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Application Algorithm Development of Pinch Technology in Heat Integration Problem

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Abstract

Pinch technology is developing and its application is widening, reaching new horizons. The original concepts of pinch approach were quite clear and, because of numerous ways, application engineer gets confused among these numerous flexibilities. Therefore, there is a need for a rigorous and robust model which could guide the optimisation engineer on deciding the applicability of the pinch approach and direct sequential step of procedure in predefined workflow, so that the precision of approach is ensured. Exploring the various options of a novice hands-on algorithm development that can be coded and interfaced with GUI and keeping in mind the difficulties faced by designers, an effort was made to formulate a new algorithm for the optimisation activity. As such, the work aims at easing out application hurdles and providing hands-on information to the developer for use during preparation of new application tools. This paper presents a new algorithm, the application which ensures the designer does not violate basic pinch rules. To achieve this, intermittent check gates are provided in the algorithm, which eliminate violation of predefined basic pinch rules, design philosophy, and Engineering Standards and ensure that constraints are adequately considered. On the other side, its sequential instruction to develop the pinch analysis and reiteration promises maximum energy recovery (MER).

Keywords: Pinch analysis; Pinch approach; Robust algorithm; Heat integration; Heat recovery; Integration of heat exchanger network (HEN); Energy optimisation

Introduction

Since its genesis, pinch analysis is continuously evolving and its application is widening, reaching new horizons. The prime reason perhaps is the awareness and willingness amongst industries and environment regulating bodies to reduce carbon footprint in fulfilling their corporate responsibilities in environment conservation. Pinch technology is a powerful tool that can guarantee maximum energy recovery at optimum cost. Hence, its popularity is rising enormously. However, efficacy of the application of pinch technology depends on various parameters. As pinch approach is more of conceptual nature, there are multiple ways to its application. Consequently, it becomes very difficult for the designer to choose from available flexibilities. Often, this leads to the designer ending up with either major flaws in technical integrity of design or capital cost and operating cost. Due to such difficulties in the selection of application of pinch approach, there is a urgent need for conceptual process design team to collaborate with various core engineering domains and develop an integrated and robust process solution for the industries. A small initiative in solving the problem has been done and demonstrated in this paper [1-9].

Objective

Conceptually, the original pinch approach is clear and can definitely guarantee MER. But, its effectiveness depends wholly on the application methodology selected. For pinch approach to be successful and readily endorsed by the industry, there is a need to develop a methodology that assists the designer in selecting the right application on heat integration problem, which would be in-line with basic concept of pinch analysis and guarantees energy savings, if there is any scope of optimisation in the design. Bearing in mind all such requirements of a designer and optimisation engineer, a small initiative in solving the problem has been taken up and demonstrated in this paper [1]. This paper illustrates the algorithm which can guide the coder with sequential steps of procedure. The algorithm encompasses check gates for rules, standards, philosophy and constraints to prevent the design going haywire. The Coded pinch approach can also be interfaced with graphical user interface. This robust tool enables design engineer or optimisation engineer to carry out pinch analysis without very few hassles. The same algorithm can be used for manual application.

Major Procedural Steps of Pinch Analysis

The major procedural steps in formulating an effective pinch approach design are (Figure 1):

Step 1: Formulate process integration problem

Step 2: Assess application feasibility of pinch analysis

Step 3: Construct initial design process flow diagram

Step 4: Identify hot, cold and utility streams in the process

Step 5: Extract thermal data of process and utility streams

Step 6: Construct actual T-H diagram, actual composite curves and actual cascade diagram at $\Delta T_{min}=0$

Step 7: Set optimum energy targets and select initial value ΔT_{min}. Apply pinch rules and other predefined constraints

Step 8: Construct revised design process flow diagram

Step 9: Construct shifted T-H Diagram, feasible cascade diagram, shifted composite curves and grand composite curve

