HEAT EXCHANGER NETWORK RETROFIT UNDER FOULING EFFECT

Jaturaporn Yanyongsak

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By: Jaturaporn Yanyongsak

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Thesis Advisors: Asst. Prof. Kitipat Siemanond

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……………………………….... College Dean

(Prof. Suwabun Chirachanchai)

Thesis Committee

………………………………....

(Asst. Prof. Kitipat Siemanond)

………………………………....

(Prof. Pramoch Rangsunvigit)

………………………………....

(Asst. Prof. Chanin Panjapornpon)

ABSTRACT

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Keywords: HENs/ Retrofit/ Optimization/ Fouling/ Cleaning schedule

The energy conservation by heat exchanger network (HEN) is important in process design according to an increase of energy costs and global environmental concerns. To minimize the energy consumption with positive net present value (NPV), the retrofitted HEN plays an important role in process energy systems. The HEN retrofit model is based on stage-wise superstructure by Yee and Grossmann (1990). In addition, fouling deposition on the surface area of heat exchangers causes extra energy consumption, production loss and maintenance costs. The new proposed model is retrofitting HEN with fouling effects. This method achieves HEN with the optimal trade-offs between energy savings, and investment over operating period. For cleaning schedule, retrofitted HEN shows better capability to recover heat and NPV higher than base-case considered from a lower number of cleaning requirement. In this study, the proposed model is combined between cleaning schedule strategy and HEN retrofitting with fouling effect to achieve profitable HEN.

บทคัดย่อ

จตุรพร ยรรยงศักดิ์ : การปรับปรุงโครงข่ายเครื่องแลกเปลี่ยนความร้อนภายใต้ผลกระทบของคราบตะกรัน (Heat Exchanger Network Retrofit with Fouling Effects) อ. ที่ปรึกษา : ผศ.ดร. กิติพัฒน์ สีมานนท์ 94 หน้า

ปัจจุบันการอนุรักษ์พลังงานในระบบโครงข่ายแลกเปลี่ยนความร้อนมีความสำคัญอย่างมากในการออกแบบโครงข่ายเครื่องแลกเปลี่ยนความร้อนเนื่องจากการเพิ่มขึ้นของต้นทุนทางพลังงานและนโยบายจากภาครัฐ การปรับปรุงโครงข่ายความร้อนสำคัญอย่างมากในการลดการใช้พลังงานโดยที่สามารถสร้างมูลค่าปัจจุบันสุทธิ (NPV) ของระบบพลังงานในกระบวนการ ในงานวิจัยอ้างอิงแบบจำลองการปรับปรุงโครงข่ายเครื่องแลกเปลี่ยนความร้อนด้วยหลักการ stage-wise superstructure โดย Yee and Grossmann นอกจากนี้การเพิ่มขึ้นของค่าใช้จ่ายในการดำเนินงาน การสูญเสียผลผลิต และค่าซ่อมบำรุง ซึ่งเกิดจากการเสื่อมลงของประสิทธิภาพการแลกเปลี่ยนความร้อนเนื่องจากการเกิดคราบตะกันในเครื่องแลกเปลี่ยนความร้อนเป็นสิ่งที่ต้องพิจารณาเช่นกัน ในงานวิจัยจึงมุ่งเน้นการพัฒนาแบบจำลองการปรับปรุงโครงข่ายเครื่องแลกเปลี่ยนความร้อนซึ่งสามารถปรับปรุงสมดุลระหว่างการประหยัดพลังงาน เงินการลงทุน และค่าใช้จ่ายระหว่างดำเนินการ ในการดำเนินการศึกษาพบว่าแบบจำลองการปรับปรุงโครงข่ายเครื่องแลกเปลี่ยนความร้อนร่วมกับการดำเนินการทำความสะอาดในช่วงการดำเนินงานสามารถสร้างกำไรและลดการใช้พลังงานได้อย่างมาก

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CHAPTER I
INTRODUCTION

Most HEN synthesis methods rely on sequential or step-wise procedures (Gundersen and Naess, 1988) which decompose design problem for synthesized network targets. After that, Dolan et al. (1987, 1989) and Yee and Grossmann (1990) proposed HEN model accounting for all types of costs simultaneously. Dolan et al. proposed the method of simulated annealing as a synthesis technique, while Yee and Grossmann formulated the model as mixed integer nonlinear programming (MINLP) model for synthesis and retrofit design. Both methods approach optimal operating and capital cost network.

In addition, the main problem caused by fouling deposition has negative effects on thermal and hydraulic performance of heat exchangers. Fouling decreases overall heat transfer coefficient and thermal effectiveness of heat exchangers, resulting in extra hot and cold utilities consumption. In most of the cases, the cleaning schedule is applied for recovering heat exchanger efficiency as a systematic method to determine the optimal cleaning sequence in HENs under fouling. For predicting the fouling behaviours, the appropriate models are required. Ebert and Panchel (1995) was the first to give concept of fouling threshold. After that several modified models were proposed for improving the accuracy of crude oil fouling behaviour. In Polley's model (2002a), wall temperature and Reynold number were used instead of film temperature and shear stress term Polly's model is more accurate and easier to calculate comparing with Ebert and Panchel's model. In addition, Rangfak et al. (2017) proposed HEN retrofit with fouling effects which help save utility for crude preheat train operation and achieve high NPV in long period. The combination of cleaning schedule strategy and HEN retrofitting with fouling effect will save more utilities and gain more profits.

The purpose of this study is to retrofit HENs under fouling from oil refinery or petrochemical processes. The HENs with fouling effect model will be divided into sub-periods. The model of each period is formulated based on a stage-wise superstructure of Yee and Grossmann (1990). The HEN retrofitting under fouling effect model will be performed. And the cleaning schedule is applied to reduce energy consumption caused by fouling and get higher profit.

CHAPTER II

THEORETICAL BACKGROUND AND LITERATURE REVIEW

In industrial processes, the energy conservation can be applied by heat exchanger network synthesis and retrofit strategies. In order to achieve the best optimal design, heat exchanger network under fouling effects could be mitigated by synthesized and retrofitted design. To deal with fouling problems, production period is divided into sub-periods and solved by multi-period model while apply an optimal cleaning program and fouling mitigating strategies.

2.1 Heat Integration

The meanings of Heat Integration term include two meanings. First, heat integration term refers to the physical arrangement of equipment, process sections, production plants, entire sites, and even the process surroundings in case of heating zone or cooling zone. Second, it refers to the result of Process Synthesis which indicates the total area of heat exchanger network, with methods and tools aiming at increased energy efficiency in industrial processes and energy plants. From the result of Process Synthesis, not only improved energy efficiency can be achieved, but also heating and cooling demands will be improved. Therefore the external heating and cooling requirements will be reduced.

In designing method of heat recovery system, there are two fundamental difference that are designing heat exchanger networks for new designs or 'grassroots design' and modifying heat recovery systems for existing plants or 'retrofit'. In the same way, the design process contains the same stages for the two cases; however, there is some different content. More specifically, the stages in design of heat recovery systems as follows:

- **Data Extraction** refers to collecting and processing data about heating and cooling requirements as well as the energy requirements in evaporation and condensation of process streams that often referred to as Stream Data and also economic data are needed, such as the cost of heat exchangers and utilities, economic parameters, etc.

- **Performance targets** refer to establishing measures for best performance ahead of design based only on information available in the stream data, utility data and economic data. Typical targets for Heat Exchanger Networks include minimum external heating (QH,min) and cooling (QC,min) demands, minimum number of heat exchangers (Umin), and minimum total heat transfer area (Amin). With multiple utilities, targets can also be established for the cost-optimal utility mix.
- **Process modifications** refer to the consideration of making changes in the basic process (reactor system, separation system, recycle system, etc.) in such a way that the scope for heat recovery is improved.
- **Network design** refers to establishing a network of heat exchangers that achieves the Performance Targets for energy consumption and number of heat exchangers, referred to as a Maximum Energy Recovery (MER) design.
- **Design evolution primarily** refers to refining MER designs by removing small heat exchangers resulting from the use of the process design. This activity is also referred to as Energy Relaxation, since the removal of units will require more utilities (energy) and possibly to have more heat transfer area. The motivation for this stage is cost reduction as well as reduction in network complexity (fewer units, which is often followed by fewer stream splits).
- **Process simulation** refers to testing the feasibility of the Heat Exchanger Network that has been designed and optimized in the previous stages of the design process.

In order to design heat exchanger network for optimization in term of economic, there are three proposed methods; sequential design procedure, simultaneous method, and sequential framework.

2.1.1 <u>Sequential Design Procedure</u>

The sequential design procedure divides problem into subproblems and sequentially be optimized. A sequence of smaller problems can be easily solved and manageable.

The sequential design procedure relies on Pinch design method (PDM) that was comprehensively described by Linnhoff and Hindmarsh (1983). The PDM provides a strategy for developing the network in a sequential manner deciding on one heat exchanger at a time with rules for matching hot and cold streams for these heat exchangers. The method also indicates when and how stream splitting should be applied. The key elements of a simplified version of the PDM are the following design actions and rules:

1) Decompose the heat recovery problem at the Pinch.
2) Develop separate networks above and below Pinch, starting at the Pinch.
3) Start network design immediately above and immediately below Pinch, since this is where the problem is most constrained (small driving forces) and thus where the degrees of freedom to match hot and cold process streams are most limited.
4) Assign Pinch Exchangers first (units that bring hot streams to Pinch Temperature above Pinch and cold streams to Pinch Temperatures below Pinch), then assign the other process-to-process units, and finally install utility exchangers where required to reach the target temperatures for the streams.
5) Use the CP rules (equation (1)) to decide on the matching between hot and cold process streams in the Pinch Exchangers
6) Whenever the CP rules cannot be applied or the topology rules (equation (2)) are broken, stream splitting has to be considered.
7) For each accepted match, maximize the duty of the heat exchanger to increase the probability of reaching the target for fewest numbers of units (i.e. The 'tick-off' rule).

Pinch Exchangers will have minimum allowed driving forces (Δ Tmin) in the cold end (units above Pinch) or the hot end (units below Pinch) of the heat exchanger. When the minimum driving forces are achieved, there cannot be further reduction, and the CP rules assure exactly that. Also, there has to be at least one stream (or branch of a stream) of the opposite type to bring the hot streams (above Pinch) and cold streams (below Pinch) to the Pinch Temperature. The resulting CP rules and topology rules are fundamental when applying the PDM:

$$\text{Above Pinch: } CP_{Cj} \geq CP_{Hi} \quad \text{Below Pinch: } CP_{Hi} \geq CP_{Cj} \tag{1}$$

$$\text{Above Pinch: } N_C \geq N_H \quad \text{Below Pinch: } N_H \geq N_C \tag{2}$$

If either the topology rules equation (2) are not satisfied for the entire set of streams, or the CP rules equation (1) are not satisfied for each and all of the Pinch Exchangers, then stream splitting is required to reduce energy consumption, total heat transfer area, and the number of units as shown in Figure 1.

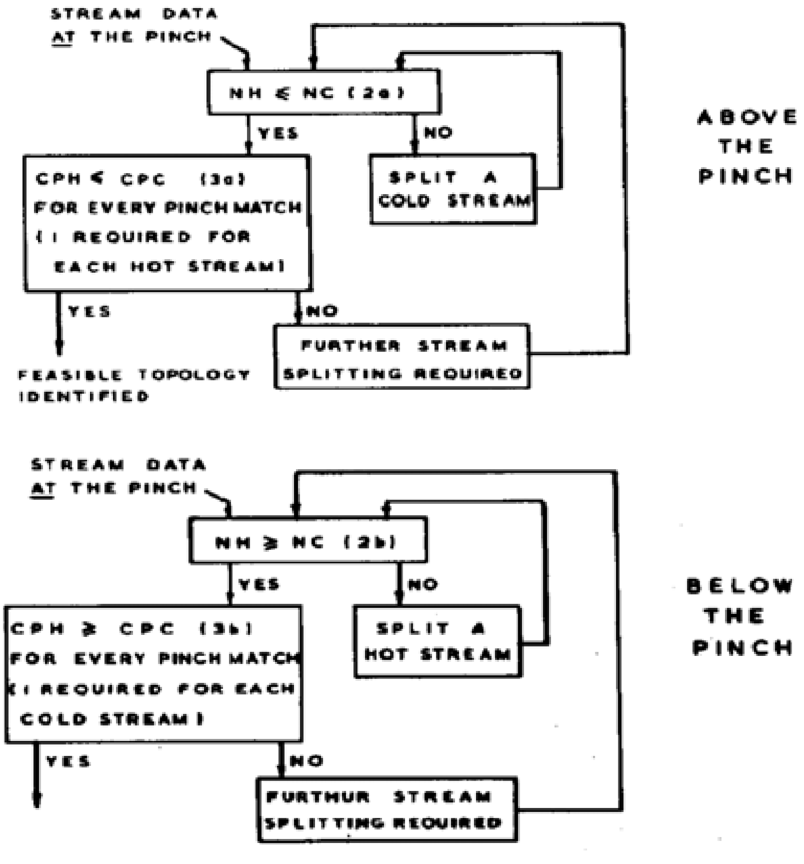


Figure 1 Hot end and cold end pinch design procedure.

When installing the pinch exchangers complete, then, the utility exchanger could be considered for any remaining heat in the hot streams above Pinch and any remaining cooling in the cold streams below Pinch. This can be achieved by adding more process-to-process units, and in this case the matches are no longer restricted by the CP rules, since the driving forces have opened up when moving away from the Pinch. Whenever a match does not follow the CP rules, however, the temperature difference of the heat exchanger must be investigated.

In addition, the MAGNETS program by Floudas and Grossmann (1986) is an example of mathematical programming for sequential heat exchanger network synthesis according to Figure 2 that the basic idea is behind the proposed synthesis strategy is to decompose the problem in order to achieve minimum utility cost, fewest number of units for this utility target and minimum investment cost. The design problem is decomposed into three major phrases:

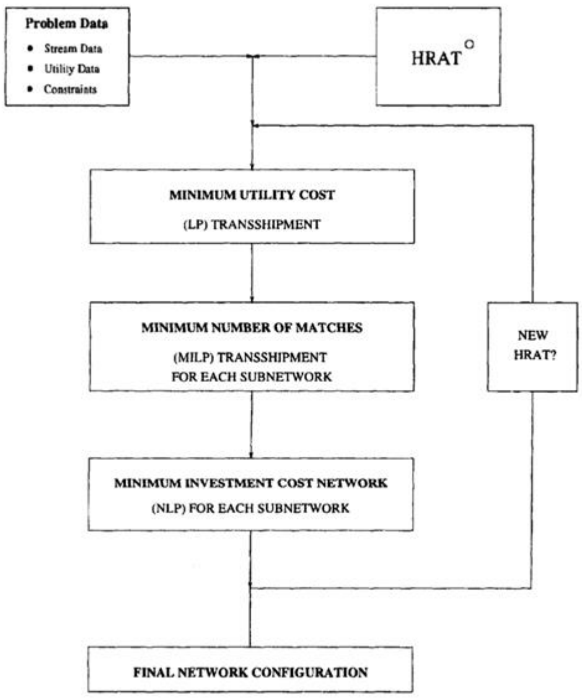


Figure 2 Steps of sequential HEN synthesis approach (C. A. Floudas, 1986)

- **Step1** utility cost calculation for minimum utility cost by a linear programming (LP) transshipment problem

- **Step 2** determinations of matches for minimum number of units by mixed-integer linear problem (MILP) transshipment model (Papoulias and Grossmann, 1983)
- **Step 3** network derivations for minimum investment cost by nonlinear programming (NLP) problem that optimizes a superstructure that has embedded all the options of flow patterns for the selected matches (Floudas and Grossmann, 1986)

As pointed out by Gundersen and Grossmann (1990), the second stage has multiple solutions, where each solution is referred to as a heat load distribution (HLD) with information on the pairs of streams (i, j) that are matched and the corresponding heat duty Qij. These HLDs tend to have many different properties when it comes to total area and cost of the networks that can be developed. Gundersen and Grossmann (1990) used insights from Pinch Analysis, i.e. vertical heat transfer reduces total area, to improve the selection of HLDs in the MILP stage. Since strict vertical heat transfer does not guarantee minimum area, the MILP model was further developed in order to account for differences in film heat transfer coefficients.

The limitation of a sequential synthesis method is the design cannot be optimized simultaneously in term of different costs associated and one design decision is made at a time, although sequential match reduction approach is simple, reasonably fast and allow splitting and non-isothermal mixing assumptions. Moreover, that different cost associated with the design cannot be optimized simultaneously.

2.1.2 Simultaneous Method

Simultaneous optimization models were established to overcome the limitations of the sequential approach. These Mixed Integer Non-Linear Programming (MINLP) models that were proposed by Yee and Grossmann (1990) and Ciric and Floudas (1991) are extremely hard to solve for two reasons

1) The binary variables cause a combinatorial explosion and prohibitive computer times for large industrial problems.

2) The non-linear relations in the model (both physical and economical) are non-convex, which means there is a tendency to end up in local rather than global optimal.

Yee and Grossmann (1990) proposed simultaneous optimization models for heat integration that mixed integer nonlinear programming (MINLP) model is presented which can generate networks where the trade-offs between utility cost, exchanger areas and selection of matches are optimized simultaneously. The proposed model does not rely on the assumption of fixed temperature approaches (HRAT or EMAT), or on the prediction of the pinch point for the partitioning into sub networks but the model based on stage-wise.

There are three parts of simultaneous optimization models for heat integration paper series (Yee et al., 1990a, Yee and Grossmann, 1990, Yee et al., 1990b). The model for the simultaneous targeting of energy and area for heat networks with fixed flows, fixed supply and target temperatures by NLP model was introduced. The proposed synthesis model representation does not rely on heuristics that are based on the concept of the pinch point and the assumption of HRAT and EMAT. The superstructure is a stage-wise representation where within each stage of heat exchanger has potential to exchange between each hot and each cold steam as shown in Figure 3. Heat recovery approach temperature (HRAT) and minimum approach temperature (EMAT) are treated as variables and not to be fixed. Main assumptions in the proposed method as the following:

- Constant heat capacity flow rates.
- Constant heat transfer coefficients.
- Counter current heat exchangers.
- Isothermal mixer

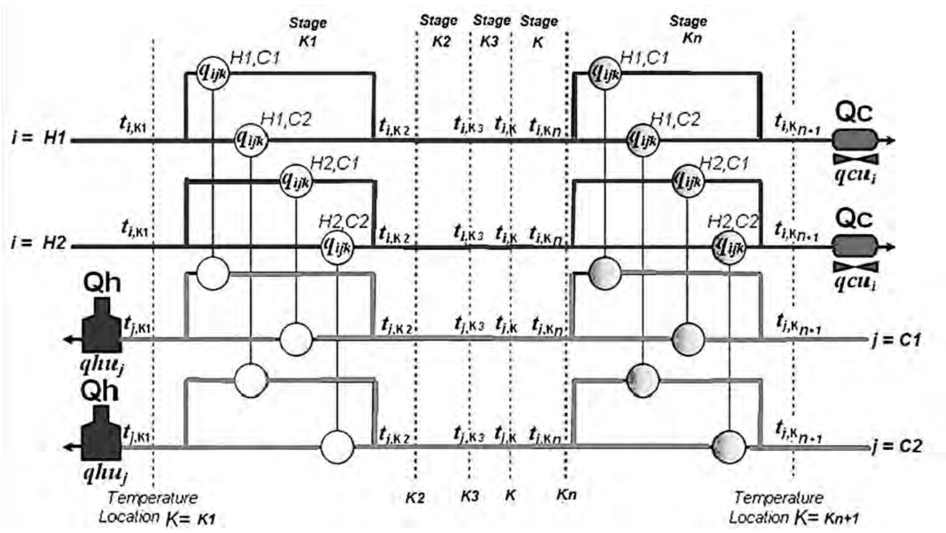


Figure 3 Representation of stage-wise heat exchanger network superstructure for two hot streams and two cold streams. (Yee and Grossmann, 1990, Yee et al., 1990a)

In order to formulate the NLP model for area and energy targeting for the proposed superstructure described previously, the following definitions and equation are necessary:

(i)Indices

i = hot process or utility stream j = cold process or utility stream

k = index for stage 1...NOK and temperature location1…NOK+l

(ii)Sets

HP = {i|i is a hot process stream}   HU = hot utility

CP = {j|j is a cold process stream}   CU = cold utility

ST={k|k is a stage in the superstructure, k=1…NOK}

(iii)Parameters

TIN = inlet temperature of stream   TOUT = outlet temperature of stream

F = heat capacity flow rate   U = overall heat transfer coefficient

CCU = per unit cost for cold utility   CHU = per unit cost for hot utility

CF = fixed charge for exchangers   C = area cost coefficient

B = exponent for area cost   NOK = total number of stages

QCU = total cold utility usage   QHU = total hot utility usage

(iv)Variables

q_{ijk}= heat exchanged between hot process stream i and cold process stream j in stage k

qcu_i = heat exchanged between hot stream i and cold utility

qhu_j = heat exchanged between hot utility and cold stream j

$t_{i,k}$ = temperature of hot stream i at inlet of stage k

$t_{i,k}$ = temperature of cold stream j at outlet of stage k

(v)Equation

Overall heat balance for each stream

$$(TIN_i - TOUT_i)F_i = \sum_{k\in ST}\sum_{j\in CP} q_{ijk} + qcu_i \qquad i \in HP \tag{3}$$

$$(TOUT_j - TIN_j)F_j = \sum_{k\in ST}\sum_{j\in HP} q_{ijk} + qhu_i \qquad j \in CP \tag{4}$$

Heat balance at each stage

$$(t_{ik} - t_{i(k+1)})F_i = \sum_{j\in CP} q_{ijk} \qquad i \in HP, k \in ST \tag{5}$$

$$(t_{jk} - t_{j(k+1)})F_j = \sum_{j\in HP} q_{ijk} \qquad i \in CP, k \in ST \tag{6}$$

Assignment of Superstructure inlet temperatures

$$TIN_i = t_{i,1} \qquad i \in HP \tag{7}$$

$$TIN_j = t_{i,(NOK+1)} \qquad i \in CP \tag{8}$$

Feasibility

$$t_{ik} \geq t_{i(k+1)} \qquad i \in HP, k \in ST \tag{9}$$

$$t_{jk} \geq t_{j(k+1)} \qquad i \in CP, k \in ST \tag{10}$$

$$TOUT_j \geq t_{j,1} \qquad i \in CP \tag{11}$$

$$TOUT_i \geq t_{i,(NOK+1)} \qquad i \in HP \tag{12}$$

Hot and cold utility load

$$(t_{i,(NOK+1)} - TOUT_i)F_i = qcu_i \qquad i \in HP \tag{13}$$

$$(TOUT_j - t_{j,1}) = qhu_j \qquad i \in CP \tag{14}$$

LMTD term (Chen approximation 1987)

$$LMTD_{ijk} = [(dt_{ijk})(dt_{ijk+1})\frac{dt_{ijk}+d_{ijk+1}}{2}]^{1/3} \tag{15}$$

Where dt_{ijk} and dt_{ijk+1} represent the approach temperatures for exchanger (i,j) in stage k.

Second part, Yee and Grossmann proposed the synthesis model which accounts for all type of the costs simultaneously requiring very reasonable solution times. The proposed model is based on a stage-wise superstructure representation which does not require the specification of sub-networks or the selection of fixed temperature approaches. Based on a simplification for stream splits, it is shown that the problem can be formulated as an MINLP which has the desirable feature that all the constraints are linear. If this structure involves split streams, then an NLP sub-optimization problem is formulated with the fixed configuration and variable flows and temperatures, and solved to determine optimal split flow rates and area distribution for the exchangers as shown in Figure 4. The solution scheme determines the network which exhibits final optimum annual cost by optimizing simultaneously for utility requirement (HRAT), minimum approach temperature (EMAT), the number of units, the number of splits and heat transfer area.

