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# Synthesis of heat exchanger network considering pressure drop and layout of equipment exchanging heat

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ABSTRACT

The present work is related to development of a MINLP (Mixed integer non linear programming) model for the synthesis of HEN (heat exchanger network) considering pressure drop through connecting pipelines, heat exchangers and the layout of the equipment exchanging heat simultaneously. The pressure drop of shell and tube sides in a heat exchanger is considered in the model. Further, detailed plant layout is considered for accounting pressure drop in pipe line as well as piping cost. The objective function of the MINLP model is the TAC (total annual cost), which considers utility cost, capital investment cost of exchangers, pipe investment cost and pumping cost due to pressure drops in exchanger as well as in pipe length. The developed model is illustrated using a case study. The results show that the TAC of HEN is reduced by 27.4% than that obtained for the topology without considering pressure drop in exchanger. However, placement of exchangers in the layout contributes to 4.5% in TAC. Results found through the present model are compared with that of published models.

## 1. Introduction

A HEN (heat exchanger network) depicts the interaction between process streams and utilities to meet the plant requirement and can be designed efficiently using process integration. Developments in the field of process integration show that there is huge potential for energy and capital savings by optimally integrating the energy sources with sinks in a plant. Using this insight companies like ICI and BASF had reported 30% reduction in energy consumption in their plants in 1980s. Since then, the scope of process integration has improved manifold and it has been widely applied to optimize mass exchanger networks, carbon emission, water utilization, etc. in industries.

The seeds of process integration were sown by Linnhoff in the year 1977, who developed the pinch analysis method for synthesizing an optimal HEN. Graphical plots like composite curves by Hohmann [1] and algorithms like problem table algorithm by Linnhoff and Flower [2] and bath algorithm by Townsend and Linnhoff [3] were useful in deriving preliminary estimate of energy and area targets. A systematic method to design the HEN using principles of pinch analysis was introduced by Linnhoff and Hindmarsh [4]. Different procedures to calculate the investment cost of exchangers were proposed by Linnhoff and Ahmad [5] and Hall et al. [6]. With the advent of high speed computing, LP (Linear programming) models were developed using the pinch analysis to minimize utility as discussed in the work of Cerda et al. [7] and Papoulias and Grossmann [8]. To optimize area and TAC (total annual cost), NLP (Non linear programming) models were framed by Saboo et al. [9] and Colberg and Morari [10]. Research is still being conducted in this field as the scope for improvement is very large. However, sequential estimation of targets does not account for trade-offs and results in a sub-optimal network.

To effectively counter this drawback, mathematical models using a superstructure representation were proposed [11–17]. These models simultaneously optimized the energy, number and area of exchangers to achieve economically feasible networks. However, due to non availability of a robust solver, the solution is mostly trapped near the local optima. If the model is able to mimic reality by incorporating constraints and bounds that limit the search space, this problem is circumvented and a globally optimum solution assured. Amongst these models the formulation proposed by Huang et al. [17] claimed that it did not require a feasible starting point and solved much faster and better than some commercial MINLP (Mixed integer non linear programming) solvers. Recent investigation is ongoing in this direction. Some notable improvements to the superstructure model consist of methods to include

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non-isothermal mixing by Huang et al. [17], stream composition dependent enthalpies by Ravagnani and Cabarello [18], multipass HENs using standard $F_T$ design method by Ponce-Ortega et al. [19], etc. Further, it was observed that appropriate allocation of process streams to shell and tube side in multipass exchangers affected the network cost estimation considerably [20]. Simultaneous design of HEN considering detailed design of heat exchanger, which strongly affected the final HEN, was also carried out by Liporace et al. [21]. Further, a two stage superstructure based model was proposed for the synthesis of flexible and controllable HEN where the authors considered specified range of expected variations in the inlet temperatures and flow rates of the process streams [22].