Step 10: Estimate minimum energy cost targets

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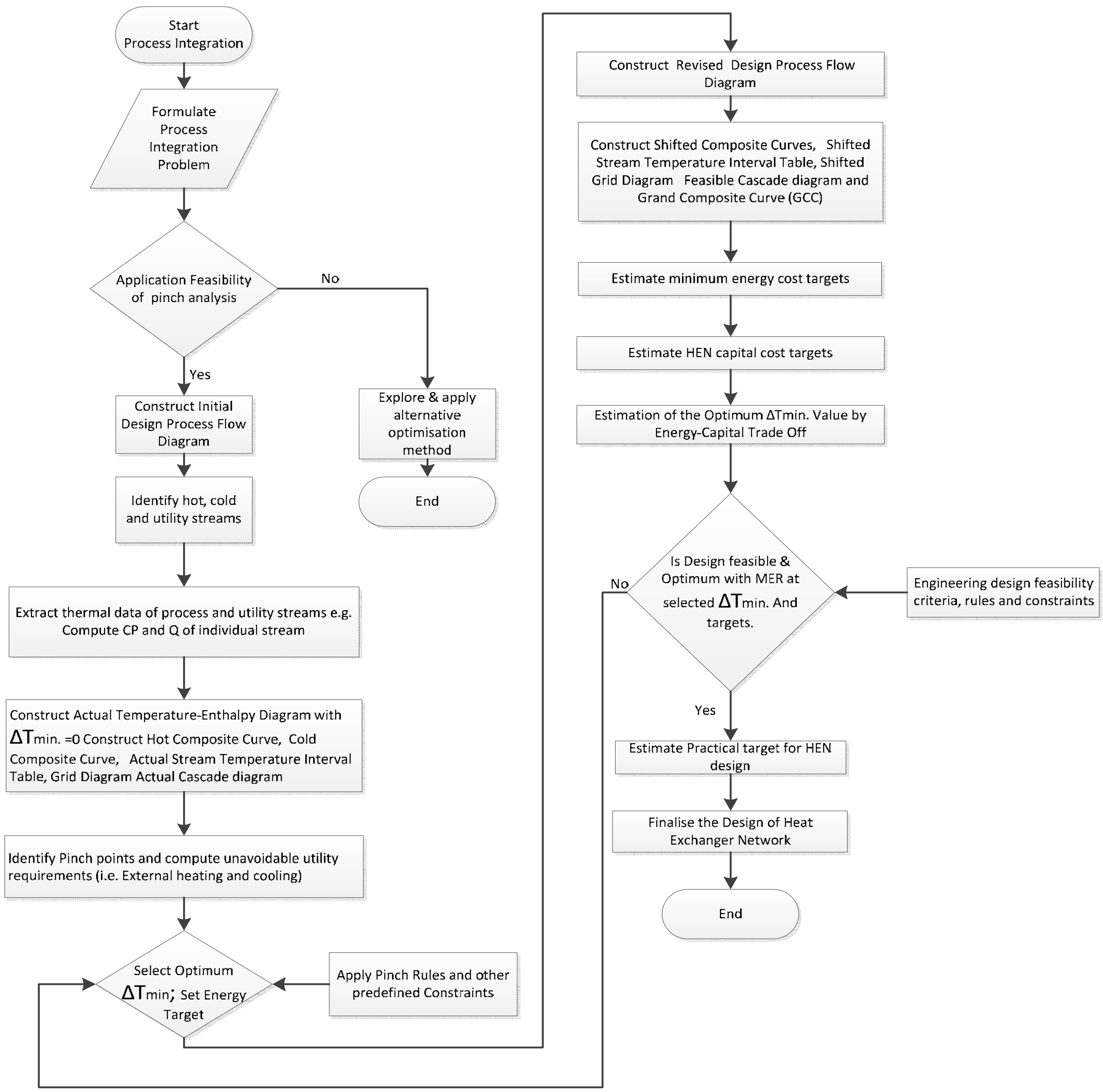

Figure 1: Application algorithm for pinch analysis.

Step 11: Estimate HEN capital cost targets

Step 12: Estimate optimum ΔT_{min} value by energy-capital trade off

Step 13: Assess the optimum design feasibility with regard to engineering design criteria, rules and constraints

Step 14: Estimate practical target for heat exchanger network design

Step 15: Finalise the design of the heat exchanger network

Step 1: Formulate process integration problem

Process integration involves integration of various sections of plants or units. This generally includes understanding concepts, study of feasibility, durability and economic aspects of the application. The process integration problem should be formulated in consideration of the components mentioned above. Pertaining to scope of thesis heat integration problem will be focused.