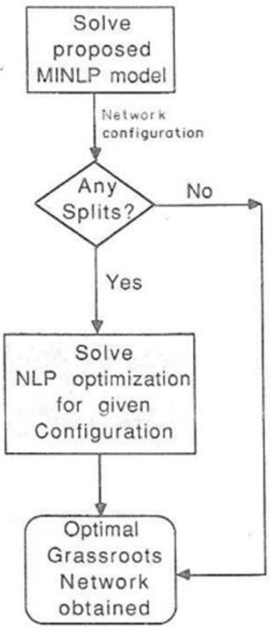


Figure 4 Proposed synthesis strategy (Yee and Grossmann, 1990)

In order to formulate the proposed MINLP model, logical constraints and binary variables represented by z ijk are needed to determine the existence of process stream match (ij) in stage k, in addition zcui and zhuj for matches involving cold and hot utilities respectively. The following equations are also necessary:

Logical Constraints (to count exchangers)

$$q_{ijk} - \Omega \mathrm{z}_{ijk} \leq 0 \qquad i \in HP, j \in CP, k \in ST \tag{16}$$

$$qcu_i - \Omega \mathrm{zcu}_i \leq 0 \qquad i \in HP \tag{17}$$

$$qhu_i - \Omega \mathrm{zhu}_i \leq 0 \qquad i \in CP \tag{18}$$

Calculation of approach temperatures

$$dt_{ijk} \leq t_{i,k} - t_{j,k} + \Gamma(1 - \mathrm{z}_{ijk}) \qquad i \in HP, j \in CP, k \in ST \tag{19}$$

$$dt_{ij(k+1)} \leq t_{i,(k+1)} - t_{j,(k+1)} + \Gamma(1 - \mathrm{z}_{ijk}) \qquad i \in HP, j \in CP, k \in ST \tag{20}$$

$$dtcu_i \leq t_{i,(NOK+1)} - TOUT_{CU} + \Gamma(1 - \mathrm{zcu}_i) \qquad i \in HP \tag{21}$$

$$dthu_i \leq TOUT_{CU} - t_{j,1)} + \Gamma(1 - \mathrm{zhu}_i) \qquad i \in CP \tag{22}$$

Limiting temperature approach

$$dt_{ijk} \geq EMAT \qquad i \in HP, j \in CP, k \in ST \tag{23}$$

Objective function (Utility costs+ Fixed HEX installation costs)

$$Objective =$$

$$Min\{CCU \sum_{i \in HP} qcu_i + CHU \sum_{j \in CP} qhu_j + \sum_{i \in HP} \sum_{j \in CP} \sum_{k \in ST} CF_{ij} \mathrm{z}_{ijk} + \sum_{k \in HP} CF_{iCU} \mathrm{zcu}_i + \sum_{k \in CP} CF_{jHU} \mathrm{zhu}_j \tag{24}$$

In the last part of paper series (Yee et al., 1990b) the result from simultaneous optimization of process flow sheet and its heat exchanger network is presented. The stage-wise superstructure is embedded to represent as the given process flow sheet and its heat exchanger network. The main objective is optimization of total capital cost and operating cost of process and heat exchanger network, while Stream flow rates and supply and target temperatures are treated as variables that are unlike in part I and part II. Stream flow rates, temperatures, and the level of heat recovery can be affected from consequence of the process parameters have been changed. Both NLP and MINLP model are used to synthesize heat exchanger network. An NLP formulation requires small computation time but MINLP formulation gives more accurately solutions. Moreover, the suitable of each model is depended on requirement of heat exchanger match existence; MINLP model will give preferred model if binary variables are applied for heat exchanger matches.

The HRAT and EMAT are no need to be fixed but rather optimization of proposed method to minimize cost.

Isafiade and Fraser (2008) introduced the interval-based MINLP superstructure (IBMS) for simplified stage-wise superstructure of Yee and Grossmann according to Figure 5. Heat exchanger can be located between contacted streams of opposite kind within each stage of stage-wise superstructure or interval of IBMS. Each of boundary temperatures of IBMS defined by supply and target temperatures of either hot or cold set of streams. Since the model does not rely strictly on vertical heat transfer, it is able to handle HENS problems having significantly different heat transfer coefficients and constrained matches and intermediate temperatures of each stream in temperature boundaries are treated as variables. Each interval is sequenced by their supply and target temperatures. In order to avoid nonlinear mixing equation, the simplifying assumption on isothermal mixing is also required in IBMS model for solving the model in one step without NLP suboptimization. Special initializing techniques of MINLP model are not required in proposed interval method. However, a drawback of IBMS model is split streams involved in most solution networks. Isafiade and Fraser claimed the IBMS model gives better solutions when including with multiple utilities.

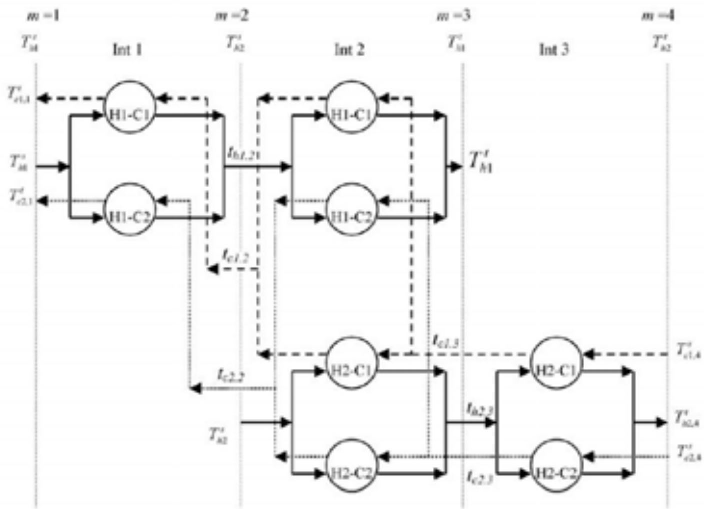


Figure 5 Interval-based heat exchanger network superstructures for two hot streams and two cold streams. (Isafiade and Fraser, 2008)

Whereas the deterministic optimization method is widely used, Dolan et al. (1987) introduced simulated annealing to determine synthesis of heat exchanger network as simultaneous optimization method. The stochastic optimization method, such as genetic algorithm (GA), simulated annealing (SA) and Tabu search method, is suitable for complex spaces and unnecessary to use initial guess and gradient for solving. However, a very large number of trials are needed. The objective function can be nonlinear and non-continuous those are special advantage compare to deterministic technique.

2.1.3 Sequential Framework

An alternative approach is to break down the MINLP problem and solve the HENs problem using a Sequential Framework (Anantharaman and Gundersen, 2007), where the three-way trade-off between energy (E), heat transfer area (A), and how this total area is distributed into number of heat transfer units (U) are addressed by adjusting key decision variables in a system of nested loops, as shown in Figure 6. The framework is based on ideas of a decomposed approach to HENS as suggested by Floudas et al. (1986) and modified vertical matching between the Composite Curves to minimize heat transfer area, where differences in film heat transfer coefficients are fully accounted for. Contrary to what would be expected with four nested loops, the framework identifies optimal solutions within 3–7 inner loop iterations for each value of HRAT. From the complex loop iterations so the model solution times remain too long. Pre-optimization (or supertargeting) is used to find a near-optimal starting value for ΔTmin (or HRAT) by combining targets for Energy, Area and Units into an estimate for Total Annual Cost (TAC) for various values of HRAT. The core engines of the sequential framework are the vertical MILP model for matching streams and providing heat load distributions (HLD), and the NLP model for generating and optimizing the network. The framework allows considerable user interaction, and practical aspects such as complexity and operability can be addressed together with TAC to select the best HEN.

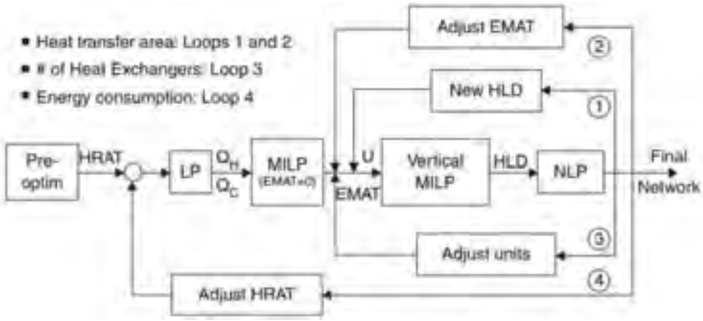


Figure 6 Sequential frameworks for HEN Synthesis. (Anantharaman and Gundersen, 2007)

2.2 Optimization of the cleaning schedule for heat exchanger network

Fouling deposition is the major unresolved problem of significant interest in the heat exchanger network design and operation in oil refinery or industry. The main problems from fouling deposition give the negative effect in term of reduction of overall heat transfer coefficient in heat exchanger. Moreover, fouling not only reduces thermal efficiency which resulting in more energy consumption or more utility usage but also modifies cross sectional area available for flow that affect to operating conditions. In order to mitigate negative effect of fouling, the periodic cleaning is the most strategy which is used although the exchanger will be shut down for cleaning resulting in production loss.

However, the cleaning plan must to be done carefully due to the removal of some heat exchangers for cleaning while the rest of the network continues in operation may greatly affect to the performance of network. In paper of Georgiadis and Papageorgiou (2000), there is the relation between the operating cost and the number of cleaning tasks that the operating cost decreases at the beginning with the number of cleaning tasks because both variable cleaning and utility costs decrease, until reaches a minimum (optimal solution), then starts increasing as the fixed cleaning costs become dominant according to Figure 7. So, periodic cleaning and energy management of HENs have been considered. The formulation in this paper presented both MINLP and MILP model, the former was used for linearize the objective function includes only utility and cleaning costs and the latter is used for solved the global optimality yields.

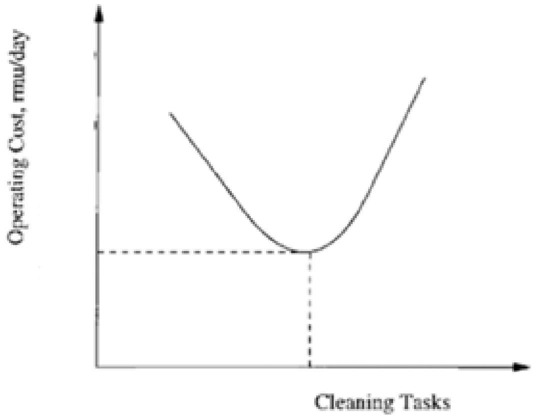


Figure 7 Operating cost as a function of the number of cleaning tasks (Georgiadis and Papageorgiou, 2000)

The cleaning schedule were optimized using the same approach proposed with Smaı¨li (Smaı¨li et al., 2001, 2002) by C. Rodriguez and R. Smith (2007). The method dividing the period of study into time span and applied binary variables to describe the cleaning status of each heat exchanger; indicate if an exchanger is in operation or has been taken out of service for cleaning. In order to improve the model to have high accuracy and the number of binary variables in the model at easily manageable levels, an alternative discretization approach is used for modeling the cleaning status of HENs. Each period is further divided in two sub-periods: an operating sub-period, in which cleaning is not allowed, and a cleaning sub-period, in which cleaning actions can take place as shown in Figure 8. Instead solved the problem with MINLP model, Simulated Annealing optimization (SA) is preferred for this non-convexity normally associated with the nonlinear equations and the combinatorial nature introduced by the discrete variables.

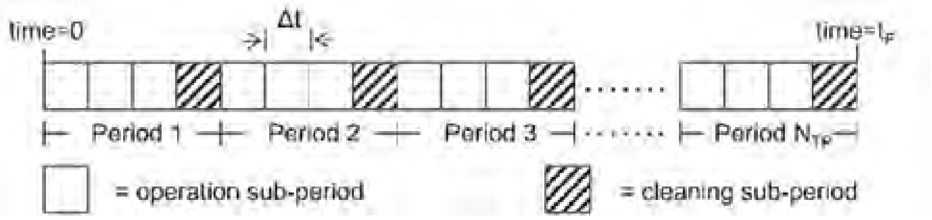


Figure 8 Time discretization for modeling cleaning in HEN. (C. Rodriguez and R. Smith, 2007)

2.3 Fouling mitigation strategies and design tools

Although periodic cleaning of fouled exchangers is a largely used for fouling mitigation in oil refinery or general industry, but this method cannot eliminate the problems posed by fouling. Whereas the removal of fouling deposits from the heat transfer surfaces may recover the original performance of the affected equipment, this does not prevent fouling deposits from accumulating again. Therefore many techniques have been established to mitigate fouling in heat exchanger networks.

In year 2007 C. Rodriguez and R. Smith proposed the combination of the operating conditions optimization with the optimal management of cleaning actions in a comprehensive mitigation strategy. The designed tool is applied in this paper for supported fouling mitigation by the optimization of operating conditions between wall temperature and flow velocity as shown in Figure 9 or in the original model presented by Ebert and Panchal called ‘fouling threshold’, along with some subsequently proposed modifications, is presented in Table 1.

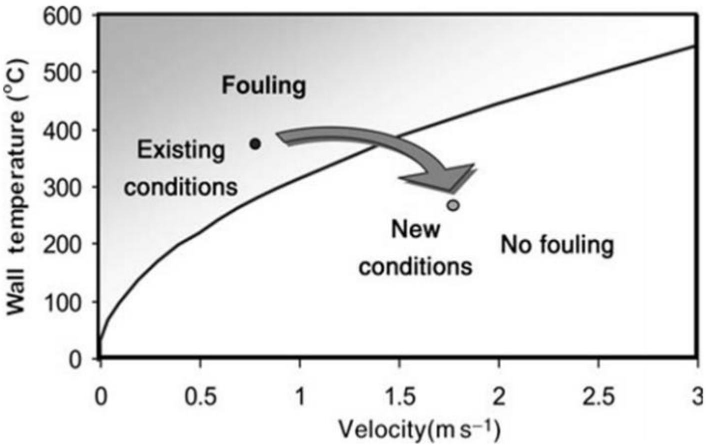


Figure 9 Threshold film temperatures as a function of flow velocity. (Knudsenet al., 1997; Panchal et al., 1997)

Table 1. Fouling threshold models

Model	Author(s)
$Rf' = \alpha Re^{\beta} EXP(-E/RT_f) - \gamma\tau$	Ebert and Panchal(1995)
$Rf' = \alpha Re^{\beta} Pr^{-0.33} EXP(-E/RT_f) - \gamma\tau$	Panchal et al.(1997)
$Rf' = \alpha Re^{-0.8} Pr^{-0.33} EXP(-E/RT_f) - \gamma Re^{-0.8}$	Polley et al.(2002)

Figure 9 show that the location of the fouling threshold conditions divides the operating space in two regions. For conditions of velocity and wall temperature below the threshold line deposition is negligible, the conditions above the threshold line deposition fouling may be expected with the severity of the deposition increases as the conditions move away from the threshold respectively. In order to avoid the severity of the fouling process, the appropriate selection of operating conditions is played an important role. By moving operating conditions from existing condition to new condition can treat by reduced wall temperature or increased velocity. From this reason, the basic idea is changing the operating conditions of existing networks without modifying the network configuration or the internal geometry of its constituent heat exchangers, so other optimization method such as stream splitting and bypassing can be used for easily introduced additional degrees of freedom that enable the manipulation of the operating variables in the network.

2.4 Review of Fouling mitigation literatures

F. Coletti, S. Macchietto, and G. T. Polley (2011) studied effects of fouling on the energy recovery performance of heat exchanger network in crude pre-heat trains (PHTs) unit in oil refineries when deposition over time of fouling on the thermal surfaces, by means of a case study. An existing industrial PHT network is simulated using a dynamic, distributed mathematical model for shell-and-tube heat exchangers undergoing crude oil fouling. To systematically assess the impact of fouling at the network level, several key performance indicators are proposed and used to analyze three retrofit options aimed at maximizing overall heat recovery. Simulation results show that retrofitted heat exchanger networks with design to maximize energy recovery at steady state are not the best when fouling occurs. It is concluded that a proper retrofit design must include consideration of time varying fouling effects.

M. Markowski, M. Trafczynski, and K. Urbaniec (2012) studied the method of identification of the influence of fouling on the heat recovery in a heat exchanger network (HEN). The method is based on mathematical models which enable interpretation from operating parameters of the HENs in general industrial measurements. The models are developed for shell and tube heat exchanger. The crucial assumption is that measurements of the mass flow rate and inlet and outlet temperature, and chemical composition are available for each process stream, this making evaluation of fouling-induced reduction in the recovered energy flow possible. Using the proposed identification method and an industrial data base acquired in a typical crude distillation unit, the mathematical models are thoroughly tested. The developed approach allows long-term monitoring of changes in the condition of the HENs and assisting plant operator decisions aimed at maximizing heat recovery over the period of plant operation. On the basis of information collected from past operation periods, it is possible to predict future changes in HEN performance and to implement preventive measures aimed at the reduction of detrimental effects of fouling.

Y. Wang, S. Zhan, and X. Feng (2015) studied a proposed method for optimizing crude oil velocity to reduce fouling of the heat exchanger tubes so get maintaining heat transfer rates and reducing pressure drop that all affect to minimize the total cost. A simulated annealing algorithm is proposed to describe and optimize the interactions between heat transfer, pressure drop and fouling by adjusting fluid velocity. A specific crude oil heating system is used as a case study to verify the application of the algorithm. From the results, it is found that velocity is sensitive to fouling, duty of heat exchangers, and heat capacity flow rates. The reason is that for the exchangers prone to fouling, higher velocity is required for mitigating fouling. From case study showed that total annual cost can be reduced by 6.4%, indicating that a better performance from velocity redistribution using proposed method.

M. Pana, I. Bulatov, and R. Smith (2015) studied the implementation of heat transfer intensified technologies for HEN retrofitting. It is the first study to implement hiTRAN (one commercial tube-insert technology) into heat exchangers to increase HEN heat recovery with the consideration of detailed exchanger performances including heat transfer intensifications, pressure drop constraints, and fouling mitigation. The overall retrofit profit is maximized based on the best trade-off among energy savings, intensification implementation costs, exchanger cleaning costs, and pump power costs. To solve such complex optimization problems, a new mixed-integer linear programming (MILP) model has been developed to consider fouling effects in retrofitting HENs with heat transfer intensification. An efficient iterative optimization approach is then developed to solve the MILP problem. In case studies, the new proposed approach is compared with the existing methods on an industrial scale problem, demonstrating that the new proposed approach is able to obtain more realistic solutions for practical industrial problems.

J. Tian, Y. Wang, and X. Feng (2016) studied fouling mitigation by combining optimizing operation condition and cleaning schedule simultaneously. For optimization of operation condition, flow velocity is selected as a key variable since it can correlate fouling, heat transfer and pressure drop. The optimal network performance can be achieved through redistribution of velocity. However in oil refinery, fouling cannot be completely prevented by optimization of operation conditions, so the cleaning action is still important. In order to deal with the remained fouling, the cleaning actions are optimized with SA (Simulated annealing). The results from case study show higher energy saving and economic efficiency compared with existing methods

CHAPTER III
METHODOLOGY

3.1 Materials and Equipment

3.1.1 Equipment:

ASUS A45V Series (Intel® Core™ i7-3610QM CPU @ 2.30GHz, 8GB of RAM, Windows 10 Pro (64-bit Operating system))

3.1.2 Software:

a. Generic Algebraic Modeling System (GAMS)
b. Microsoft Office 2013: Excel

3.2 Experimental Procedures

3.2.1 Heat Exchanger Network (HEN) with Fouling Effect

a. Formulate mathematical programming model of HEN based on stage-wise superstructure.
b. Input flow and temperature of all streams into proposed model including fouling factor.
c. Solve model by GAMS.
d. Interpret GAMS's output results.
e. Analyze and validate HEN.

3.2.2 Retrofitted Heat Exchangers Network with Fouling Effect.

a. Apply retrofitted strategy through mathematical programming model of HEN based on stage-wise superstructure.
b. Input flow and temperature of all streams into proposed model and data from operated HEN with fouling.
c. Solve model by GAMS.
d. Interpret GAMS's output results to present HEN.
e. Analyze and validate HEN.

3.2.3 Optimization of Cleaning Schedule with HEN.

a. Apply cleaning schedule strategy through mathematical programming model of HEN based on stage-wise superstructure.
b. Input flow and temperature of all streams into proposed model.
c. Solve model by GAMS.
d. Interpret GAMS's output results to present HEN.
e. Analyze and validate HEN.

3.2.4 Optimization of the Combination of Heat Exchangers Cleaning Schedule and Retrofitted HEN with Fouling Effect

a. Formulate retrofit mathematical programming model that already applied with cleaning schedule strategy.
b. Solve model by GAMS.
c. Interpret GAMS's output results to present optimized HEN.
d. Analyze optimized HEN and compare with others.
e. Validate optimized HEN.

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Model Development

In this study, the model of HEN retrofit is MINLP based on stage-wise approach. In order to modify former stage-wise model to HEN retrofit model, the constraints for existing exchanger matches have to be added to the synthesis model. The objective function of HEN retrofit model is maximizing profit as a function of utilities saving revenue and total investment cost from additional area and new heat exchanger units. In HEN retrofit part, the main assumptions are shown, as follows.

- Constant heat capacities
- Constant specific heat capacities
- Counter current heat exchangers

In order to formulate the MINLP model for the proposed superstructure described previously, the following definitions and equations are based on Yee and Grossmann (1990). And the modified model for retrofitting is proposed as follows.