The primary limitation in these models is that these do not consider concept of pressure drop or pumping cost and piping cost in the synthesis of HEN. Homšak and Glavič [23] solved the problem of high pressure exchangers through pinch technology and exergy analysis in a temperature vs power availability diagram. Using mathematical modelling a few authors synthesized the HEN considering pressure drop [24–26]. Zhu and Nie [24] also optimized $\Delta T_{min}$ through three-way trade-offs between area, utility and pressure drop at the targeting stage using mathematical modelling. Silva and Zemp [26] proposed a non-linear model, which estimated the additional area required for HEN with available pressure drop based on economical optimization. Polley et al. [27] proposed a model where allowable pressure drop of exchanger was predicted using exchanger area and heat transfer coefficient. Further, Serna [28] suggested the incorporation of pressure drop effects into the synthesis stage based on pinch technology. However, a MINLP model was developed considering the effects of pressure drop in HEN, which was accounted in terms of pumping cost [29]. Moreover, these authors did not incorporate piping cost in the network. As, piping cost contribute around 80% of the purchased equipment cost or 25% of the fixed capital investment [30] in a process plant, it is a significant amount and thus, should be included in the synthesis of HEN.

Akbarnia et al. [31] proposed the expression for piping costs of HEN based on experimental data over a range of pipe sizes for piping associated with a single heat exchanger. They presented the cost of piping associated with a heat exchanger for one stream based on pipe diameter. To calculate the total piping cost for one stream, the calculated piping cost for one heat exchanger is multiplied by the number of heat exchanger units used for that stream. The piping cost based on length and diameter was accounted in the optimization of hydrogen network [32]. Pouransari and Maréchal [33] presented a MILP (Mixed integer linear programming) model which selects geographically close matches by including piping cost in the TAC and obtained a very different network topology. The above investigations show that the inclusion of these effects in the heat integration formula is not without merit.

Thus, based on above backdrops the present paper develops a MINLP model that accounts for pressure drops in heat exchanger as well as pipe line and placement of exchangers for synthesis of a HEN. Further, the results found through this model are compared with that of published literature.

## 2. Problem statement

To analyse the effect of pressure drop and layout of equipment exchanging heat on HEN performance a case study is taken from Shenoy [34], which involves a simplified portion of a petrochemical process.

### 2.1. Case study

The PFD (process flow diagram) of the case study is shown in Fig. 1. The process involves an exothermic reaction followed by separation using distillation. Four relevant streams for heat integration are taken namely; H1, H2, C1 and C2. C1 and H1 are the inlet and effluent streams from reactor (R). H2 and C2 are the bottoms and top product from DC (distillation column), respectively. Along with these process streams, steam and cooling water are supplied as utilities. The stream data is taken from Serna-González et al. [35] and shown in Table 1. The thermo physical properties and maximum allowable pressure drop of the process streams are taken from Frausto-Hernández et al. [29] and given in Table 2. The required economic data is taken from Soltani and Shafiei [25] as shown in Table 3. The heat transfer coefficient for steam is taken as 5.0 kW/m$^2$ °C and that for cooling water as 2.5 kW/m$^2$ °C.

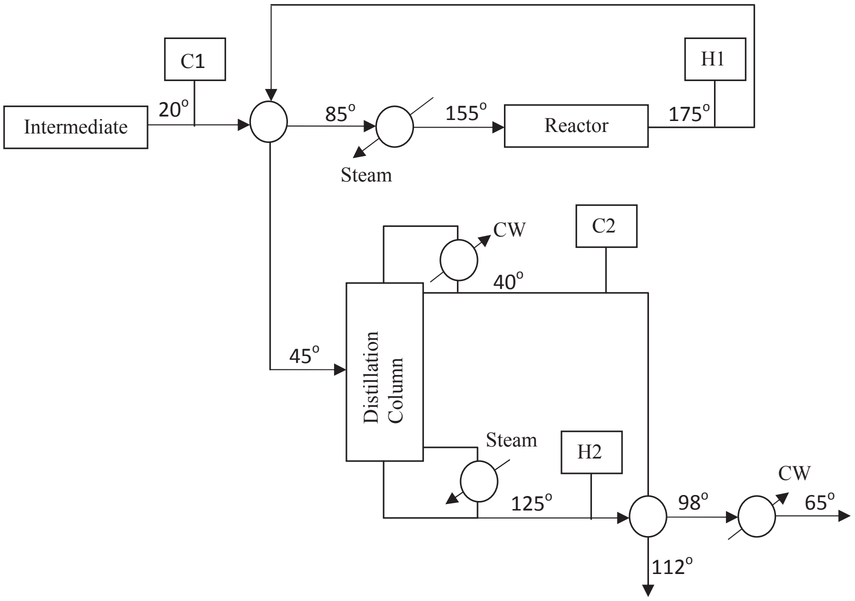

**Fig. 1.** PFD of the case study.