Step 2: Assess application feasibility of pinch analysis

This step involves assessment of applicability of pinch technique based on available data, nature of the problem and expectation from the application. Additionally, past experience of application may aid in decision making. Pinch analysis is mostly applicable to all process integration problems, however, sometimes other optimisation techniques may prove to be more appropriate than pinch analysis. If it is inferred that pinch analysis is applicable, move to step 3. If not, terminate the analysis and search for alternate method.

Step 3: Construct initial design process flow diagram

The process flow diagram should represent existing plant/design which needs to be optimized [5].

Step 4: Identify cold, hot and utility streams in the process

Identify the cold streams, hot streams and utility streams from initial design process flow diagram.

Hot stream-process stream which is to be cooled.

Cold stream-process stream which is to be heated.

When it is not economically feasible to exchange heat across process streams, external utilities-steam, hot oil, coolant, etc. are employed to mitigate the process requirement of heating or cooling.

Step 5: Extraction of thermal data of process and utility streams

Extract the following thermal data from identified cold streams, hot streams and utilities.

- Stream supply temperature -T_S °C
- Stream target temperature -T_T °C
- Heat capacity flowrate -(CP kW/K)

It is a product of mass flowrate (m kg/s) of the fluid stream and specific heat capacity C_p (kJ/kg K)

$$CP = m \times C_p \tag{1}$$

As per first law of thermodynamics (in terms of heat flow),

$$Q = \int_{TS}^{TT} CPdT = CP\left(T_T - T_S\right) = \Delta H \tag{2}$$

During heat exchange, no mechanical work is done on or by the system. So, ΔW=0

Step 6: Construct actual T-H Diagram, actual composite curves, actual cascade diagram at ΔT_{min} (minimum temperature difference)=0

Construct actual T-H diagram, actual composite curves, actual cascade diagram at ΔT_{min}=0. This helps visualise underlying opportunities in the application of pinch analysis.

Step 7: Set optimum energy targets and select initial value ΔT_{min} (minimum temperature difference) apply pinch rules and other predefined constraints

The design of heat transfer equipment always follows 2nd law of thermodynamics which restricts any crossover of temperature between cold fluid stream and hot fluid stream i.e., a minimum heat transfer driving force is always allowed to ensure feasible heat transfer design. Exchangers must always have a minimum temperature difference (ΔT_{min}) between hot and cold fluid streams. This ΔT_{min} value represents the threshold limit of heat recovery [10].

The following heat transfer equation should be used to set energy target at selected ΔT_{min}

$$Q = U \times A \times \Delta T_{LM} \tag{3}$$

Where,

$$\Delta T_{LM} = \frac{\Delta T_H - \Delta T_C}{ln\frac{\Delta T_H}{\Delta T_C}} = \frac{T_{h1} - T_{c2} - T_{h2} - T_{c1}}{ln\left(\frac{T_{h1} - T_{c2}}{T_{h2} - T_{c1}}\right)} \tag{4}$$

Step 8: Construct revised design process flow diagram

This step requires construction of revised design process flow diagram based on outcomes of the application of pinch rules and other predefined constraints after setting optimum energy targets and selecting initial value ΔT_{min}.

Step 9: Construct shifted T-H (Temperature vs. Enthalpy) diagram, feasible cascade diagram, shifted composite curves and grand composite curve

Composite curve (CC): Temperature vs. Enthalpy (T-H) curve is also known as composite curve.

Shifted composite curve: It represents overall energy targets but it does not clearly represent the amount of energy that must be externally supplied by different utility levels. The utility mix can be calculated from grand composite curve.

Shifted grand composite curve (GCC): It can be used for selecting utilities and its requirement. It is also used for determining the temperature of various utilities.

Feasible cascade diagram: It serves the same purpose as GCC does in calculating overall energy target and selecting utilities and its requirement.

GCC and feasible cascade diagram are basic tools. Either of them can be used in pinch analysis for choosing adequate levels of utility and for targeting a given set of multiple utility levels [1,7].

Step 10: Estimate minimum energy cost targets

After selection of ΔT_{min}, determination of minimum cold utility and minimum hot utility from CC, GCC or feasible cascade diagram will be feasible.