Maximize Profit = utilities saving revenue – total investment cost

$$\begin{aligned}
&= CCU\times(Qcu_{base}-\textstyle\sum_i qcu_i) + CHU\times(Qhu_{base}-\textstyle\sum_j qhu_j) \\
&\quad - cf\times \textstyle\sum_{i,j,k} (z_{i,j,k}-z_{base,i,j,k}) - cfcu\times \textstyle\sum_i (zcu_i-zcu_{base,i}) - cfhu\times \textstyle\sum_j (zhu_j-zhu_{base,j}) \\
&\quad - CA\times \textstyle\sum_{i,j,k} (a_{i,j,k} - a_{base,i,j,k})^B \\
&\quad - CAC\times \textstyle\sum_i (acu_i - acu_{base,i})^B - CAH\times \textstyle\sum_j (ahu_j - ahu_{base,j})^B
\end{aligned} \tag{1}$$

4.1.1 HEN Retrofit under Fouling Effects Strategy

As mention above, the main problem in energy handling in industry is extra energy consumption caused by fouling deposition. In order to recondition thermal efficiency of HEN, there are many fouling mitigation strategies. Most common strategy used to operate HEN with fouling deposition is design of cleaning schedule but this strategy have to shut-down some exchangers or add spare exchangers. Thus, the production loss problem and extra investment cost may involve. In this study, new proposed model composed of three main steps is shown in

Figure. 10. For first step, the model is divided into twelve one-month periods for one year and then base-case HEN is simulated for twelve months with fouling accumulation by GAMS software. Without any periodic cleaning, HEN has to consume more utility due to decreasing heat recovery and overall heat transfer coefficient of network. The fouling deposition is based on fouling threshold model. In this study the fouling threshold models refer to Polly et a. (2002a)

$dRf/dt = \alpha Re^{-0.8} Pr^{-0.33} EXP(-E/RT_w) - \gamma Re^{0.8}$ (2)

The idea is to retrofit HEN during the shut-down period around the end of twelfth month. Thus, the HEN consumes lower energy consumption and gets better heat recovery by the increased an area of each existing exchanger. For second step, base-case HEN at twelfth month under fouling condition is retrofitted by MINLP model using GAMS. For the third step, the retrofitted HEN from second step is operated under fouling effects for twelve months and utilities usage is calculated. The equations of fouling deposition and HEN retrofit are shown below:

$Rf_t = Rf_{t-1} + Rf'_t \cdot \Delta t$ (3)

$1/U = 1/hh + 1/hc + Rf$ (4)

Objective = Minimize total utilities cost for twelve month (5)

$= CCU \times \sum_{i,t} qcu_{i,t} + CHU \times \sum_{j,t} qhu_{j,t}$

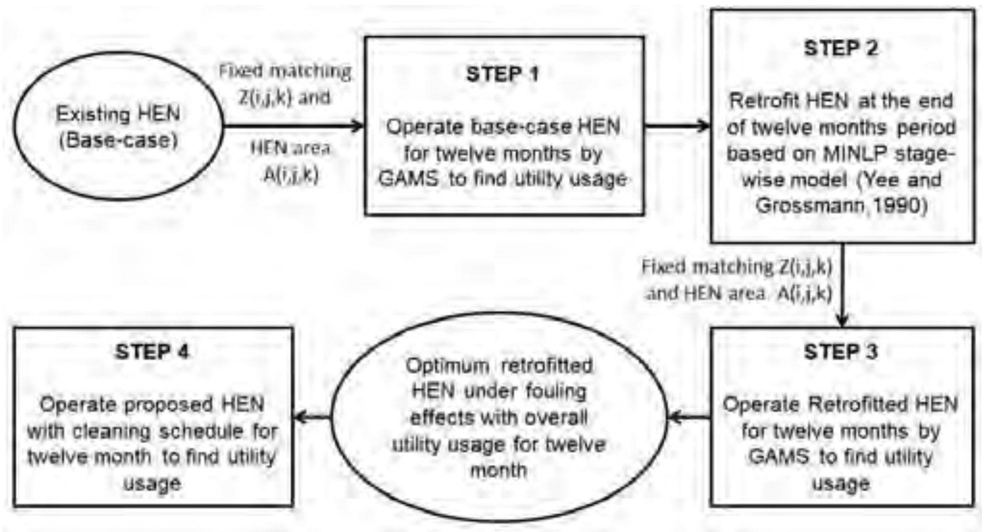


Figure 10 Scheme of HEN retrofit model under fouling effects with cleaning schedule

In Example the retrofit model have to be solved by using discrete strategy because the optimal HEN from retrofit model give network which contains a lot of exchanger causing too high investment costs. In order to find the alternative case, the discrete strategy is used by reducing number of heat exchanger to find the minimum heat exchanger which gives positive NPV following Figure 11.

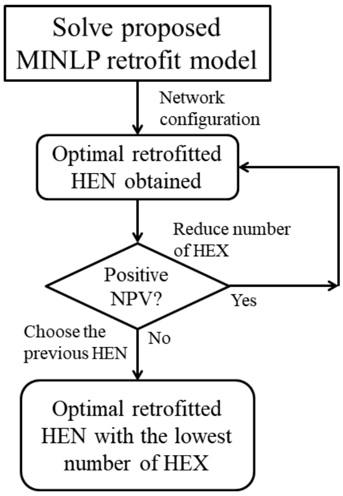


Figure 11 Scheme of retrofit by discrete strategy

4.1.2 HEN Retrofit under Fouling Effects Strategy with Cleaning Schedule

In order to maximize profit, the cleaning schedule is applied. Wang et al. (2016) apply cleaning schedule for mitigating fouling and get the lower the cost comparing with practical fouling mitigation. The time of operation is divided into 2 types; operation and cleaning sub-periods, shown in Figure 12. The logical constraint, as shown in equation 6, defines the logic that if the thermal effectiveness of heat exchanger ($\frac{Q_t}{Q_{to}}$) is less than cleaning criteria (C), then the cleaning operation will be occurred as shown in Figure 13. The cleaning status is indicated by binary variable $X_{cl,t}$. Where $X_{cl,t}$ is one and zero referring to cleaning operation and non-cleaning, respectively. Equation 7 is used to indicate fouling resistance when cleaning operation is involved.

$$-\ \Omega \leq (C - Q_t/Q_{t0}) - (\Omega \times X_{cl,t}) \leq 0 \tag{6}$$

$$Rf_t = (Rf_{t-1} + Rf'_t) \times (1 - X_{cl,t}) + (Rf_{t0} \times X_{cl,t}) \tag{7}$$

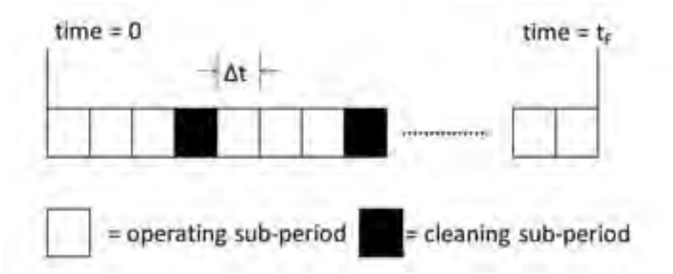


Figure 12 Time discretization for modelling cleaning in HEN

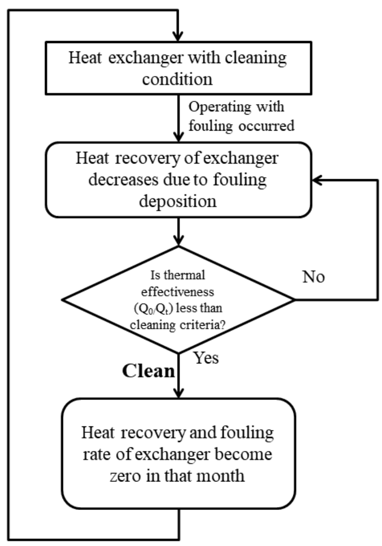


Figure 13 Scheme of cleaning schedule strategy

The base case is existing heat exchanger network of crude preheat train with 10 hot steams, 3 cold streams and EMAT equal 5 ˚C as shown in Figure 14. For heat transfer film coefficient of steams and economic data are shown in tables 2 and 3.

Table 2 Heat transfer film coefficient of steams data

Stream	h, film coefficient (kW/m^2* $^\circ$C)
Hot1	12.93
Hot2	5.063
Hot3	0.892
Hot4	1.361
Hot5	1.299
Hot6	1.344
Hot7	1.28
Hot8	1.396
Hot9	1.388
Hot10	0.502
Cold1	0.5165
Cold2	0.788
Cold3	3.328

4.2 Illustrative Example

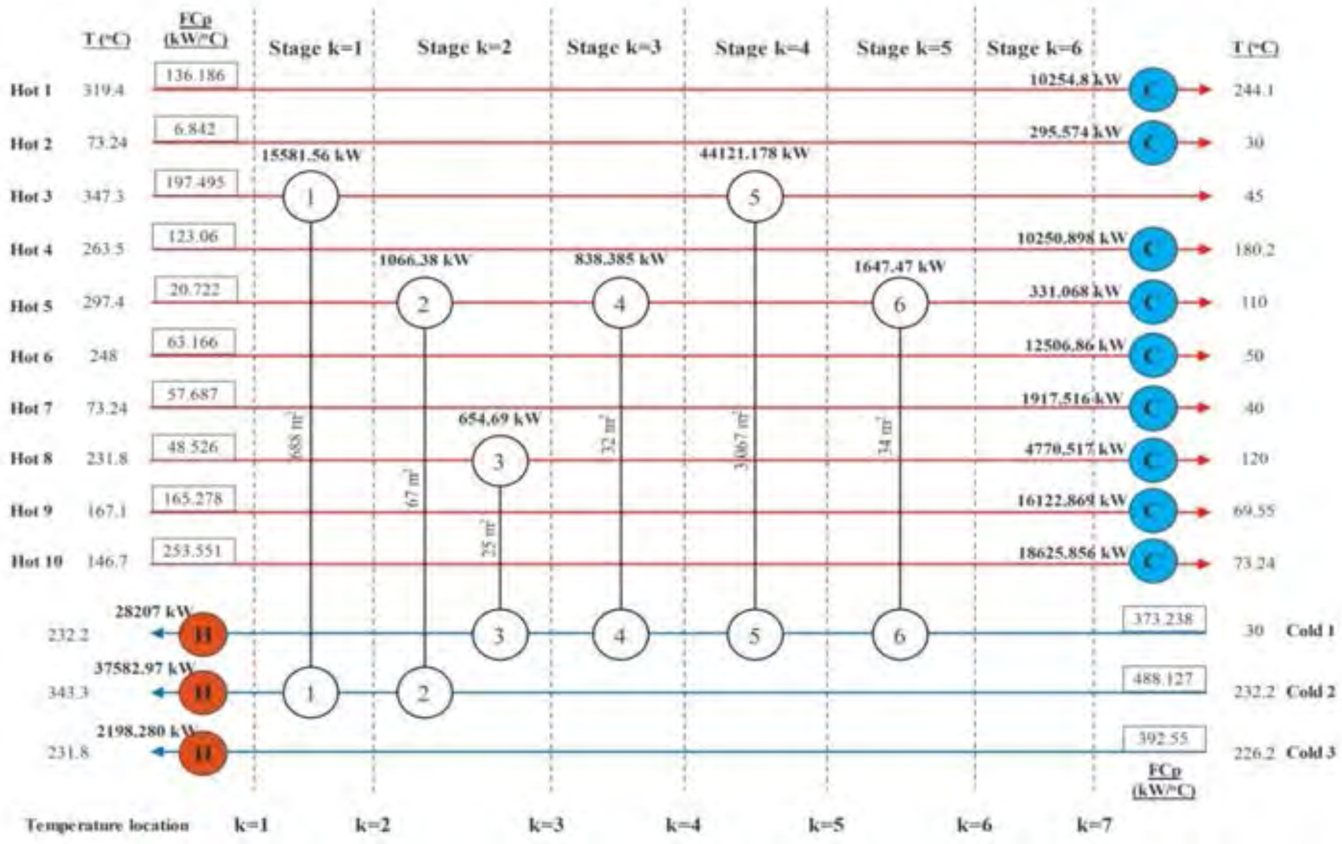


Figure 14 Existing heat exchanger network for example

Table 3 Economic data

Utility cost	
Hot ($/kW)	120.0
Cold ($/kW)	20.0
Exchanger cost	
a ($)	26460.0
b ($/m^2)	389.0
c	0.83
Annualization data	
n = Life time (yrs)	5
I = Interest rate (%)	20%

Exchanger Cost = Nmin*[a+b(A/Nmin)^c]

A : area (m^2)

Cleaning cost = $500 per time

From streams data, composite curve is taking place for studying overview of heat exchanger network when plot between heat load and temperature. In Figure 15, it can be seen that there is gap between hot and cold stream where utilities of HEN can reduced in order to achieve higher profit. However, there are trade-offs between utilities cost and area of heat exchanger that affect to total profit.

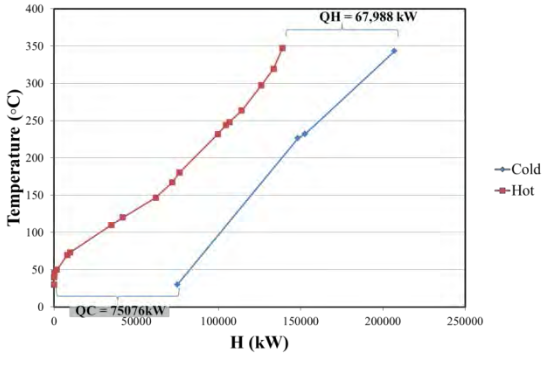


Figure 15 Composite curve of base case

4.3 Result

This crude preheat train case is used to illustrate the HEN retrofit model under fouling effects. The problem is accomplished in GAMS 24.2.1 solved by DICOPT as an MINLP solver on notebook computer (ASUS A45V Series (Intel® Core™ i7-3610QM CPU @ 2.30GHz, 8GB of RAM, Windows 10 (64-bit Operating system)). At first, this base-case HEN requires hot and cold utility for 67,988 and 75,076 kW respectively. This base-case is improved to recover heat transfer efficiency using exchanger minimum approach temperature (EMAT) of 5 ˚C.

When crude preheat train is operated for twelve months in first step, the result shows that HEN consumes more utilities due to decreasing heat recovery of HEN as shown in Figure 16. Total hot and cold utility consumptions are 70162 and 77250 kW respectively. For After twelve months, this HEN is modified by retrofit model.

In second step the retrofit HEN after twelve month, the model achieves optimum NPV at sixteen exchangers which give high investment cost. So there are two results for being alternative way. First is optimum NPV which has high investment cost and second is first positive NPV which has the lowest number of heat exchanger. Discrete method is used for searching the first positive NPV. The result is showed in Table 4.

For the first way which gives the highest NPV, the HEN retrofit shows new HEN that contains ten more exchangers than the base case as shown in Figure 17a. The area is increased from 3913 m^2 to 15727 m^2. At the start of run, retrofitted HEN required hot utility of 26127 kW and cold utility of 33215 kW. And the third step is to find utility usage from retrofitted HEN which is operated for twelve months. The result shows that hot utility and cold utility are 29206 kW and 36294 kW, respectively as shown in Figure 17b. Comparing retrofitted and base case HEN, fouling accumulation rate is increased in existing exchanger resulting in increasing of heat load and decreasing overall heat transfer coefficient during all of the operating periods. But some additional exchangers have constant heat load and fouling is not occurred as rate of fouling accumulation become zero all of the operating period as show in Figure 18 for base-case HEN and retrofit case, Figure 19 for additional exchangers Retrofitted HEN with fouling effects.

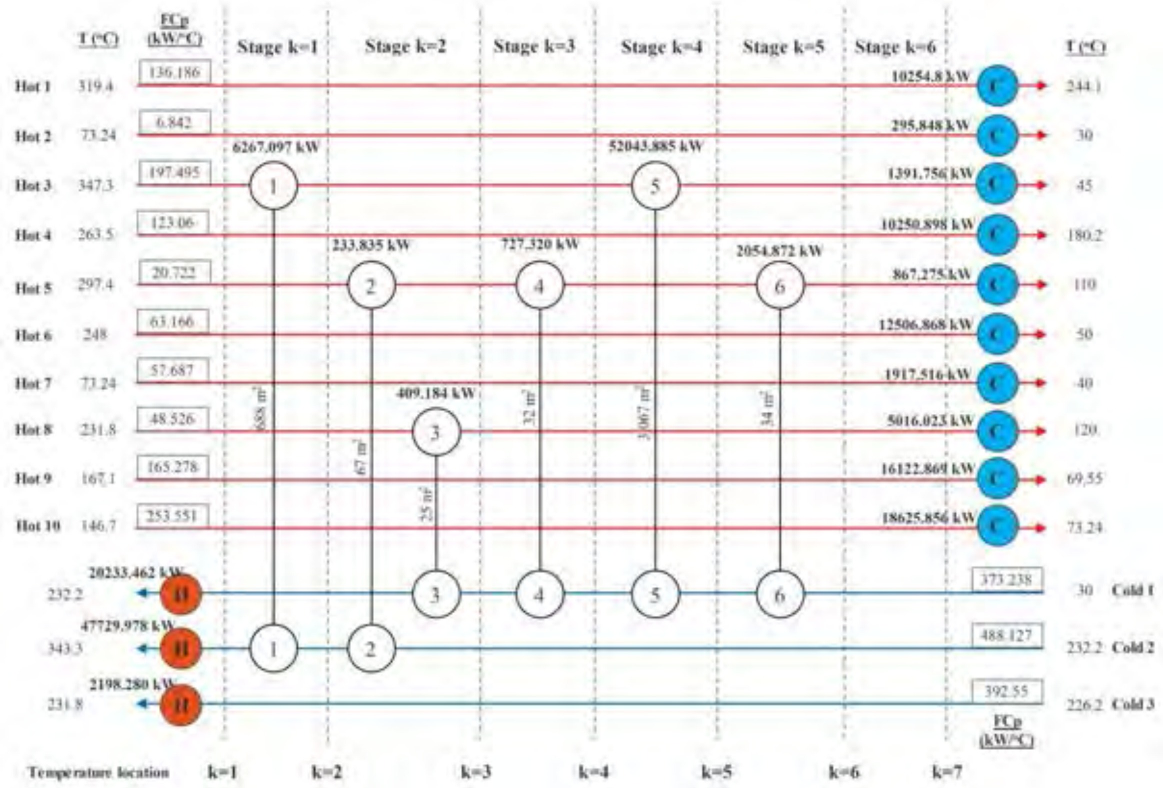


Figure 16 Existing HEN of crude preheat train (12-month)

Table 4 Result from discrete strategy

	NOHX	Heat recovery	Qc	Qh	Area	NPV
Basecase	6	63909.663	75075.96	67988.25	3913	$0
	6	64959.055	74026.85	66938.86	5339.978	-$27,925
	7	77459.621	60441.83	53353.83	8424.071	$1,278,374
	8	87511.505	51474.4	44386.41	9080.766	$2,481,181
	9	96026.896	42959.01	35871.02	13071.76	$3,252,874
	10	100162.108	38823.8	31735.81	16202.53	$3,543,928
	11	100667.942	38317.97	31229.97	16889.89	$3,537,344

Table 4 Result from discrete strategy (continue)

NOHX	Heat recovery	Qc	Qh	Area	NPV
12	103886.59	35099.32	28011.32	18151.18	$3,839,842
13	104522.807	34463.1	27375.11	19433.37	$3,813,568
14	102016.268	36969.64	29881.65	15961.61	$3,690,030
15	105694.208	33214.29	26126.30	19936.76	$3,878,428
16	102023.82	34028.75	26940.75	15854.13	$4,018,555

*NPV for 1 year at 10% interest rate

For the second way which gives positive NPV with the lowest number of exchanger, the HEN retrofit shows new one heat exchanger as shown in Figure 22a. The area is increased from 3913 m^2 to 8424 m^2. At the start of run, retrofitted HEN required hot utility of 53354 kW and cold utility 60442 kW. The result of operated HEN for twelve months shows that hot and cold utility are 63903 kW and 70991 kW, respectively as shown in Figure 22b. For the retrofitted HEN, the result of both case shows that it saves total hot and cold utility along twelve month and gets positive NPV as shown in Table 5.

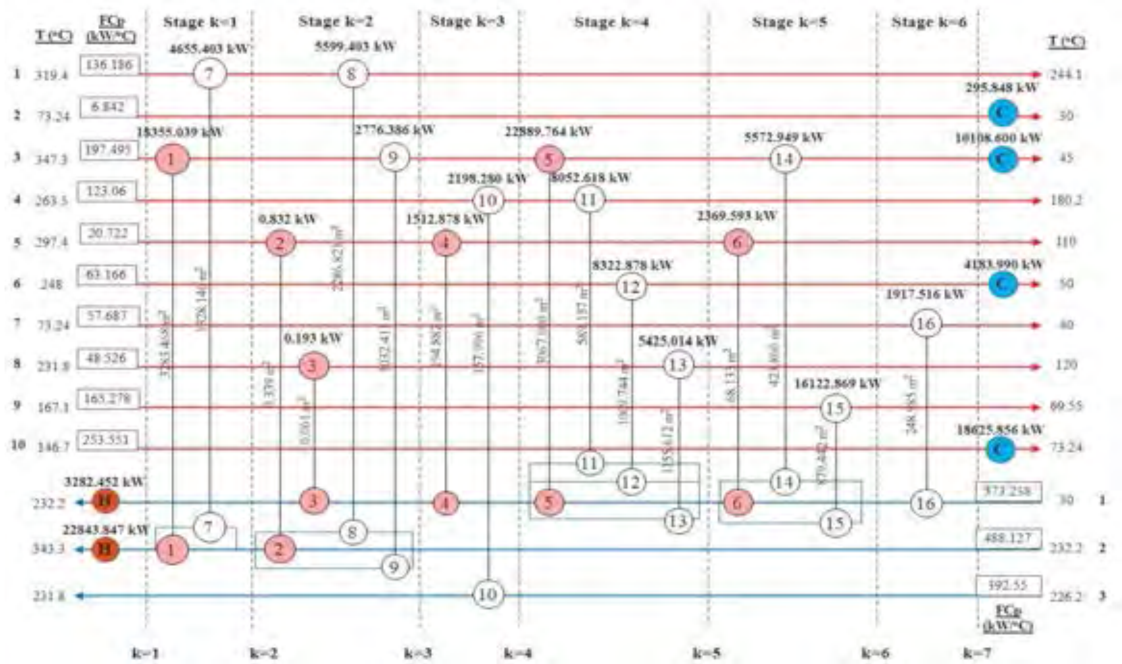


Figure 17a Retrofitted HEN of crude preheat train (0-month)

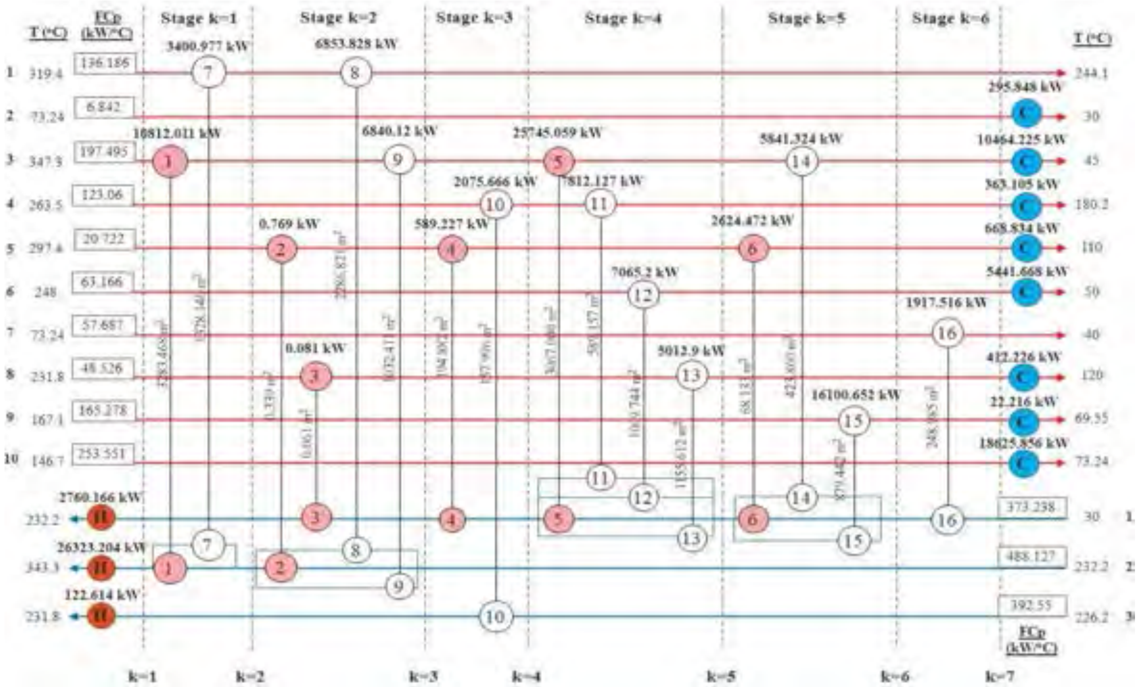


Figure 17b Retrofitted HEN of crude preheat train (12-month)

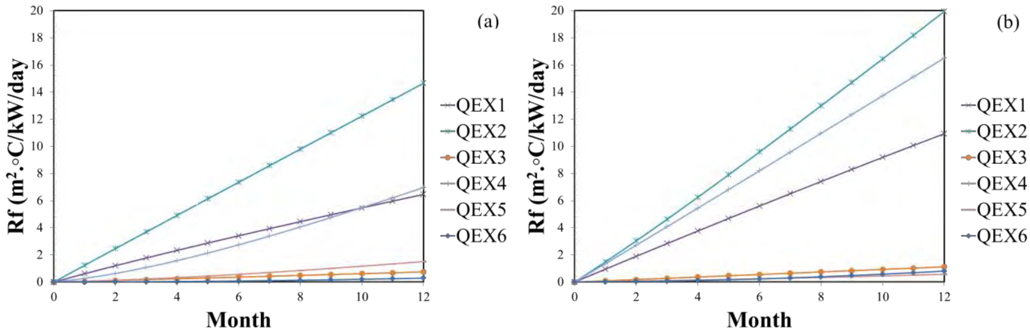


Figure 18 Cumulative fouling rate of existing exchangers in Crude oil preheat train (a) Base-case and (b) Retrofitted case

