}	0.010	**0.020**	0.000
dF_{46}	0.020	0.001	**0.032**
dF_4	0.020	0.001	0.006
dF_3	0.020	0.000	0.017
dF_5	**0.021**	0.000	0.017

4. Conclusion

A generic methodology for the IPDC problem of HEN has been presented. The proposed methodology is simple to apply, easy to visualise and efficient to solve. Here, the IPDC problem is solved by the so-called reverse approach by decomposing it into four sequential hierarchical sub-problems: (i) target selection, (ii) HEN design analysis, (iii) controllability analysis, and (iv) optimal selection and verification. A biomethanol plant has been used to test the capability of the proposed methodology in solving IPDC problem for HEN. The pinch point was selected using STEP concept as an optimal design-control solution target. From this target, the design values of the HEN were identified in Step 2.1. Then, in Step 2.2, the design values obtained in the previous step was validated using Aspen HYSYS process simulator. The validation result shows that HEN design at the selected target (pinch point) can successfully be obtained. These steps will be repeated for other non-optimal targets (below and above pinch point) representing alternative designs for validation and comparison purposes. It is expected that target at the pinch point will show better dynamics and controllability performance compared to the below and above Pinch point. This will be further analyzed in the remaining stages.

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References

Abu Bakar, S. H., Hamid, M. K. A., Wan Alwi, S. R., Manan, Z. A. (2012). Development of a New Model-Based Integrated Process Design and Control for Heat Exchanger Networks. In: Bono, A., and Sipaut, C. S. (Eds.). The 26th Symposium of Malaysian Chemical Engineers (SOMChE 2012) with the 4th International Conference on Chemical and Bioprocess Engineering (ICCBPE 2012), Sabah, Malaysia. 883-891.

Hamid, M. K. A., Sin, G., Gani, R. (2010). Integration of Process Design and Controller Design for Chemical Processes using Model-Based Methodology. Computers and Chemical Engineering, 34, 683-699.

Hernandez, S., Balcazar-Lopez, L., Sanchez-Marquez, J. A., Gonzalez-Garcia, G. (2010). Controllability and Operability Analysis of Heat Exchanger Networks Including Bypasses. Chemical and Biochemical Engineering Quarterly, 24 (1), 23-28.

Klemeš, J., Friedler, F., Bulatov, I., Varbanov, P. (2010). Sustainability in the Process Industry: Integration and Optimization. United States McGraw-Hill.

Pan, M., Bulatov, I., Smith, R., & Kim, J. K. (2011). Improving energy recovery in heat exchanger network with intensified tube-side heat transfer, Chemical Engineering Transactions, 25, 375-380.

Siemanond, K., Kosol, S. (2012). Heat Exchanger Network Retrofit by Pinch Design Method using Stage-Model Mathematical Programming, Chemical Engineering Transactions, 29, 367-372.

Wan Alwi, S. R., Manan, Z. A. (2010). STEP – A new graphical tool for simultaneous targeting and design of a heat exchanger network. Chemical Engineering Journal, 162, 106-121.