If cost of each utility unit, load and levels are known, determine the total energy cost using below energy equation [2]

$$Total\ Energy\ Costs = \sum_{U=1}^{U} Q_U \times C_U \tag{5}$$

Where Q_U-Duty of utility, kW

C_U-Utility unit cost of U, $/kW per year

U-Total number of utilities used

Step 11: Estimate HEN capital cost targets

HEN capital cost is dependent on the below three factors:

1. Overall network area
2. Total number of exchangers
3. The distribution of area among the exchangers

Heat transfer area is calculated by the following equation [1,4].

$$Area = \frac{Q}{U \times \Delta T_{LM}} \tag{6}$$

$$HEN\ area\ A_{min} = A_1 + A_2 + A_3 + \ldots\ldots\ldots\ldots + A_i \quad (7)$$

$$Exchanger\ cost\ (\$) = a + b(A_{min})^c \quad (8)$$

Where *a,b,c* are constants

Step 12: Estimate the optimum ΔT_{min} value by energy-capital trade off

To reach at an optimum value of ΔT_{min}, estimate the total annual cost (sum of total annual energy and capital costs) at various values of ΔT_{min}. The following observations will be noticed [8].

1. Reduction in values of ΔT_{min} reduces energy costs but increases capital costs
2. Increase in values of ΔT_{min} increases energy costs but reduces capital costs

Optimum value of ΔT_{min} lies on trend where the total annual cost of energy and capital costs is overlap [5].

Step 13: Assess the optimum design feasibility with regard to engineering design criteria, rules and constraints

This is a decision-making step. The engineer must assess the revised design, achieved from step 12, and study its feasibility with respect to engineering design criteria, standards, and lessons learnt, rules and constraints and check whether the design is practically feasible or is there any further opportunity for further pinch or it is over pinched. If the design is feasible, initiate step 14. Otherwise, repeat steps 7-12 with revised value of ΔT_{min}, revised set of pinch rules and constraints [11].

Step 14: Estimate practical targets for HEN design

The HEN designed on the basis of the estimated optimum values of ΔT_{min} may not always be the most feasible design. Low values of ΔT_{min} may demand very intricate network design with a large total area owing to low driving forces. This may have associated impact on CAPEX, if implemented, owing to complexity of the design. In practice, the designer chooses a high value of ΔT_{min}, perhaps 15°C, and determines the minimal increases in utility duties and required area. If the increase is marginal, the higher value of ΔT_{min} is chosen to get practical pinch point for design of HEN [3].

The following three rules of pinch technology form the basis for practical network design:

1. No external heating below the pinch
2. No external cooling above the pinch
3. No heat transfer across the pinch

Desecration of any of the above rules results in energy penalty than the MER possible [5,6].

Step 15: Finalise the design of heat exchanger network

The systematic application of the pinch analysis in the design phase of HEN allow us to achieve the energy targets within practical limits. The following two fundamental features are key to successful application of this technique:

1. Procedural steps recognize that the pinch region is the most constrained part of the problem
2. Procedural steps allow the designer to choose between match options

Basically, the HEN design inspects which fluid streams can be matched to other fluid [1,2].

Conclusion and Recommendation

The novice algorithm has been developed with an intention to minimise the hurdles of process design engineers and optimisation engineers in applying heat integration to a new or a retrofit design. The algorithm can be followed during development of new soft tool or manual application of pinch analysis. Although it is not mandate, we followed prefixed sequential algorithm follows hierarchical sequential workflow. To eliminate major jargons, flaws in technical integrity of design and minimize the energy penalty, sequential workflow was followed conservatively. Multiple intermittent reiteration check gates are provided by which the designer can optimize the overall energy target by reiteration of intermittent steps at different values of ΔT_{min} till constraint threshold is reached. Designer shall consider all constraints and flexibilities to achieve MER.

There is scope for further refining of the algorithm and incorporation of additional features on future algorithms. The designer should liaise with engineers from different domains to come up with holistic single integrated solution, which takes care of integrity algorithm, carries out coding and testing, and synchronises the code with operating system. Front end graphical templates development should be carried out simultaneously and all parts should be integrated on GUI and validated.

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