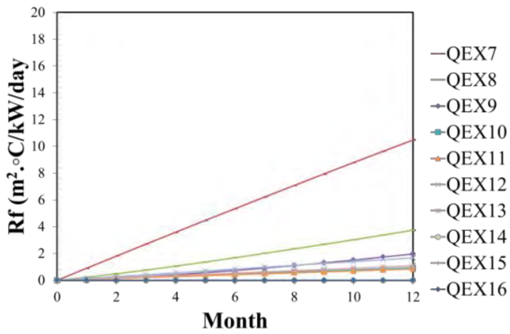


Figure 19 Cumulative fouling rate of additional exchangers in Crude oil preheat train

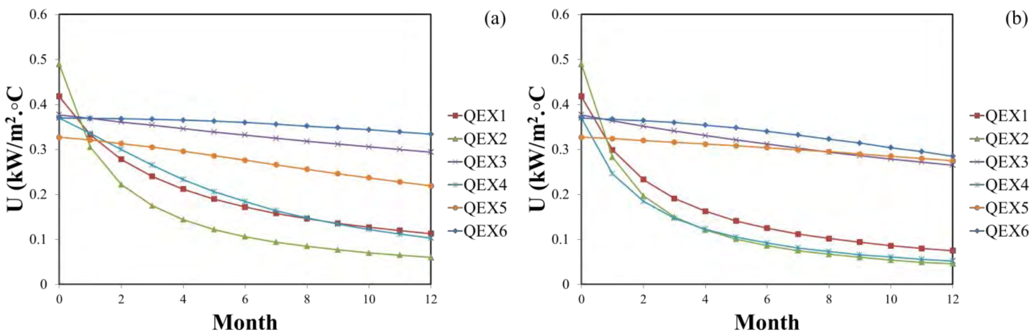


Figure 20 Overall heat transfer coefficient of existing exchangers in Crude oil preheat train (a) Base-case and (b) Retrofitted case

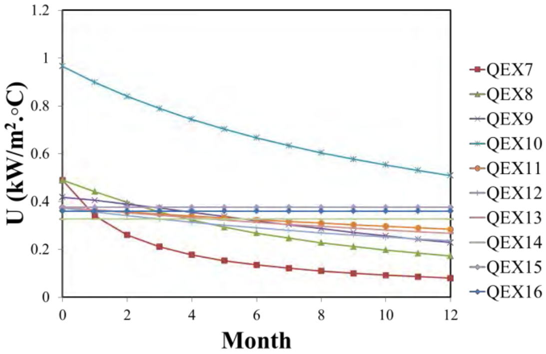


Figure 21: Overall heat transfer coefficient of additional exchangers in Crude oil preheat train

Table 5 Comparison between base-case and retrofit case

Base-case for 12 months	Retrofit case for 12 months	Retrofit case 2 for 12 months
No NPV	NPV = $28,850,236 Hot utility saving = 58.38% Cold utility saving = 53.02%	NPV = $639,165 Hot utility saving = 20.40% Cold utility saving = 18.53%
Utility cost = $1,751,709	Utility cost = $746,961 Additional area cost = $933,279	Utility cost = $1,388,779 Additional area cost = $419,755

And the last step, cleaning schedule is applied by using cleaning criteria of 50% and 70% of thermal effectiveness $\left(\frac{Q_t}{Q_{to}}\right)$ for all case; base-case, retrofitted case and alternative retrofitted case. The result shows that base-case has the highest number of cleaning operation comparing with others as shown in Table 6. The cleaning schedule by cleaning criteria of 50% and 70% are shown in Figure 25 and 26. When cleaning schedule is applied with retrofitted cases, HEN gets higher utility saving and NPV as result shown in Table 7 for 50% cleaning criteria and Table 8 for 70% cleaning criteria.

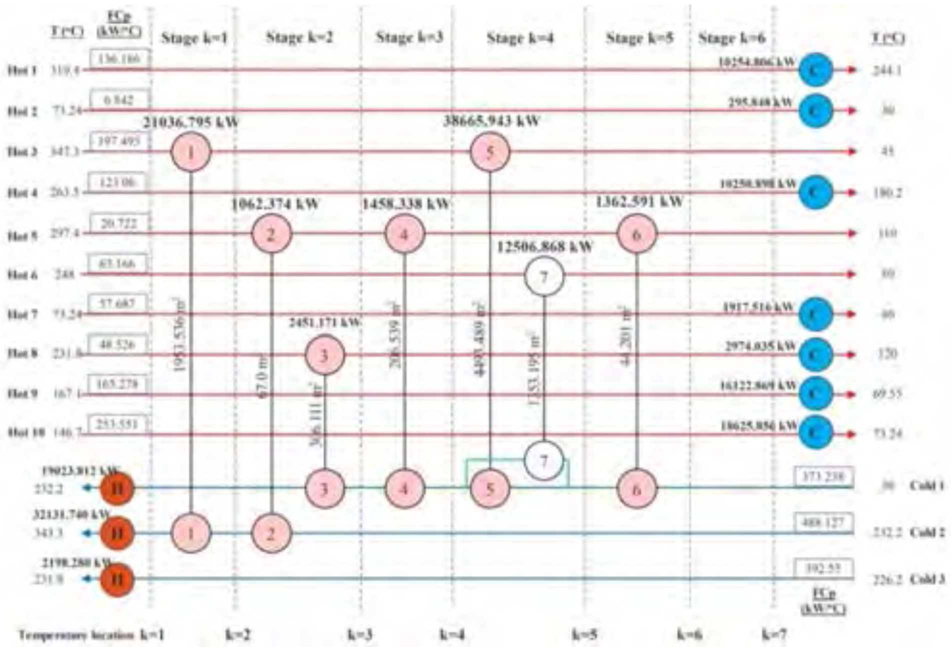


Figure 22a Retrofitted case 2 HEN of crude preheat train (0-month)

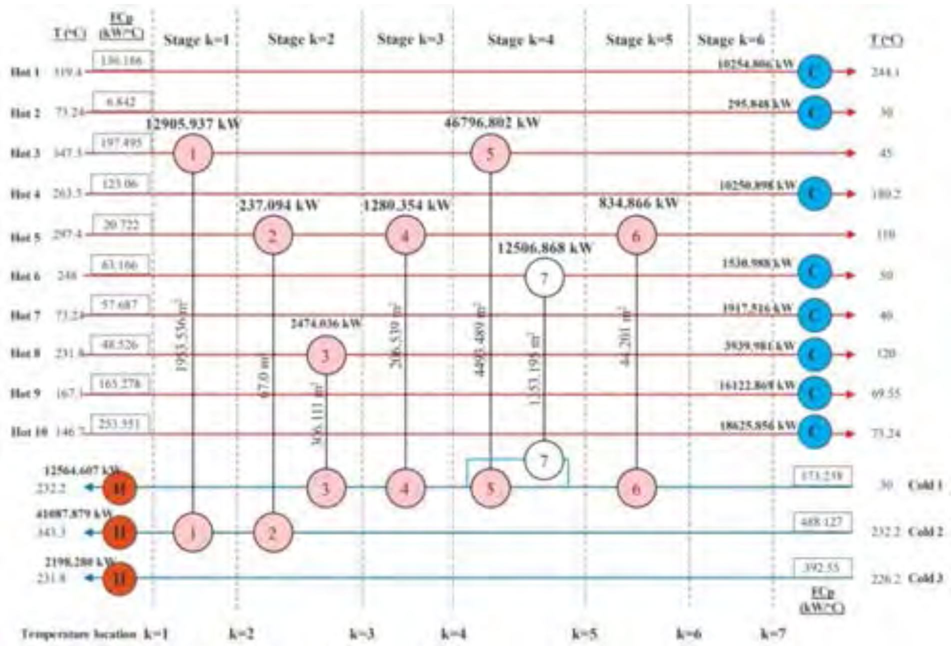


Figure 22b Retrofitted case 2 HEN of crude preheat train (12-month)

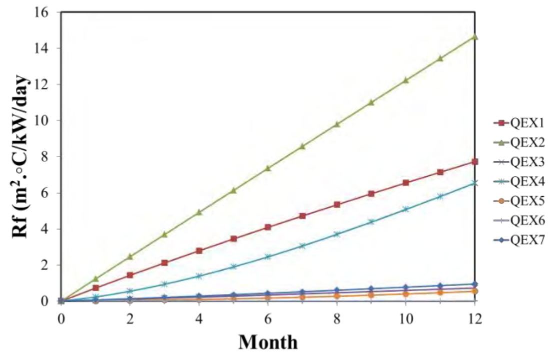


Figure 23 Cumulative fouling rate of HEN in Crude oil preheat train Retrofitted case 2

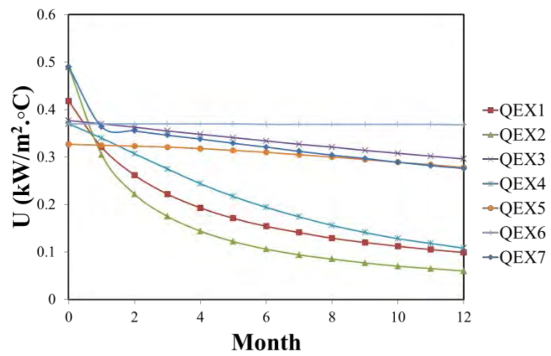


Figure 24 Overall heat transfer coefficient of HEN in Crude oil preheat train Retrofitted case 2

Table 6 Comparison of a number of cleaning operation in each case

Scenario	k	Number of cleaning operation in each case (times)		
		Base-case	Retrofit case	Retrofit case 2
1	50%	4	1	2
2	70%	7	3	4

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
HX1									■			
HX2				■				■				■
HX3												
HX4												
HX5												
HX6												

a) Cleaning schedule of base-case

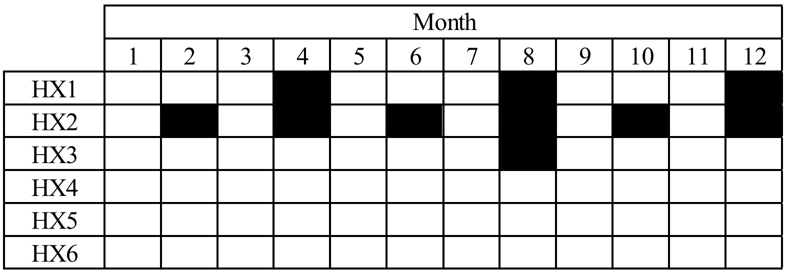
	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
HX1												
HX2												
HX3												
HX4									■			
HX5												
HX6												
HX7												
HX8												
HX9												
HX10												
HX11												
HX12												
HX13												
HX14												
HX15												
HX16												

b) Cleaning schedule of retrofit case

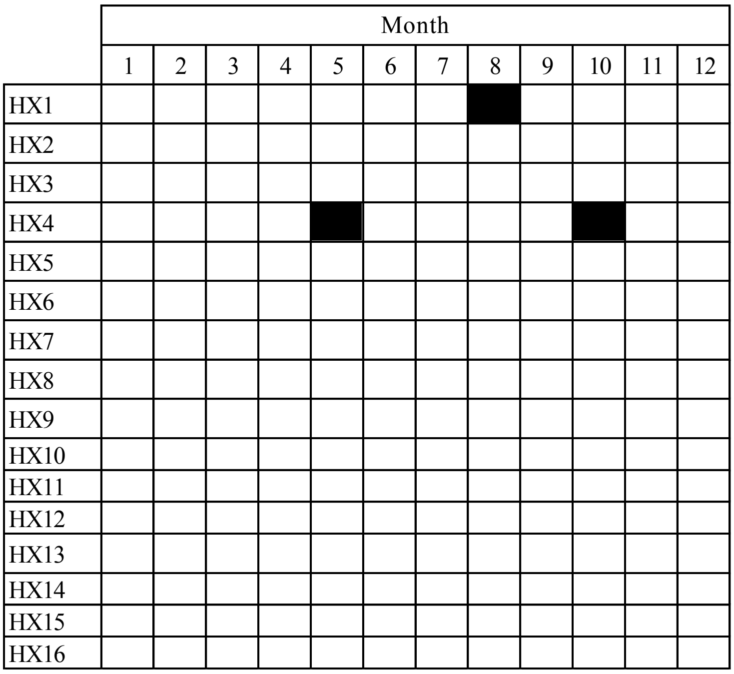
	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
HX1												
HX2				■				■				■
HX3												
HX4												
HX5												
HX6												
HX7												

c) Cleaning schedule of retrofit case 2

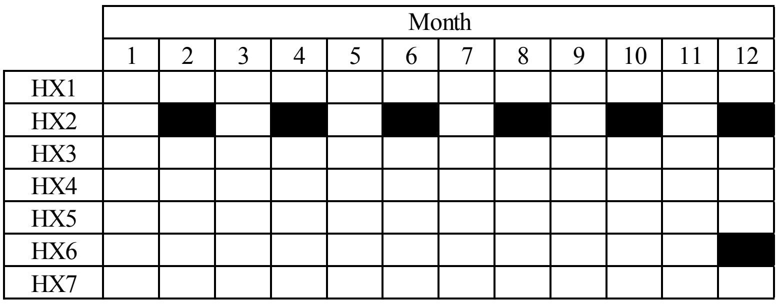
Figure 25 Cleaning schedule in each case (C=50%)



a) Cleaning schedule of base-case



b) Cleaning schedule of retrofit case



c) Cleaning schedule of retrofit case 2

Figure 26: Cleaning schedule in each case (C=70%)

Table 7 Comparison result between base-case and retrofit case with cleaning schedule (C=50%)

Base-case for 12 months	**Retrofit case for 12 months**	**Retrofit case 2 for 12 months**
NPV = $69,363 Hot utility saving = 1.43% Cold utility saving = 1.30%	NPV = $28,929,913 Hot utility saving = 60.44% Cold utility saving =54.85%	NPV = $673,527 Hot utility saving = 22.50% Cold utility saving = 20.41%
Utility cost = $1,727,846 Cleaning cost = $2,000	Utility cost = $ 744,280 Additional area cost = $933,279 Cleaning cost = $500	Utility cost = $ 1,376,788 Additional area cost = $419,755 Cleaning cost = $1,500

Table 8 Comparison result between base-case and retrofit case with cleaning schedule (C=70%)

Base-case for 12 months	**Retrofit case for 12 months**	**Retrofit case 2 for 12 months**
NPV = $15,239 Hot utility saving = 0.41% Cold utility saving =0.37%	NPV = $32,858,208 Hot utility saving = 62.97% Cold utility saving = 57.14%	NPV = $658,911 Hot utility saving = 22.24% Cold utility saving = 20.18%
Utility cost = $1,744,941 Cleaning cost = $5,000	Utility cost = $ 702,149 Additional area cost = $933,279 Cleaning cost = $1500	Utility cost = $ 1,381,006 Additional area cost = $419,755 Cleaning cost = $3,500

4.4 Sensitivity Analysis

In order to do sensitivity analysis, the life time for revamping or cleaning is changed from one year to two years (24 months), In the first step, this crude preheat train is operated for twenty four months, the result show that HEN consumes more utilities due to decreasing heat recovery of HEN as shown in Figure 27. Total hot and cold utility consumptions are 76306 and 83394 kW, respectively. After twenty four months, this HEN is modified by retrofit model.

In the second step, the HEN retrofit needs new one exchanger as shown in Figure 28. The area is increased from 3913 to 12820 m^2. To compare the utility saving of retrofitted HEN in third step, retrofitted HEN requires hot and cold utility of 54857 and 61945 kW at the start of run. When retrofitted HEN operated for twenty four months, it shows that hot and cold utilities are 58620 kW and 65708 kW, respectively as shown in Figure 29. For base-case HEN, fouling rate is increased resulting in decreasing heat load and overall heat transfer coefficient during all of the operating periods as shown in Figure 30. For the retrofitted HEN, the result shows that it saves total hot and cold utility along twenty four months about 21.90 and 19.94%, respectively. And NPV as follow Table 9.

For the last step, the cleaning schedule is applied by using cleaning criteria of 50% of thermal effectiveness (Q_t/Q_{t0}) for comparing between a number of cleaning operations of base-case HEN and retrofitted HEN. The result is shown in Figure 31. When cleaning schedule is applied with retrofitted case, hot and cold utilities saving are increased to 25.35% and 23.09%, respectively. And NPV is showed in Table 10.

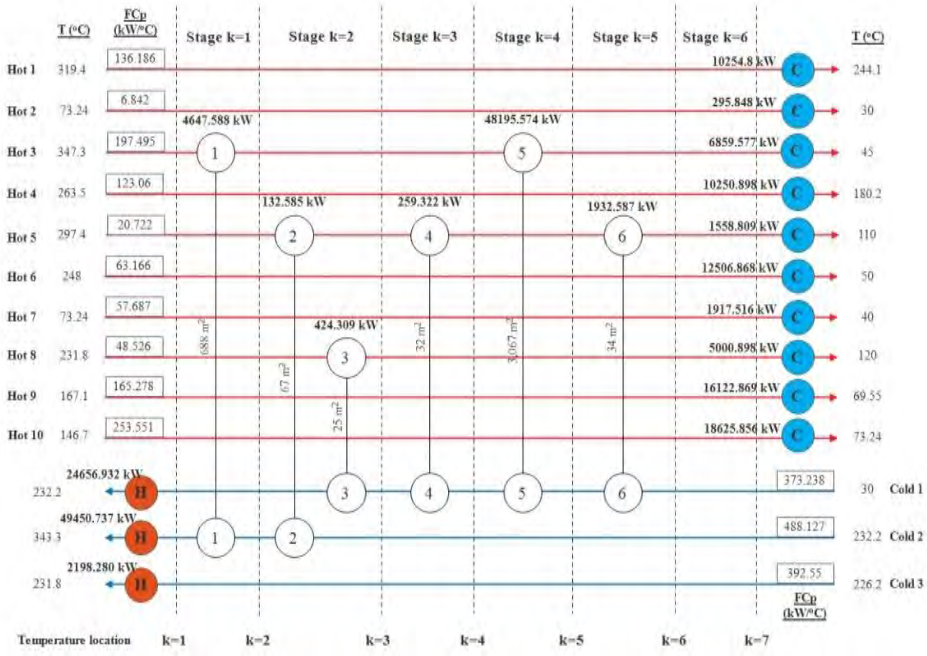


Figure 27 Existing HEN of crude preheat train (24-month)

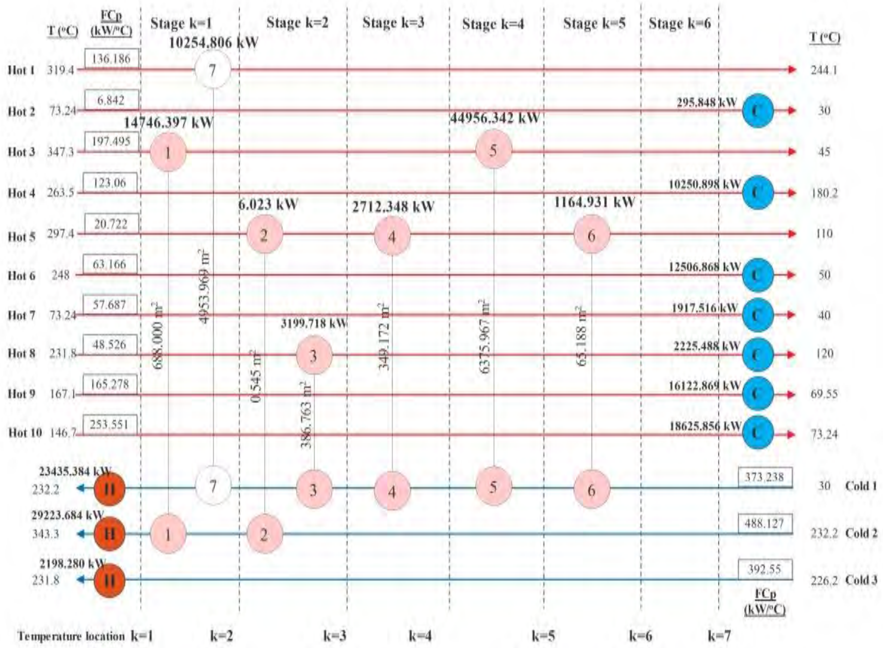


Figure 28 Retrofitted HEN of crude preheat train (0-month)

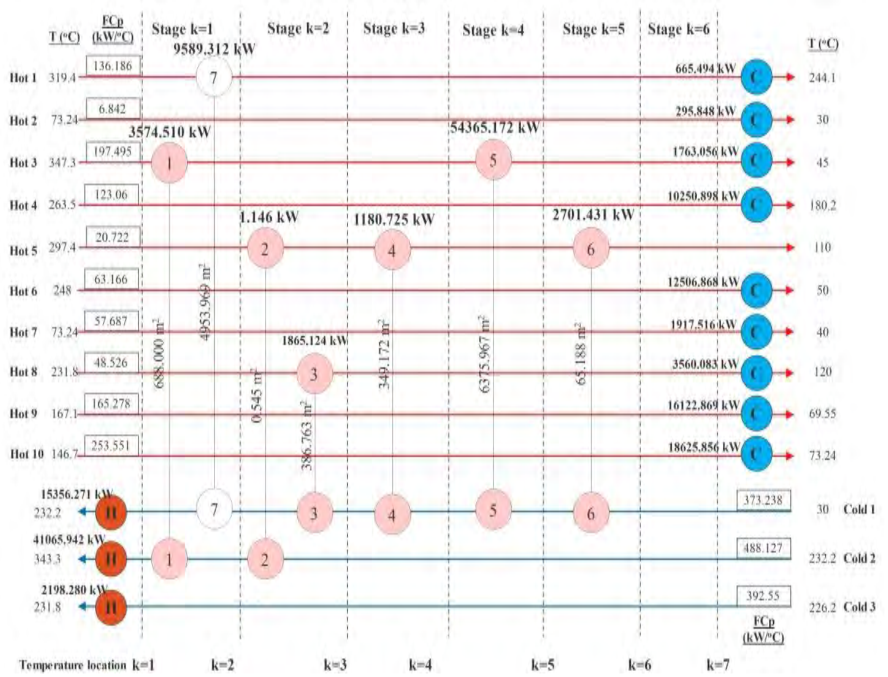


Figure 29 Retrofitted HEN of crude preheat train (24-month)

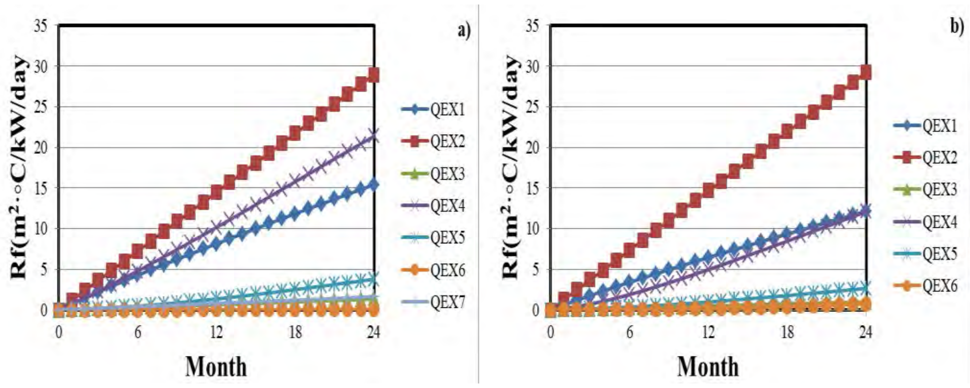


Figure 30 Cumulative fouling rate of exchangers (a) Base-case and (b) Retrofitted case

Table 9 Comparison between base-case and retrofit case for 24 mounts

	Base-case for 24 months	Retrofit case for 24 months
NPV ($)	-	$369,856
Hot utility saving (%)	-	21.90%
Cold utility saving (%)	-	19.94%
Utility cost ($/year)	$1,817,190	$1,437,801
Investment cost ($)	-	$764,750

Table 10 Comparison result between base-case and retrofit case with cleaning schedule for 24 months (C=50%)

	Base-case for 24 months	Retrofit case for 24 months
NPV ($)	$186,750	$545,665
Hot utility saving (%)	3.69%	25.35%
Cold utility saving (%)	3.36%	23.09%
Utility cost ($/year)	$1,753,240	$1,378,011
Investment cost ($)	-	$764,750
Cleaning cost ($)	$4,500	$3,000

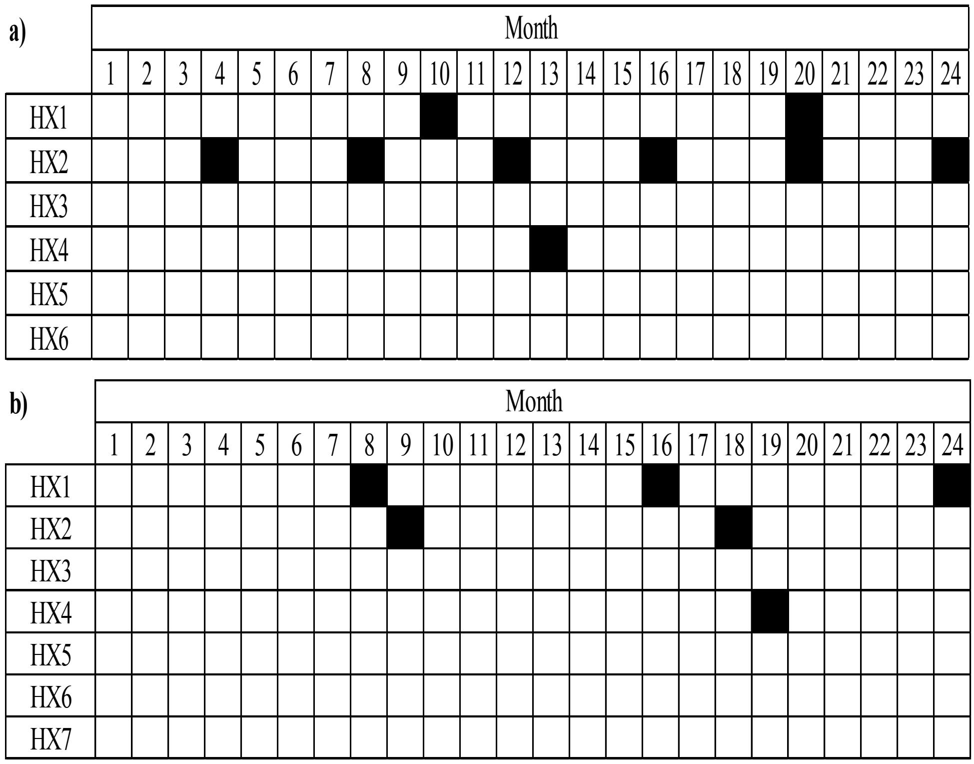


Figure 31 Optimal cleaning schedule of (a) Base-case and (b) Retrofitted case

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, the proposed HEN retrofit under fouling effects helps save total utility cost. The strategy is HEN retrofit model where network is designed involving additional area to recover more energy. Therefore the model achieve the best trade-offs between investment cost due to addition of area and exchanger and utility cost which is caused by fouling. Comparison between base-case HEN and retrofitted HEN, the retrofitted HEN with cleaning schedule overcomes the base-case one with lower number of cleaning operation. When the cleaning schedule is applied, the model shows that combination of HEN retrofit under fouling effects and cleaning schedule achieve lower energy consumption and higher NPV.

5.2 Recommendations

Based on what has been discovered in this study, the following recommendations were suggested:

- It is interesting to integrate the fouling mitigation by using fouling threshold to this work for another operating cost saving alternative.
- The model will be more accurate if the study involves non-isothermal.

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APPENDICES

Appendix A Parameters and Variables of Multi-Period HENs Retrofit.

Table A1 Constant parameters in fouling model.

E(kJ/mol)	22.62
R(kJ/°C/mol)	8.31E-03
α(m^2.°C/kW/day)	2.40E+07
γ(m^2.°C/kW/day)	3.60E-08

Table A2 Stream data parameters of real crude oil preheat train.

Stream	Thermal conductivity (kW/(m²·°C))	Viscosity (Ns/m²)	Diameter(m)	Reynolds number	Prandtl number
HOT1	0.159	0.007256	0.2000	119437.456	0.0456
HOT2	0.258	0.006921	0.2000	6290.998	0.0268
HOT3	0.159	0.007256	0.2000	173206.500	0.0456
HOT4	0.159	0.007256	0.2000	107925.729	0.0456
HOT5	0.159	0.007256	0.2000	18173.549	0.0456
HOT6	0.159	0.007256	0.2000	55397.664	0.0456
HOT7	0.322	0.008826	0.2000	53041.336	0.7841
HOT8	0.159	0.007256	0.2000	42558.134	0.0456
HOT9	0.524	0.006215	0.2000	151967.792	1.1136
HOT10	0.211	0.007647	0.2000	213823.147	0.9051
COLD1	0.159	0.008782	0.0148	3654820.531	0.0552
COLD2	0.159	0.008895	0.0148	4719114.485	0.0559
COLD3	0.406	0.008643	0.0148	4877527.959	0.8008

Table A3 Base-case cumulative fouling rate of exchangers in real crude oil preheat train ($m^2.^\circ C.\ kW^{-1}.month^{-1}$).

MONTH	QEX1	QEX2	QEX3	QEX4	QEX5	QEX6
0	0	0	0	0	0	0
1	0.614	1.235	0.056	0.271	0.059	0.004
2	1.204	2.465	0.115	0.633	0.134	0.011
3	1.775	3.691	0.176	1.073	0.223	0.02
4	2.332	4.915	0.238	1.578	0.326	0.034
5	2.876	6.136	0.3	2.138	0.441	0.052
6	3.409	7.356	0.364	2.742	0.568	0.074
7	3.934	8.574	0.428	3.385	0.705	0.1
8	4.451	9.792	0.492	4.058	0.852	0.131
9	4.961	11.008	0.556	4.756	1.006	0.165
10	5.465	12.224	0.62	5.476	1.168	0.204
11	5.964	13.439	0.684	6.212	1.336	0.245
12	6.458	14.653	0.747	6.961	1.51	0.29

Table A3 Base-case overall heat transfer coefficients of exchangers in real crude oil preheat train (KW.m^{-2}.°C^{-1}).

MONTH	QEX1	QEX2	QEX3	QEX4	QEX5	QEX6
0	0.418	0.49	0.377	0.37	0.327	0.37
1	0.333	0.305	0.369	0.336	0.321	0.369
2	0.278	0.222	0.361	0.3	0.313	0.368
3	0.24	0.175	0.354	0.265	0.305	0.367
4	0.212	0.144	0.346	0.233	0.296	0.365
5	0.19	0.122	0.339	0.206	0.286	0.363
6	0.172	0.106	0.332	0.184	0.276	0.36
7	0.158	0.094	0.325	0.164	0.266	0.356
8	0.146	0.085	0.318	0.148	0.256	0.352
9	0.136	0.077	0.312	0.134	0.246	0.348
10	0.127	0.07	0.306	0.122	0.237	0.344
11	0.12	0.065	0.3	0.112	0.228	0.339
12	0.113	0.06	0.294	0.103	0.219	0.334

Table A4 Retrofit case cumulative fouling rate of exchangers in real crude oil preheat train ($m^2.°C. kW^{-1}.month^{-1}$).

MONTH	EX1	EX2	EX3	EX4	EX5	EX6	EX7	EX8	EX9	EX10	EX11	EX12	EX13	EX14	EX15	EX16
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0.951	1.49	0.092	1.354	0.034	0.017	0.907	0.228	0.081	0.077	0.068	0.14	0.087	0	0	0
2	1.896	3.033	0.185	2.713	0.07	0.041	1.808	0.484	0.178	0.155	0.136	0.28	0.175	0	0	0
3	2.833	4.621	0.277	4.077	0.108	0.074	2.703	0.762	0.293	0.232	0.206	0.419	0.264	0	0	0
4	3.763	6.246	0.37	5.446	0.149	0.116	3.592	1.058	0.424	0.31	0.275	0.559	0.353	0	0	0
5	4.686	7.901	0.464	6.819	0.192	0.169	4.475	1.367	0.571	0.387	0.345	0.699	0.443	0	0	0
6	5.601	9.58	0.557	8.196	0.237	0.231	5.351	1.687	0.733	0.465	0.415	0.839	0.534	0	0	0
7	6.509	11.277	0.651	9.575	0.286	0.304	6.222	2.014	0.909	0.542	0.486	0.979	0.625	0	0	0
8	7.409	12.989	0.745	10.958	0.337	0.387	7.085	2.347	1.099	0.619	0.557	1.118	0.716	0	0	0
9	8.301	14.712	0.84	12.343	0.391	0.479	7.943	2.685	1.3	0.697	0.629	1.258	0.808	0	0	0
10	9.186	16.442	0.934	13.73	0.448	0.579	8.794	3.026	1.512	0.774	0.7	1.398	0.9	0	0	0
11	10.063	18.184	1.029	15.119	0.509	0.689	9.638	3.379	1.736	0.851	0.774	1.538	0.993	0	0	0
12	10.932	19.936	1.124	16.509	0.573	0.806	10.476	3.743	1.97	0.928	0.848	1.678	1.085	0	0	0

Table A5 Retrofit case overall heat transfer coefficients of exchangers in real crude oil preheat train ($KW.m^{-2}.^{\circ}C^{-1}$).

MONTH	EX1	EX2	EX3	EX4	EX5	EX6	EX7	EX8	EX9	EX10	EX11	EX12	EX13	EX14	EX15	EX16
0	0.418	0.49	0.377	0.37	0.327	0.37	0.49	0.49	0.418	0.966	0.374	0.373	0.377	0.327	0.376	0.36
1	0.299	0.283	0.364	0.246	0.324	0.367	0.339	0.441	0.405	0.899	0.365	0.356	0.365	0.327	0.376	0.36
2	0.233	0.197	0.352	0.185	0.32	0.364	0.26	0.396	0.389	0.84	0.356	0.341	0.354	0.327	0.376	0.36
3	0.191	0.15	0.341	0.147	0.316	0.36	0.211	0.357	0.373	0.789	0.348	0.327	0.343	0.327	0.376	0.36
4	0.163	0.121	0.331	0.123	0.312	0.354	0.177	0.323	0.355	0.744	0.339	0.314	0.333	0.327	0.376	0.36
5	0.141	0.101	0.321	0.105	0.308	0.348	0.153	0.293	0.338	0.703	0.332	0.301	0.323	0.327	0.376	0.36
6	0.125	0.086	0.312	0.092	0.304	0.34	0.135	0.268	0.32	0.667	0.324	0.29	0.314	0.327	0.376	0.36
7	0.112	0.075	0.303	0.081	0.299	0.332	0.121	0.247	0.303	0.634	0.317	0.279	0.305	0.327	0.376	0.36
8	0.102	0.067	0.294	0.073	0.295	0.323	0.11	0.228	0.287	0.604	0.31	0.269	0.297	0.327	0.376	0.36
9	0.094	0.06	0.286	0.066	0.29	0.314	0.1	0.212	0.271	0.577	0.303	0.26	0.289	0.327	0.376	0.36
10	0.086	0.054	0.279	0.061	0.285	0.304	0.092	0.197	0.256	0.553	0.297	0.252	0.281	0.327	0.376	0.36
11	0.08	0.049	0.272	0.056	0.28	0.295	0.086	0.184	0.242	0.53	0.29	0.243	0.274	0.327	0.376	0.36
12	0.075	0.046	0.265	0.052	0.275	0.285	0.08	0.173	0.229	0.509	0.284	0.236	0.268	0.327	0.376	0.36

Table A6 Alternative retrofit case cumulative fouling rate of exchangers in real crude oil preheat train ($m^2.^{\circ}C.\ kW^{-1}.month^{-1}$).

MOUNT	QEX1	QEX2	QEX3	QEX4	QEX5	QEX6	QEX7
0	0	0	0	0	0	0	0
1	0.726	1.235	0.052	0.234	0.016	0.00E+00	0.067
2	1.432	2.465	0.106	0.549	0.037	0.00E+00	0.136
3	2.119	3.691	0.162	0.936	0.062	3.88E-05	0.208
4	2.79	4.915	0.22	1.387	0.092	1.51E-04	0.282
5	3.445	6.136	0.279	1.896	0.128	3.78E-04	0.359
6	4.088	7.356	0.34	2.454	0.17	7.76E-04	0.439
7	4.718	8.574	0.403	3.058	0.218	1.00E-03	0.521
8	5.337	9.792	0.466	3.701	0.272	2.00E-03	0.604
9	5.947	11.008	0.531	4.376	0.333	4.00E-03	0.69
10	6.548	12.224	0.596	5.077	0.398	6.00E-03	0.775
11	7.141	13.439	0.661	5.797	0.468	8.00E-03	0.862
12	7.726	14.653	0.726	6.534	0.543	0.01	0.948

Table A7 Alternative retrofit case overall heat transfer coefficients of exchangers in real crude oil preheat train (KW.m^{-2}.°C^{-1}).

MOUNT	QEX1	QEX2	QEX3	QEX4	QEX5	QEX6	QEX7
0	0.418	0.49	0.377	0.37	0.327	0.37	0.49
1	0.321	0.305	0.37	0.34	0.325	0.37	0.364
2	0.262	0.222	0.363	0.307	0.323	0.37	0.355
3	0.222	0.175	0.355	0.275	0.321	0.37	0.346
4	0.193	0.144	0.348	0.244	0.318	0.37	0.338
5	0.171	0.122	0.341	0.217	0.314	0.37	0.329
6	0.154	0.106	0.334	0.194	0.31	0.369	0.321
7	0.141	0.094	0.327	0.174	0.305	0.369	0.312
8	0.129	0.085	0.321	0.156	0.3	0.369	0.304
9	0.12	0.077	0.314	0.141	0.295	0.369	0.297
10	0.112	0.07	0.308	0.128	0.289	0.369	0.289
11	0.105	0.065	0.302	0.118	0.284	0.369	0.282
12	0.099	0.06	0.296	0.108	0.278	0.368	0.276

Appendix B Multi-Period HENs.

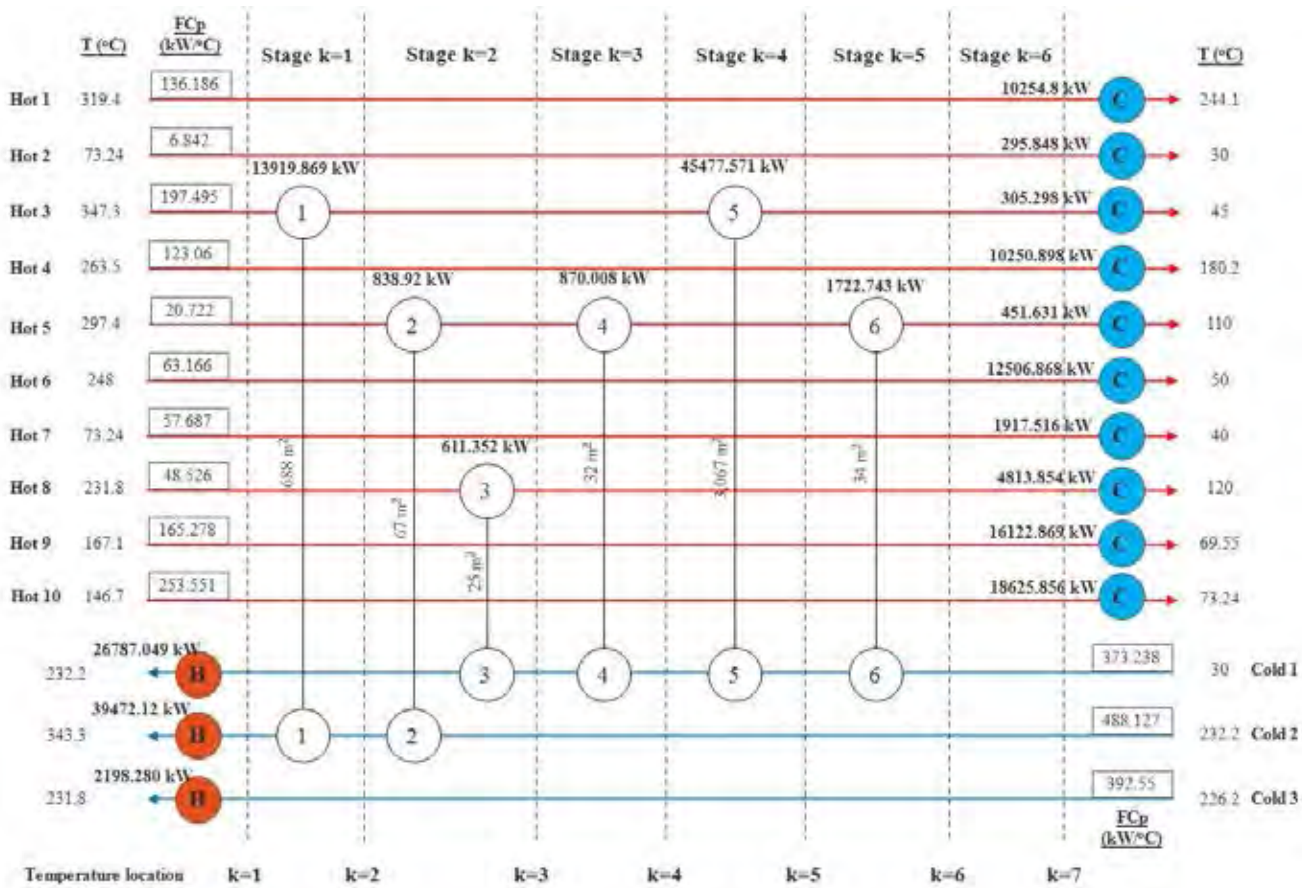

Figure B1 Base-case HEN at month 1 of real crude oil preheat train.

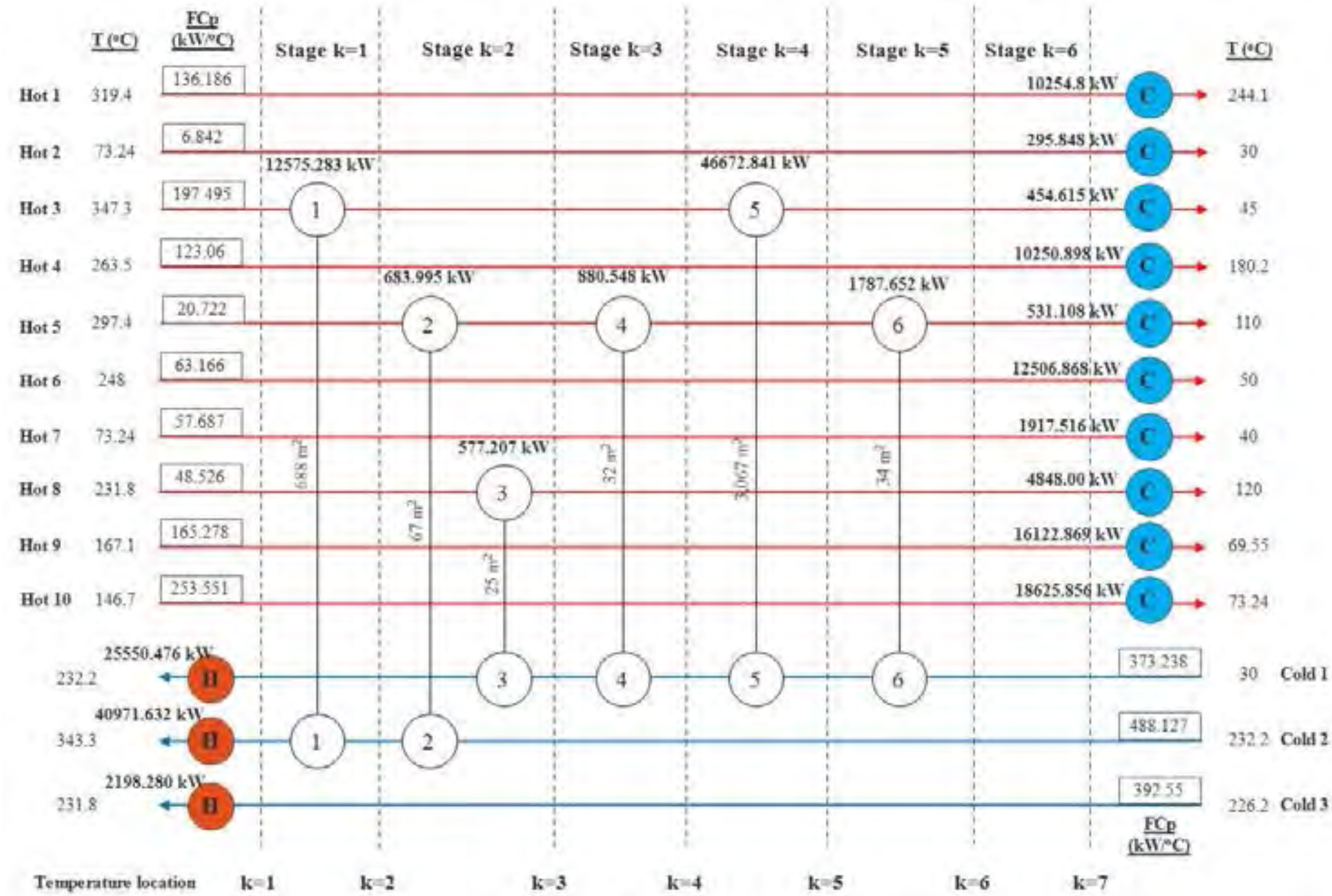

Figure B2 Base-case HEN at month 2 of real crude oil preheat train.

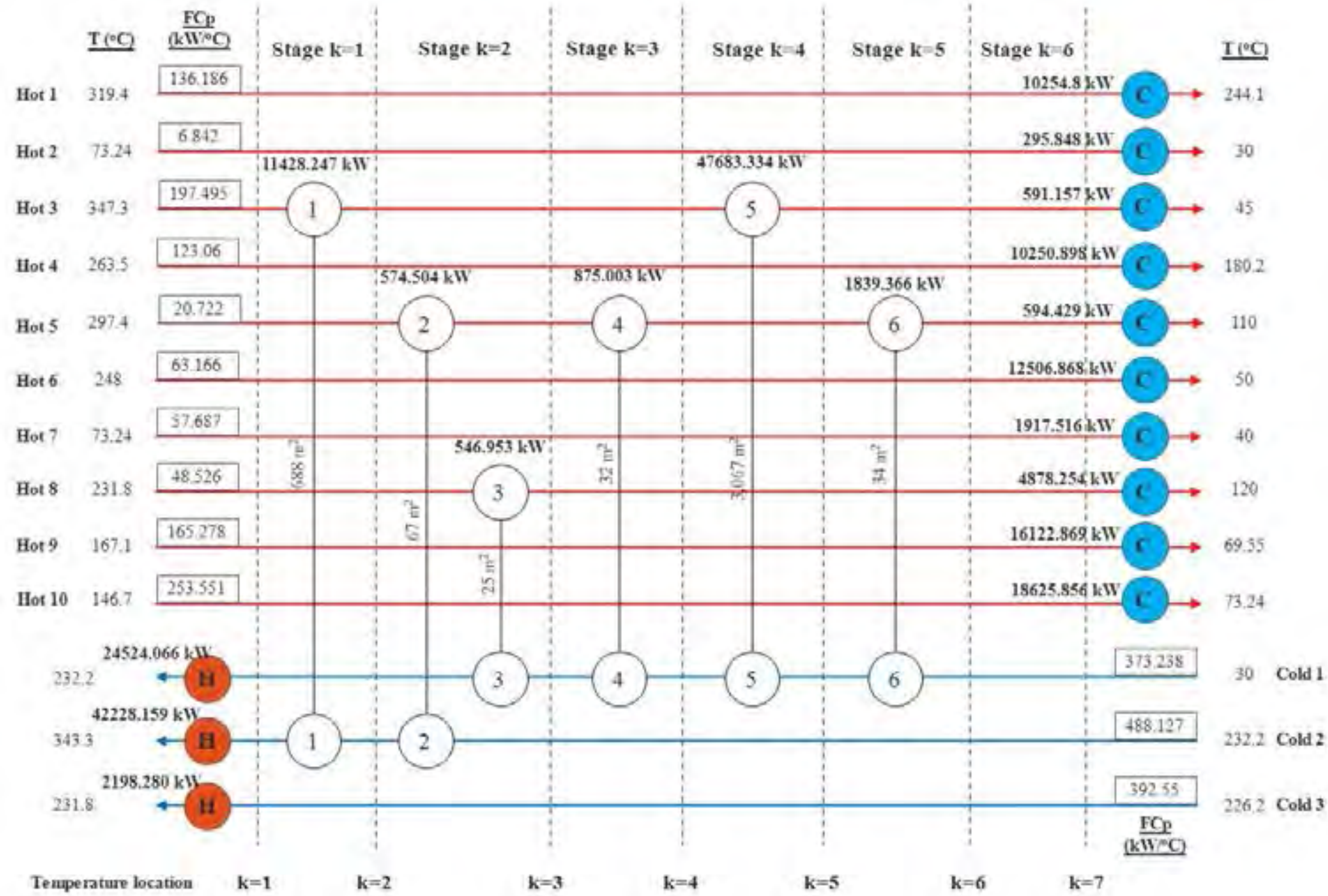

Figure B3 Base-case HEN at month 3 of real crude oil preheat train.

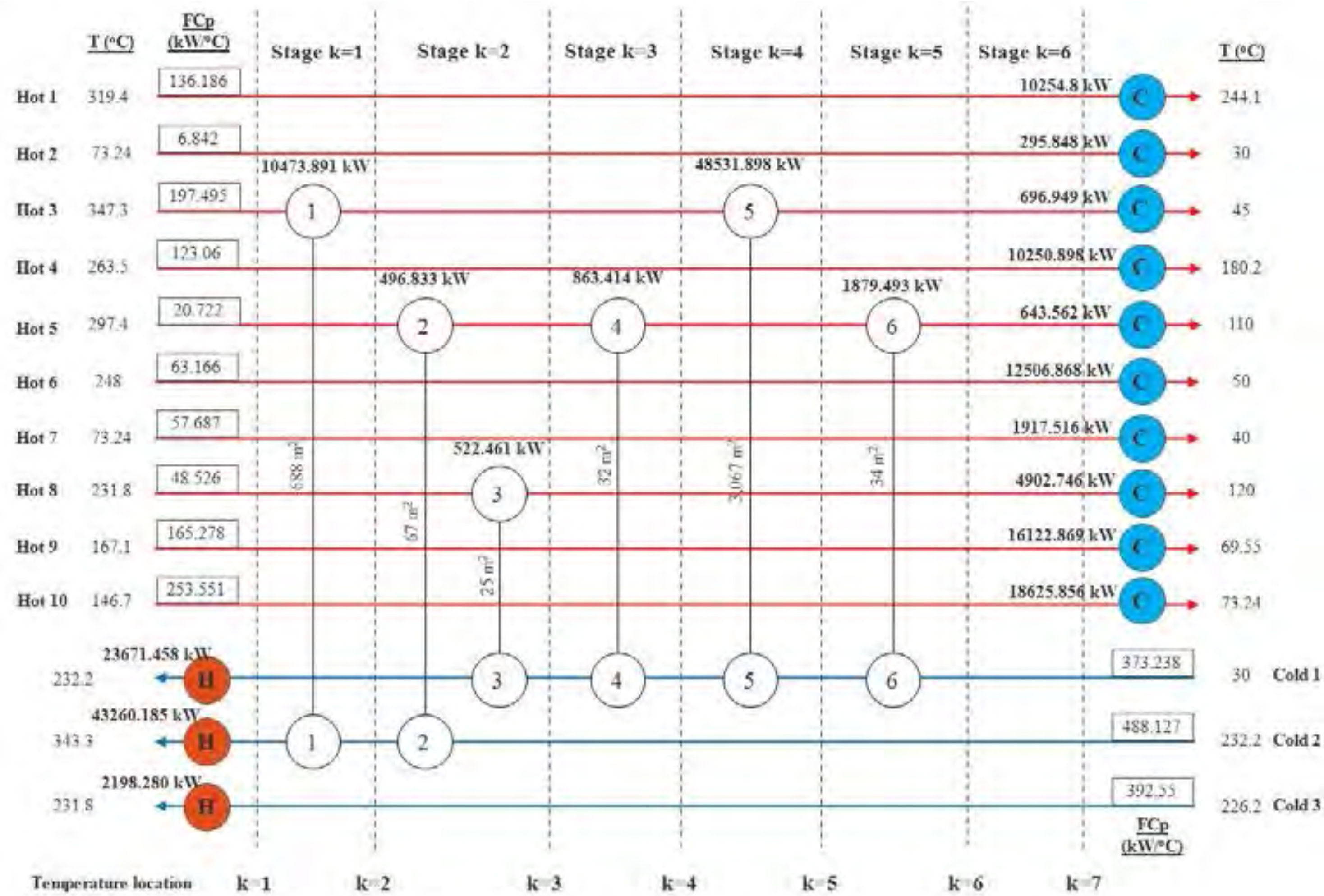

Figure B4 Base-case HEN at month 4 of real crude oil preheat train.

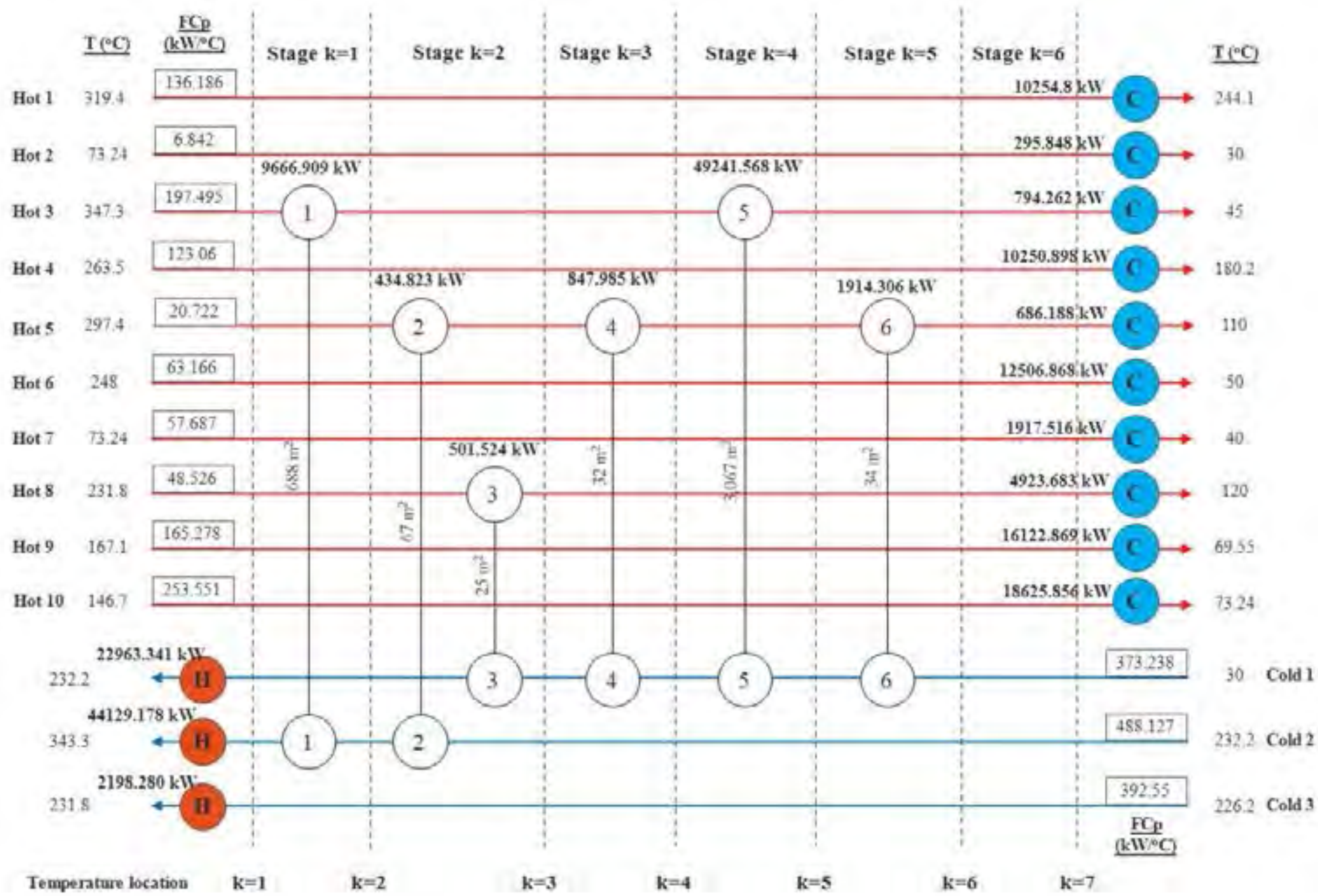

Figure B5 Base-case HEN at month 5 of real crude oil preheat train.

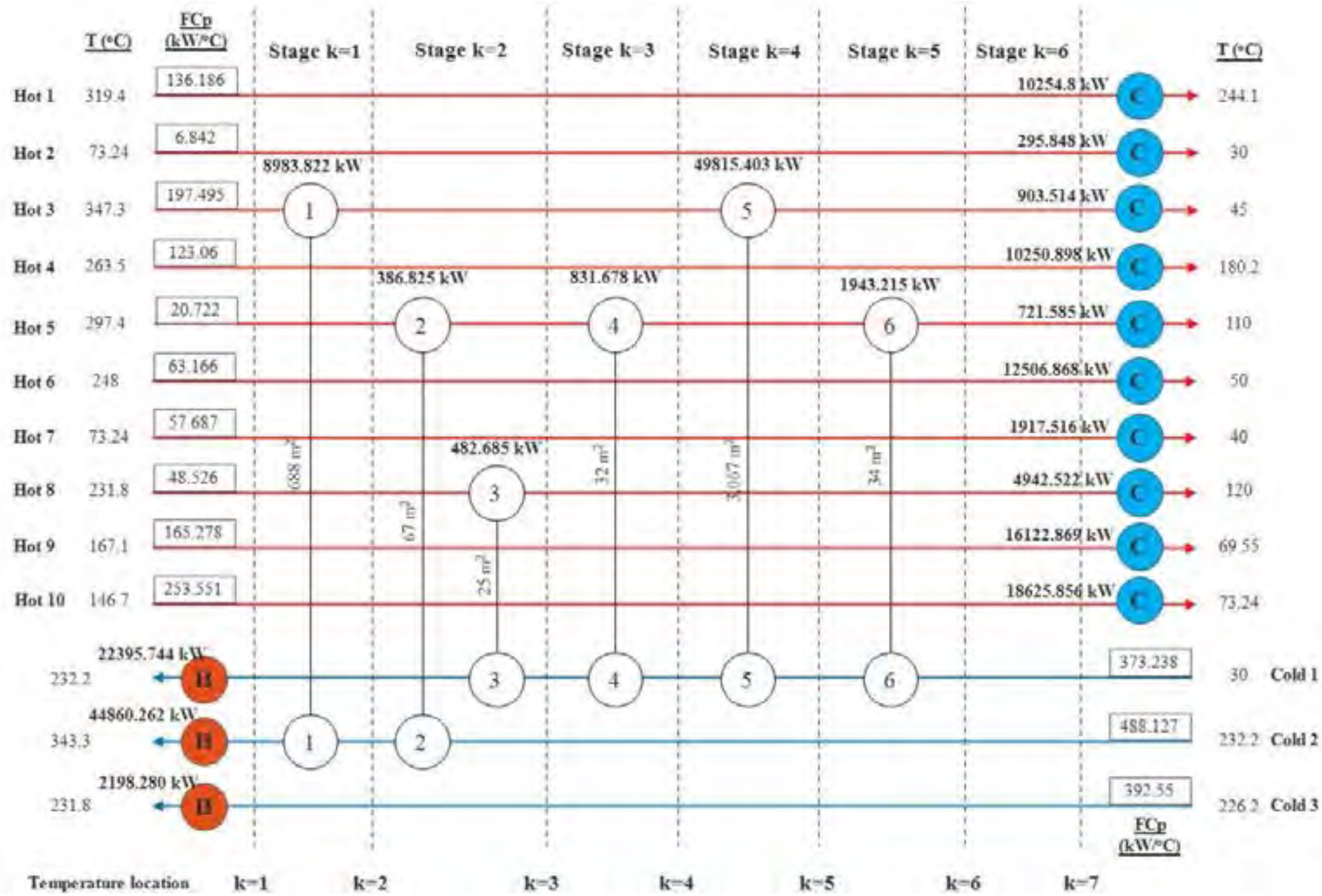

Figure B6 Base-case HEN at month 6 of real crude oil preheat train.

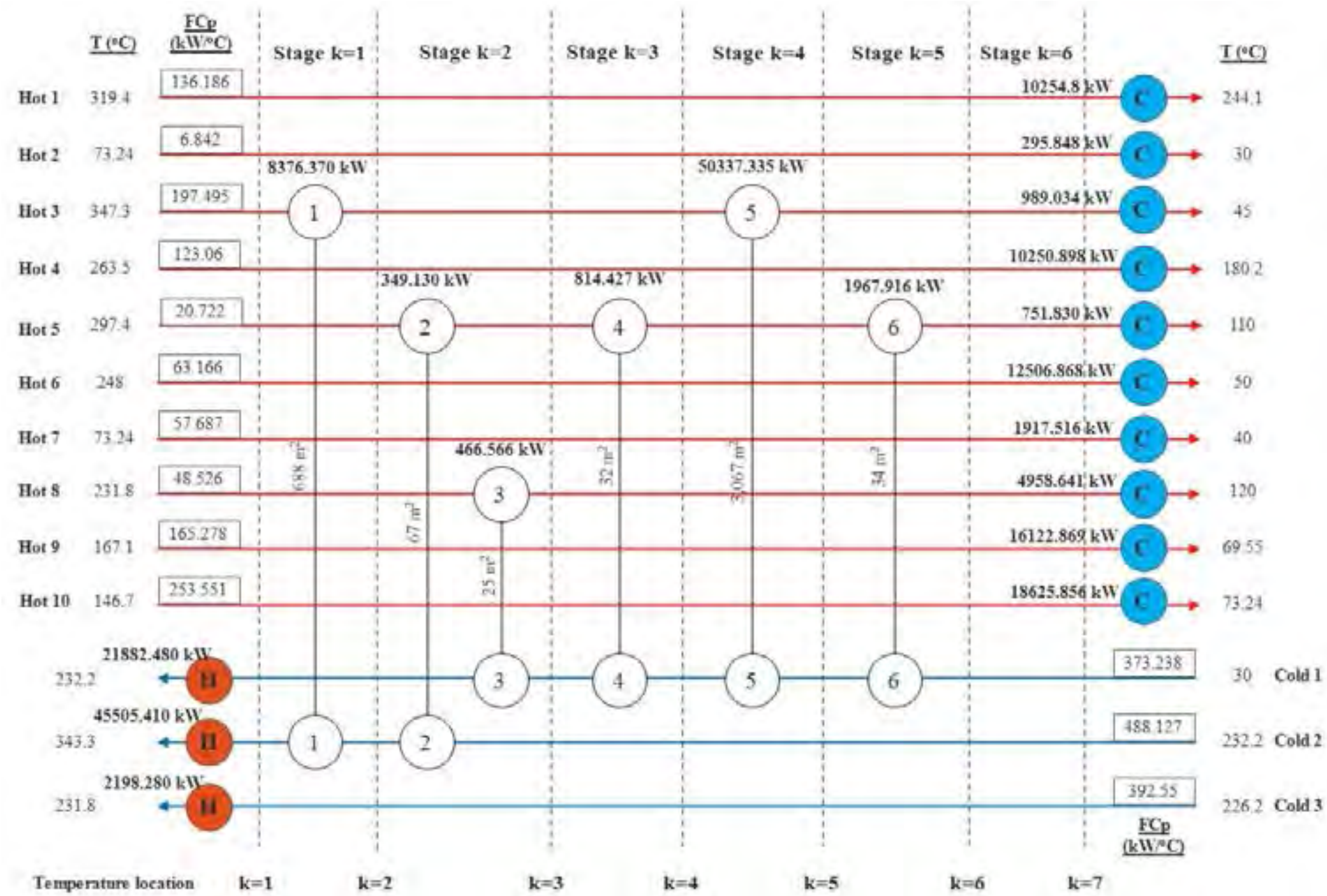

Figure B7 Base-case HEN at month 7 of real crude oil preheat train.

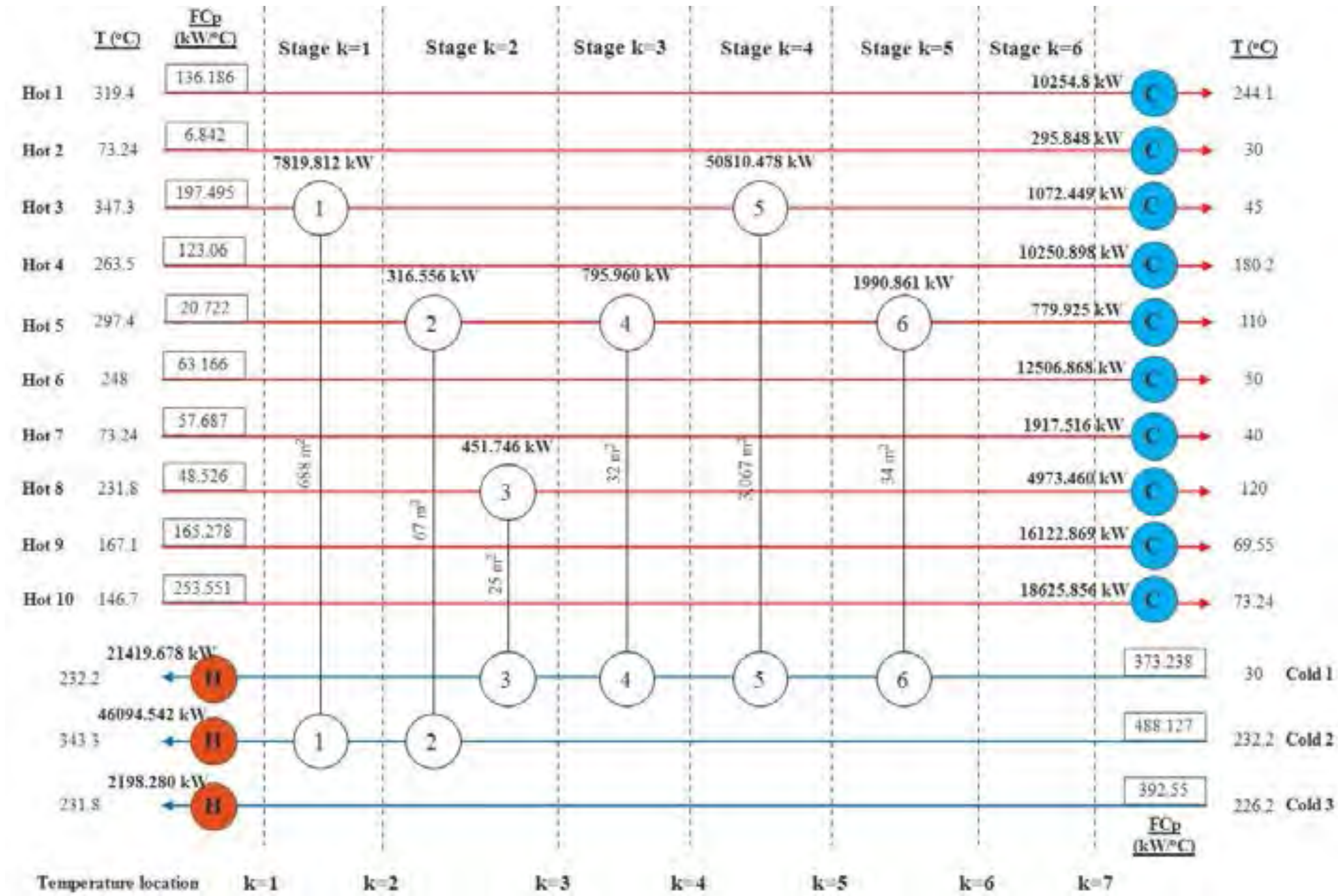

Figure B8 Base-case HEN at month 8 of real crude oil preheat train.

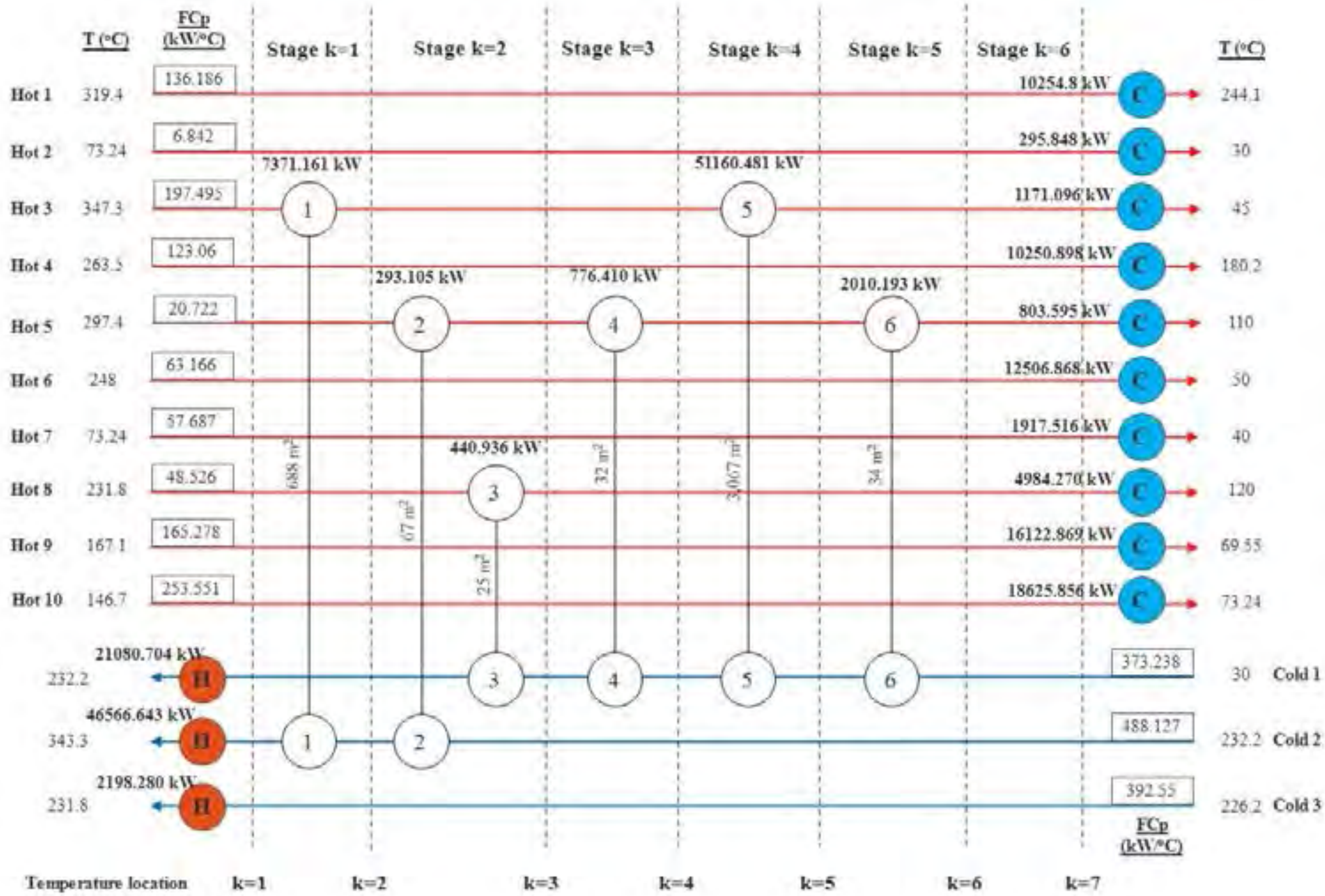

Figure B9 Base-case HEN at month 9 of real crude oil preheat train.

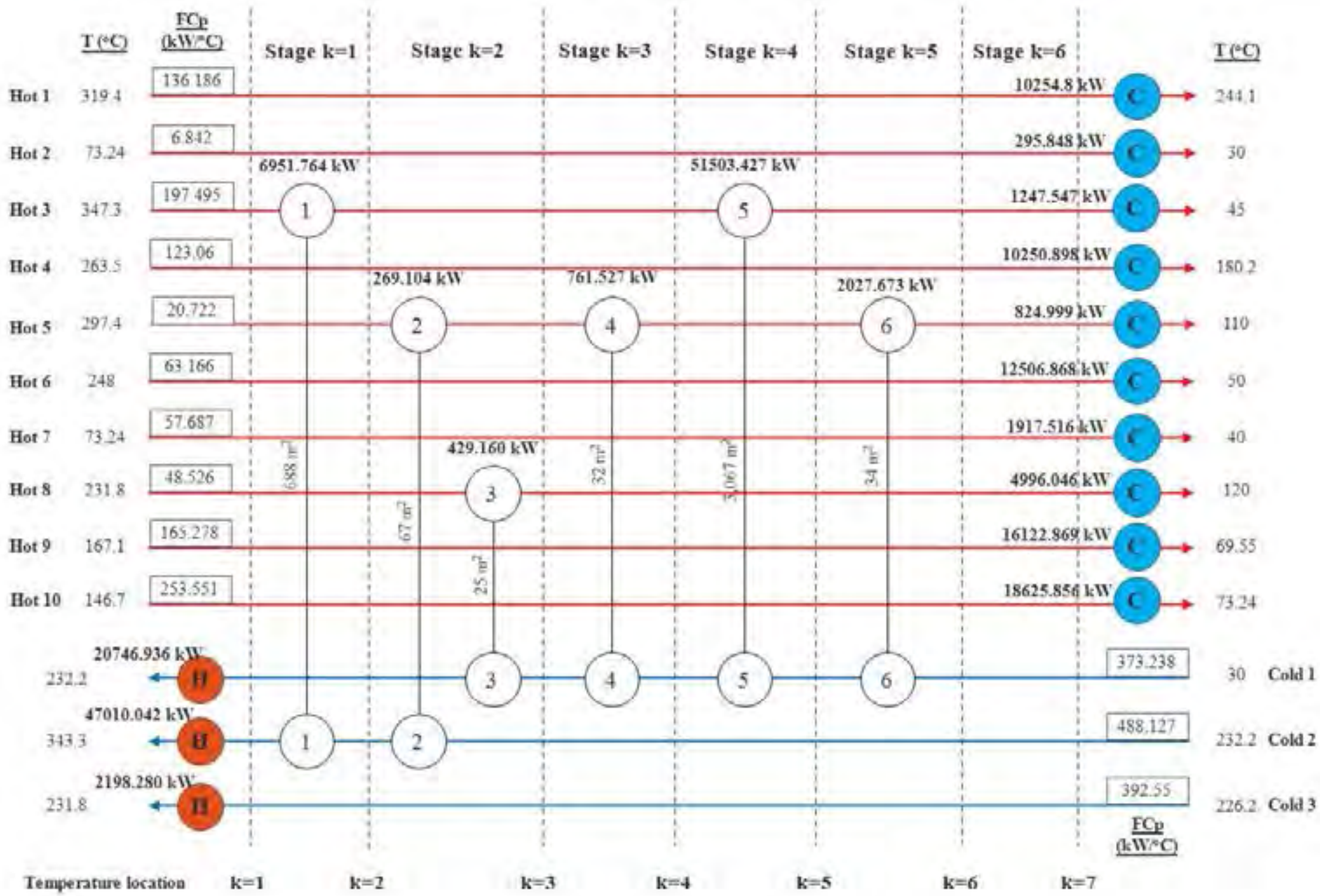

Figure B10 Base-case HEN at month 10 of real crude oil preheat train.

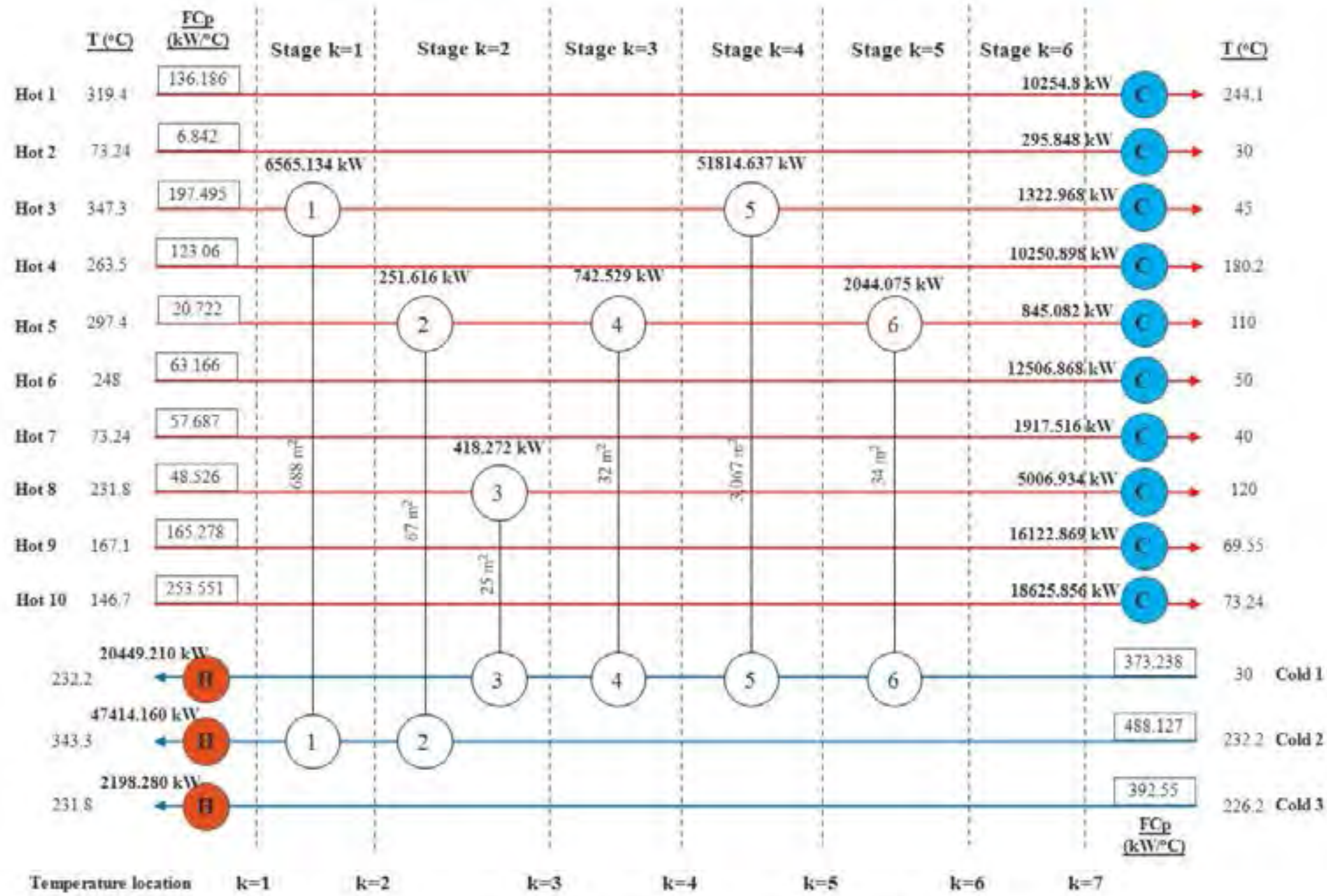

Figure B11 Base-case HEN at month 11 of real crude oil preheat train.

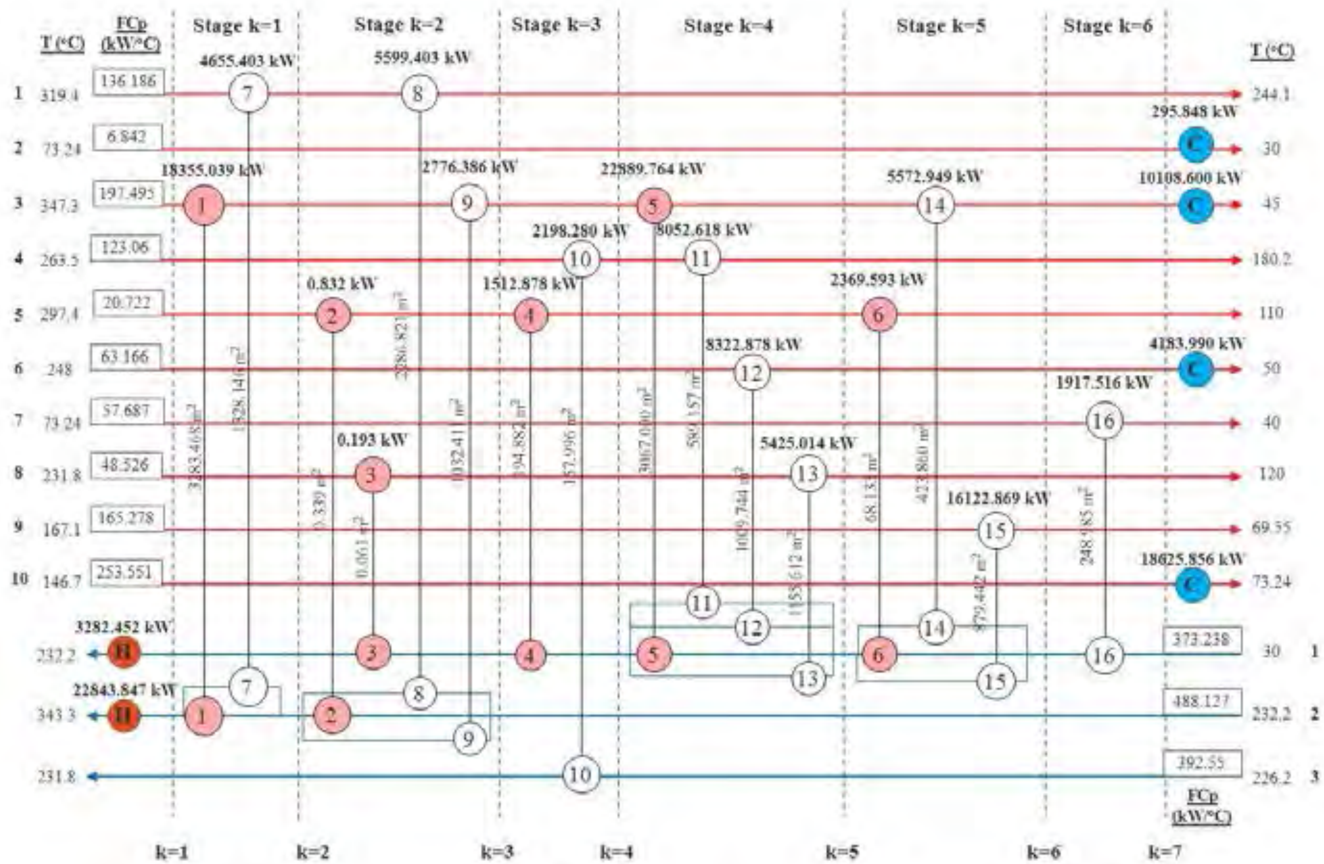

Figure B12 Retrofit case 1 HEN at month 1 of real crude oil preheat train.

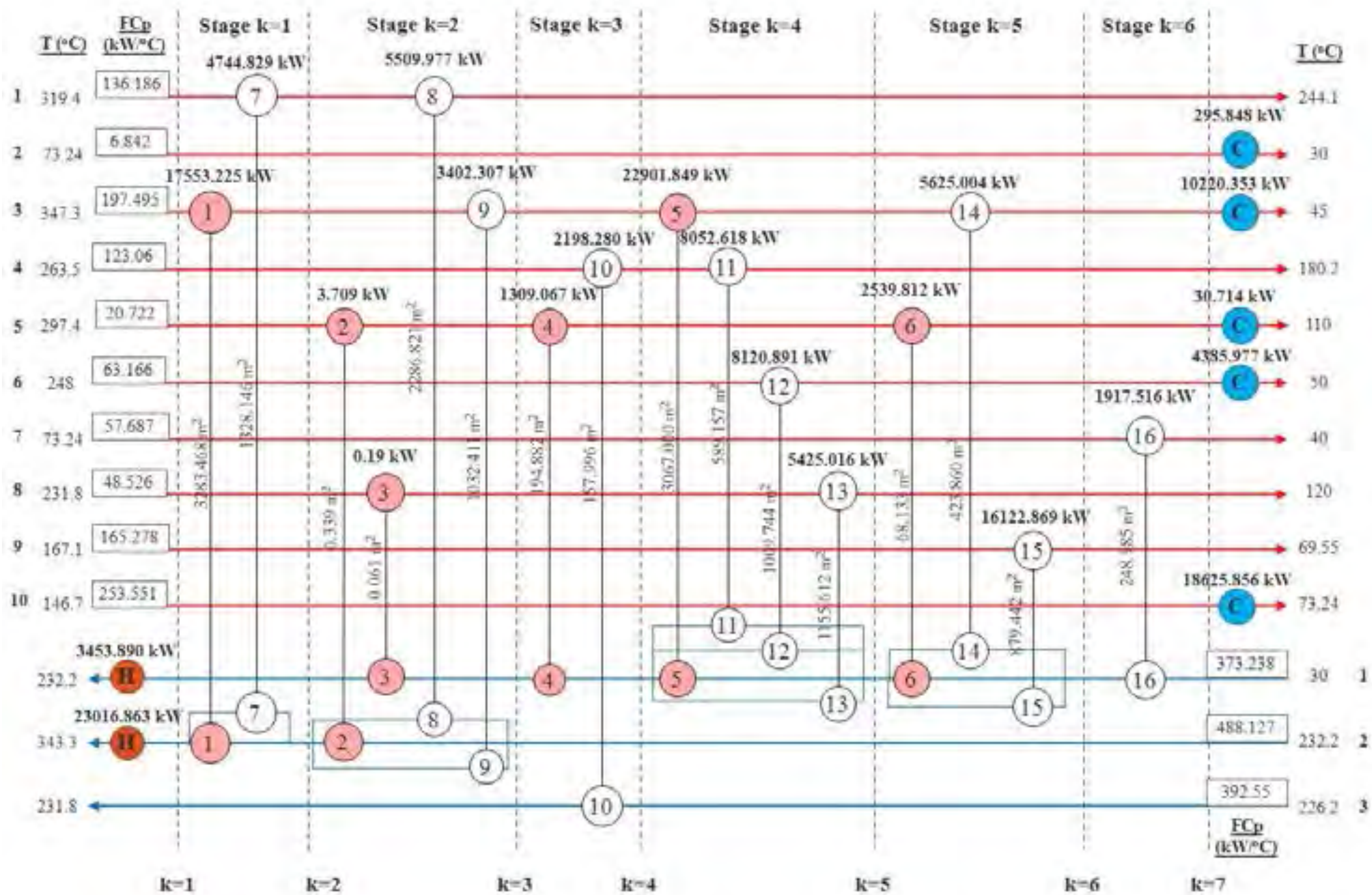

Figure B13 Retrofit case 1 HEN at month 2 of real crude oil preheat train.

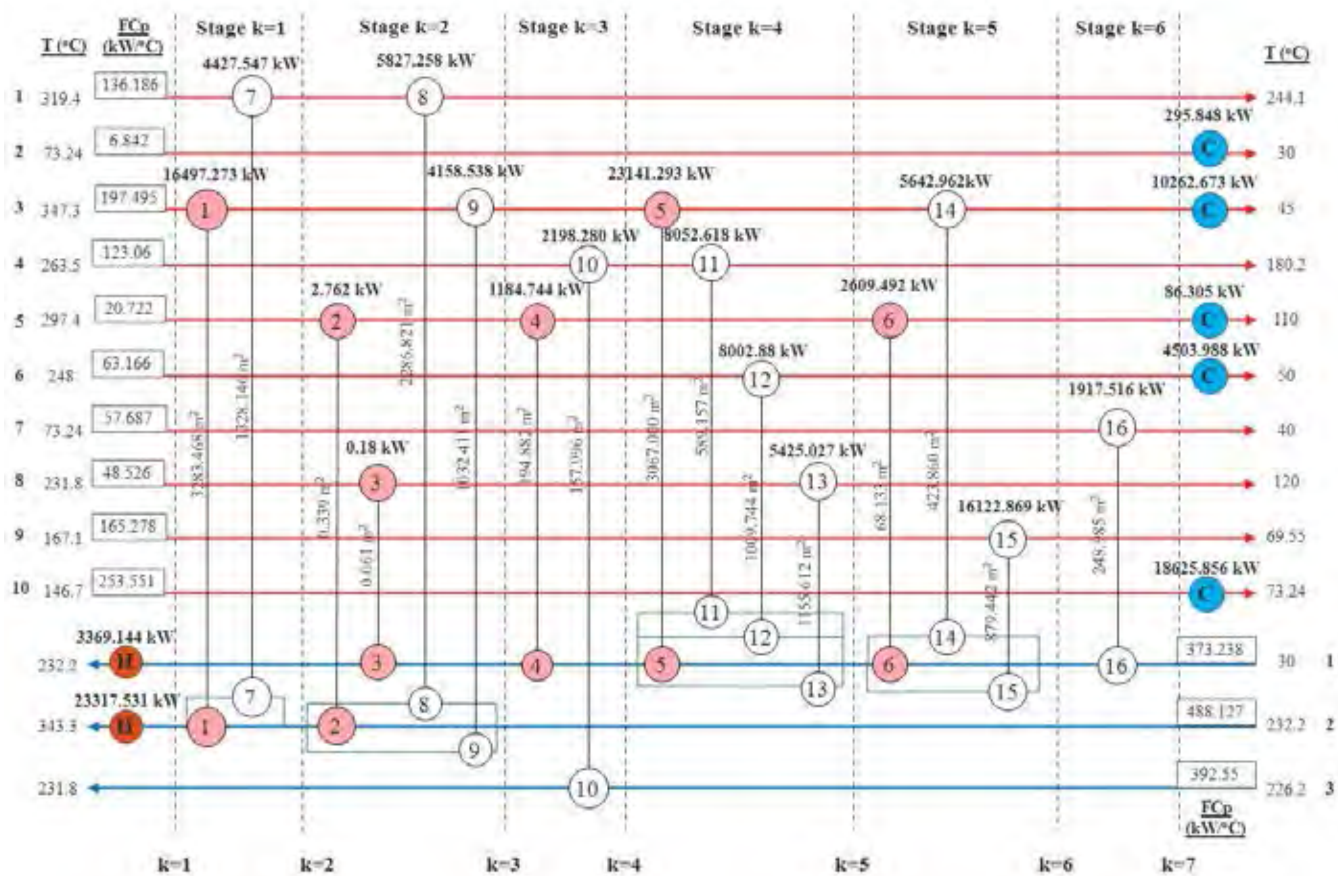

Figure B14 Retrofit case 1 HEN at month 3 of real crude oil preheat train.

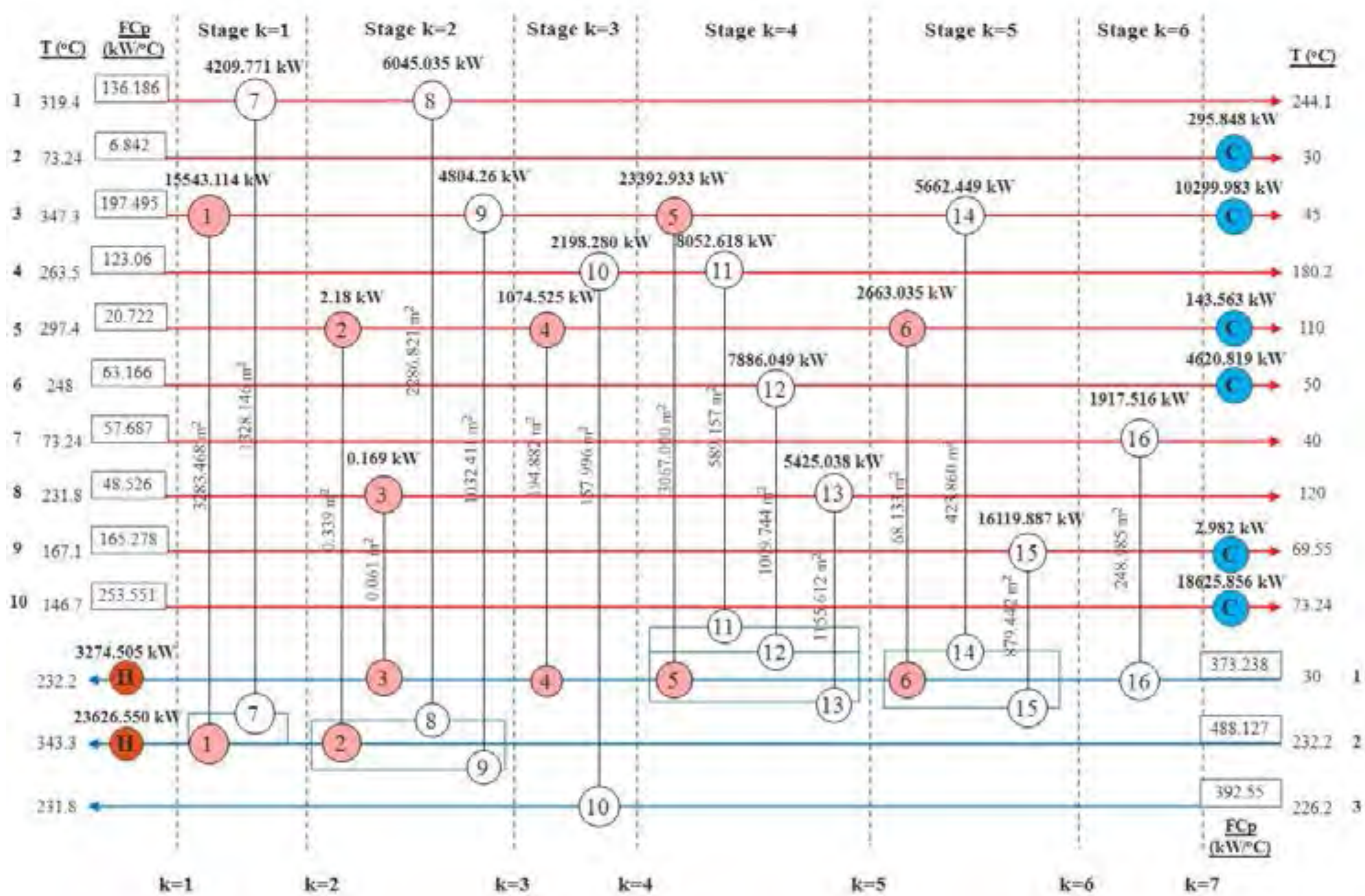

Figure B15 Retrofit case 1 HEN at month 4 of real crude oil preheat train.

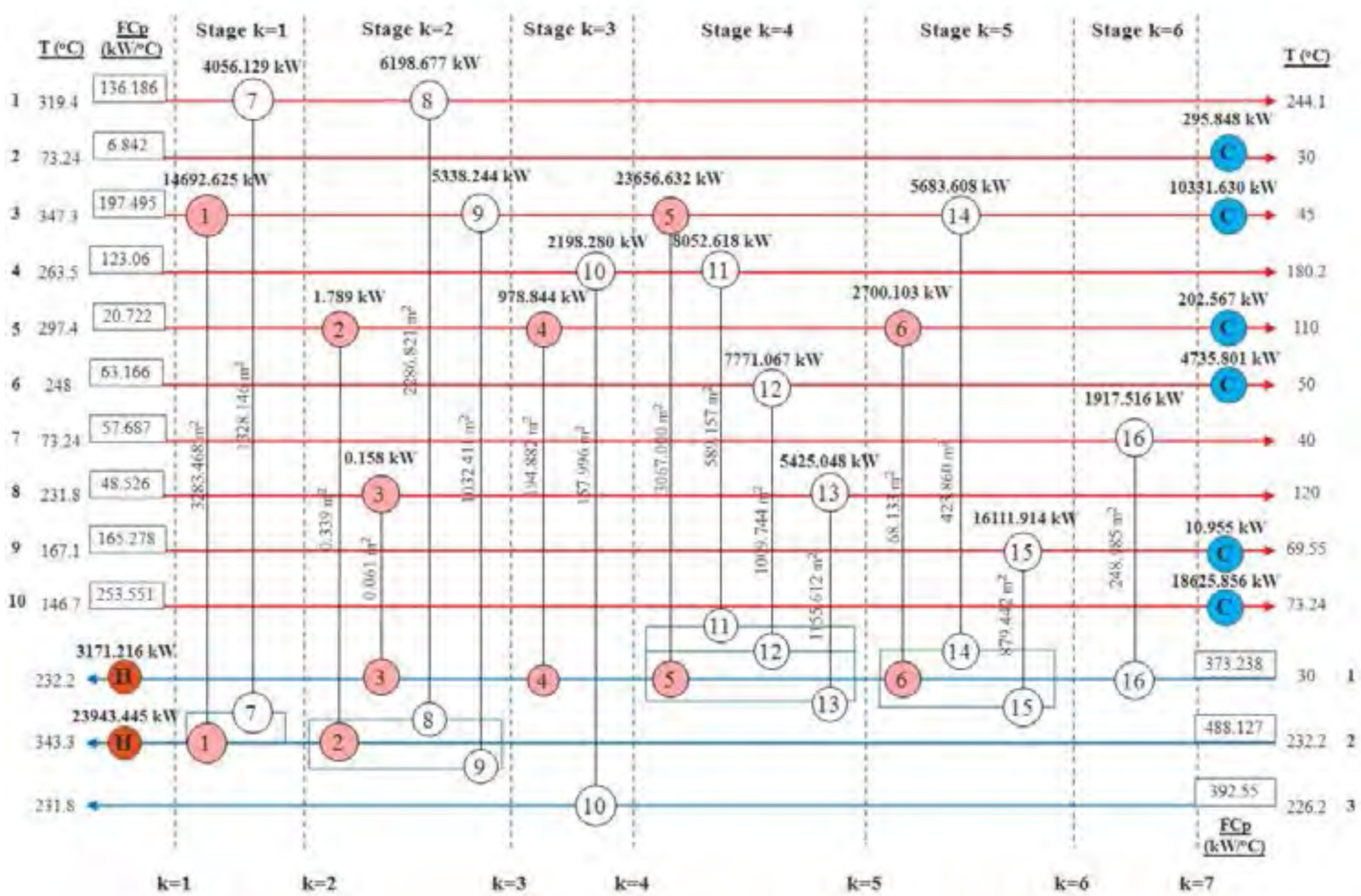

Figure B16 Retrofit case 1 HEN at month 5 of real crude oil preheat train.

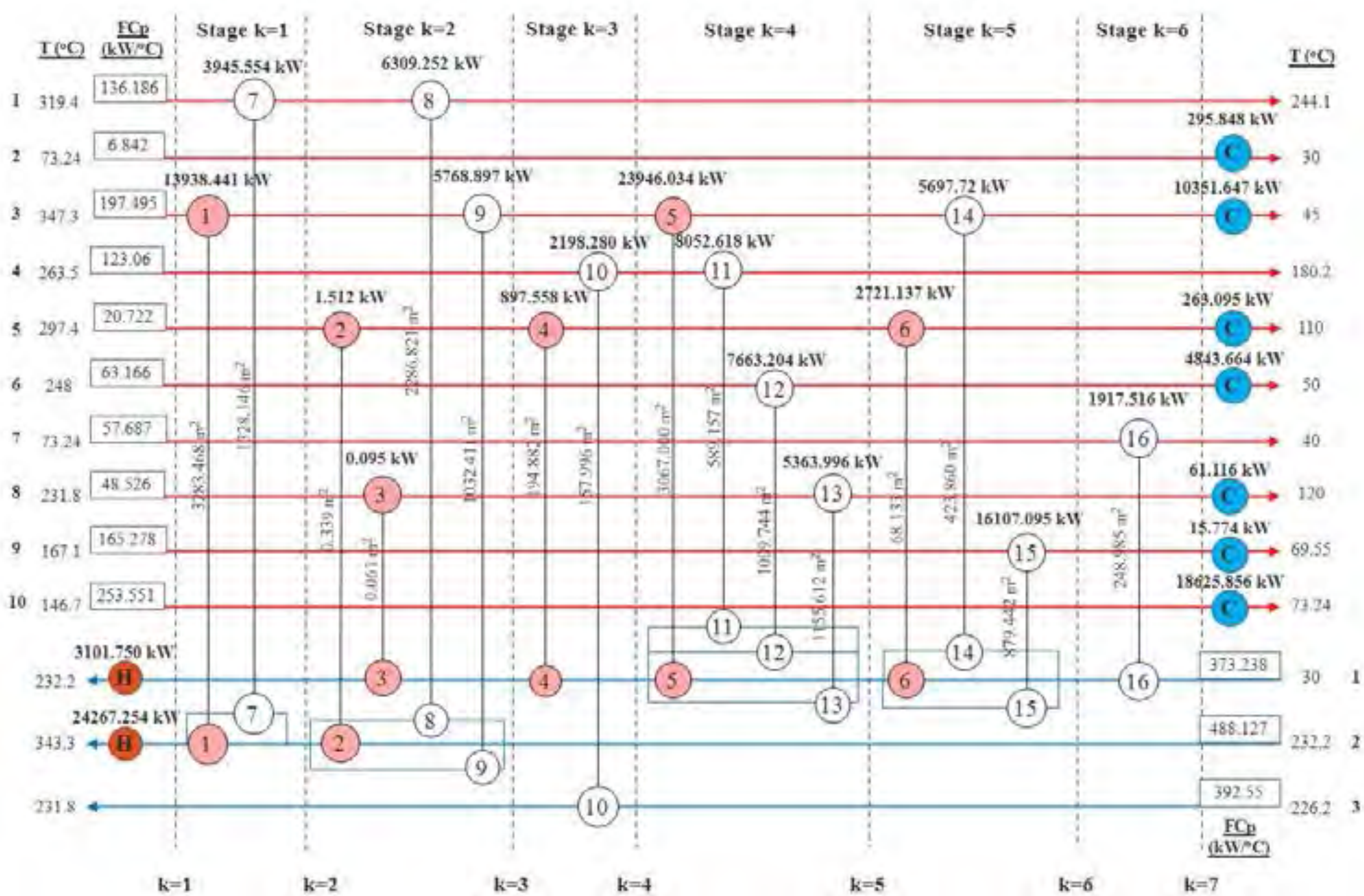

Figure B17 Retrofit case 1 HEN at month 6 of real crude oil preheat train.

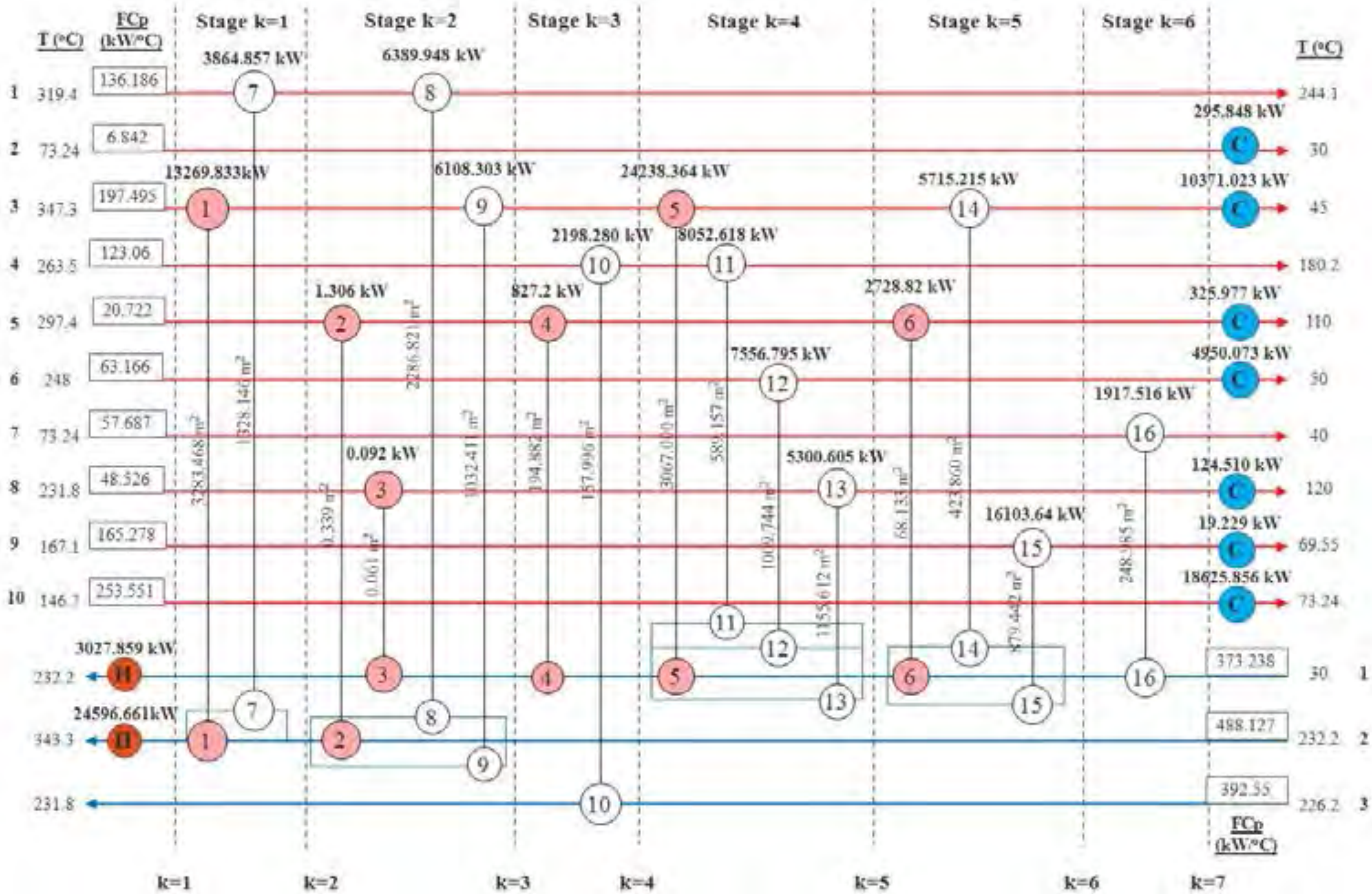

Figure B18 Retrofit case 1 HEN at month 7 of real crude oil preheat train.

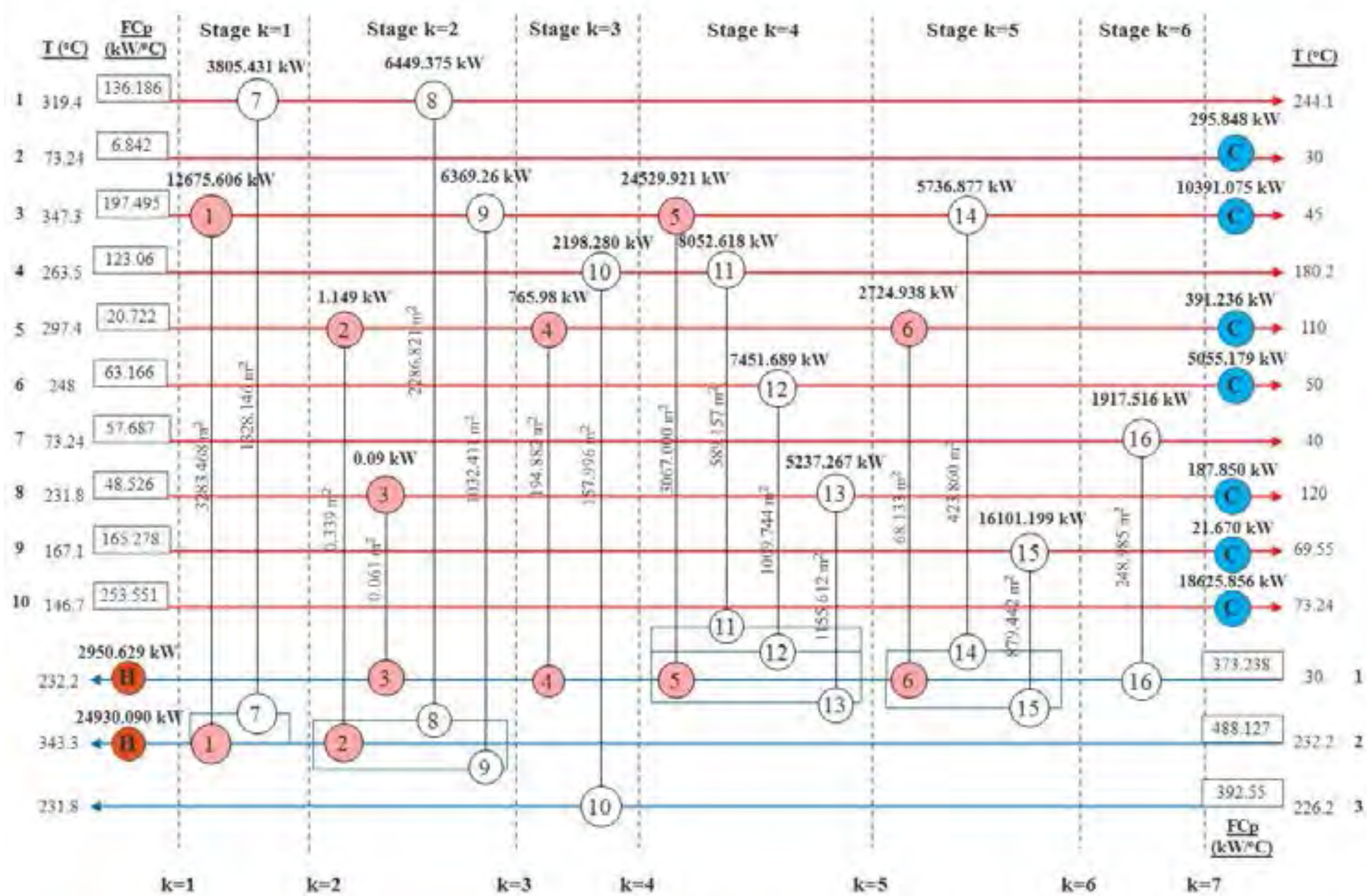

Figure B19 Retrofit case 1 HEN at month 8 of real crude oil preheat train.

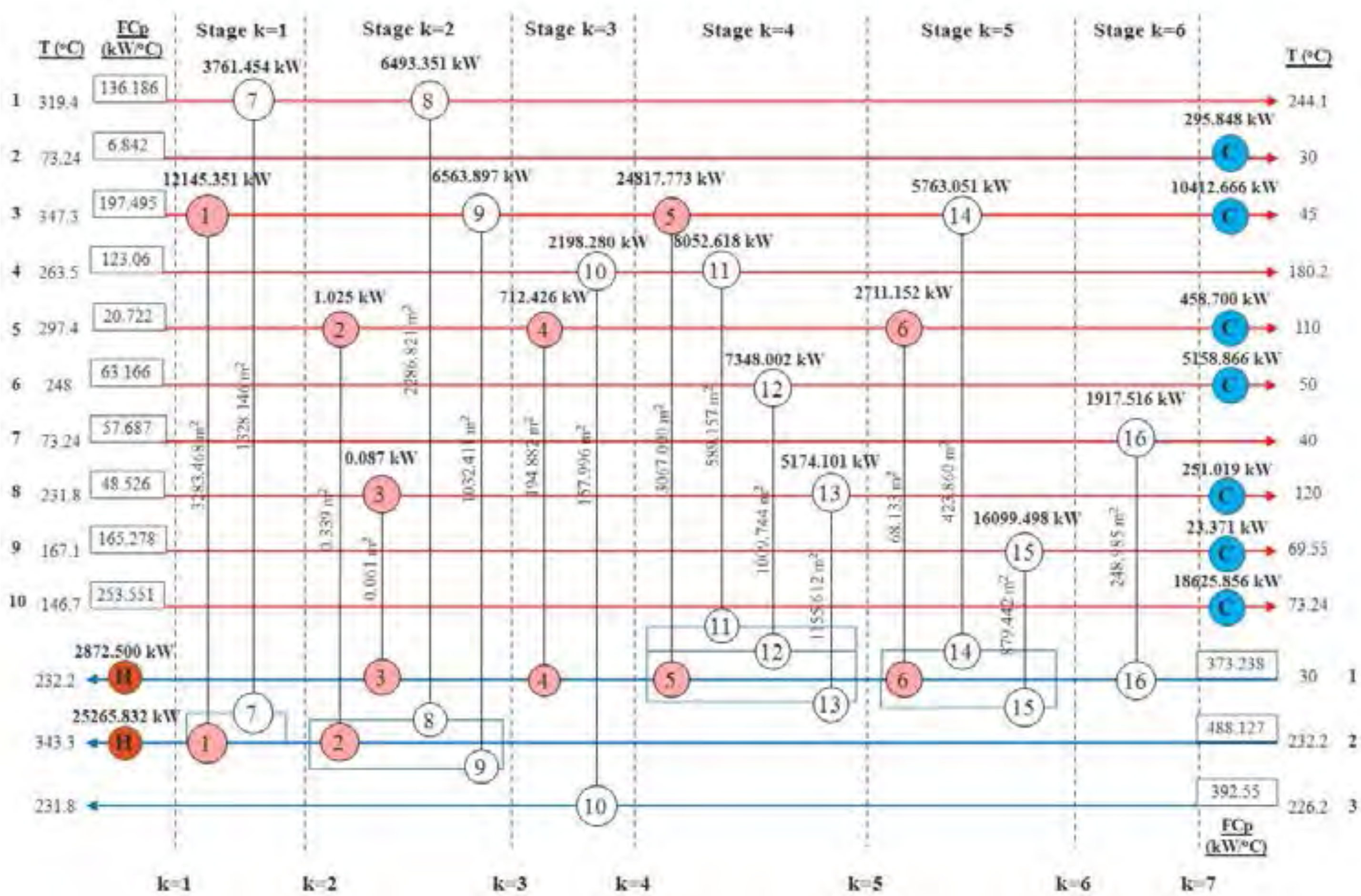

Figure B20 Retrofit case 1 HEN at month 9 of real crude oil preheat train.

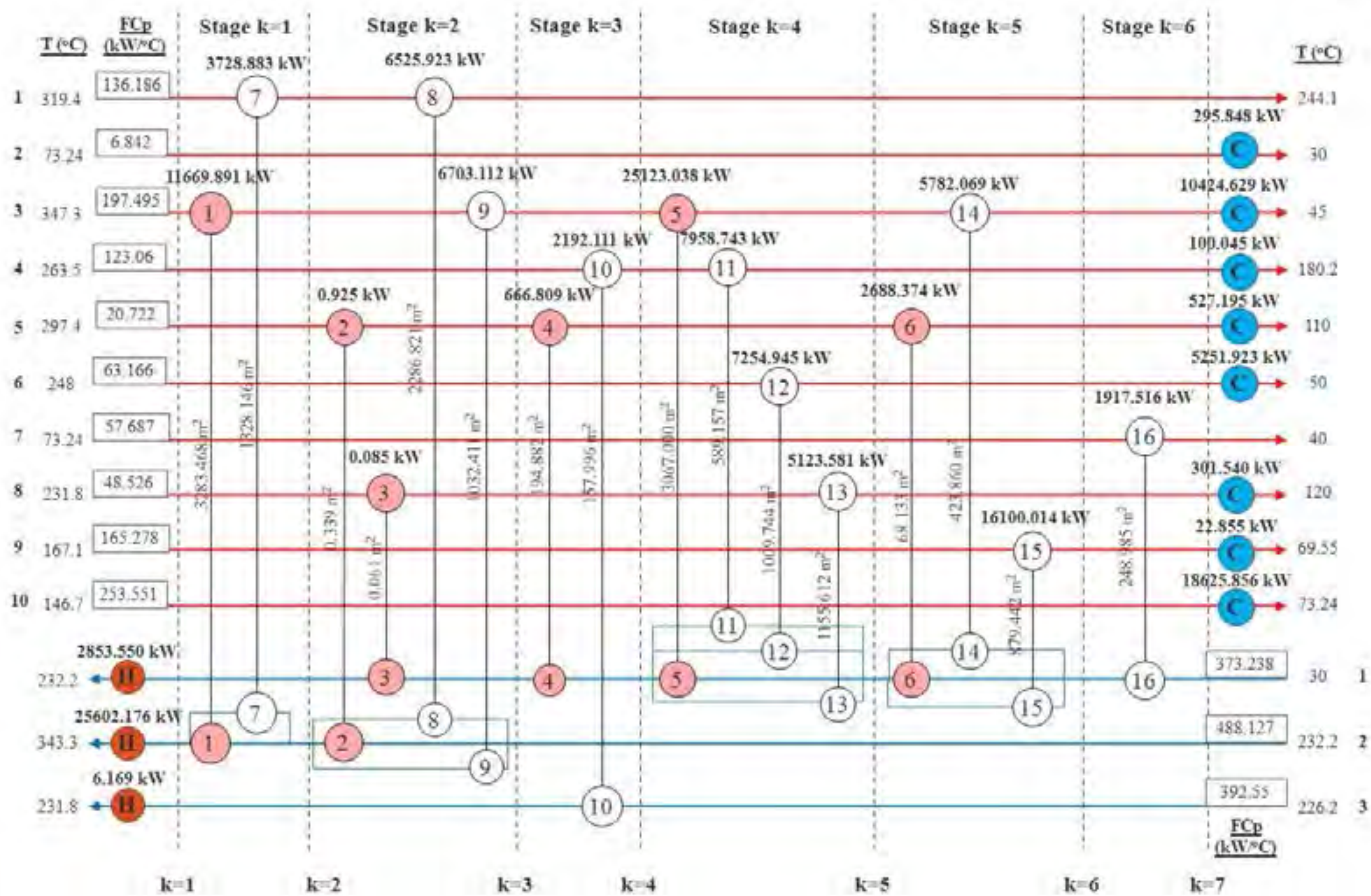

Figure B21 Retrofit case 1 HEN at month 10 of real crude oil preheat train.

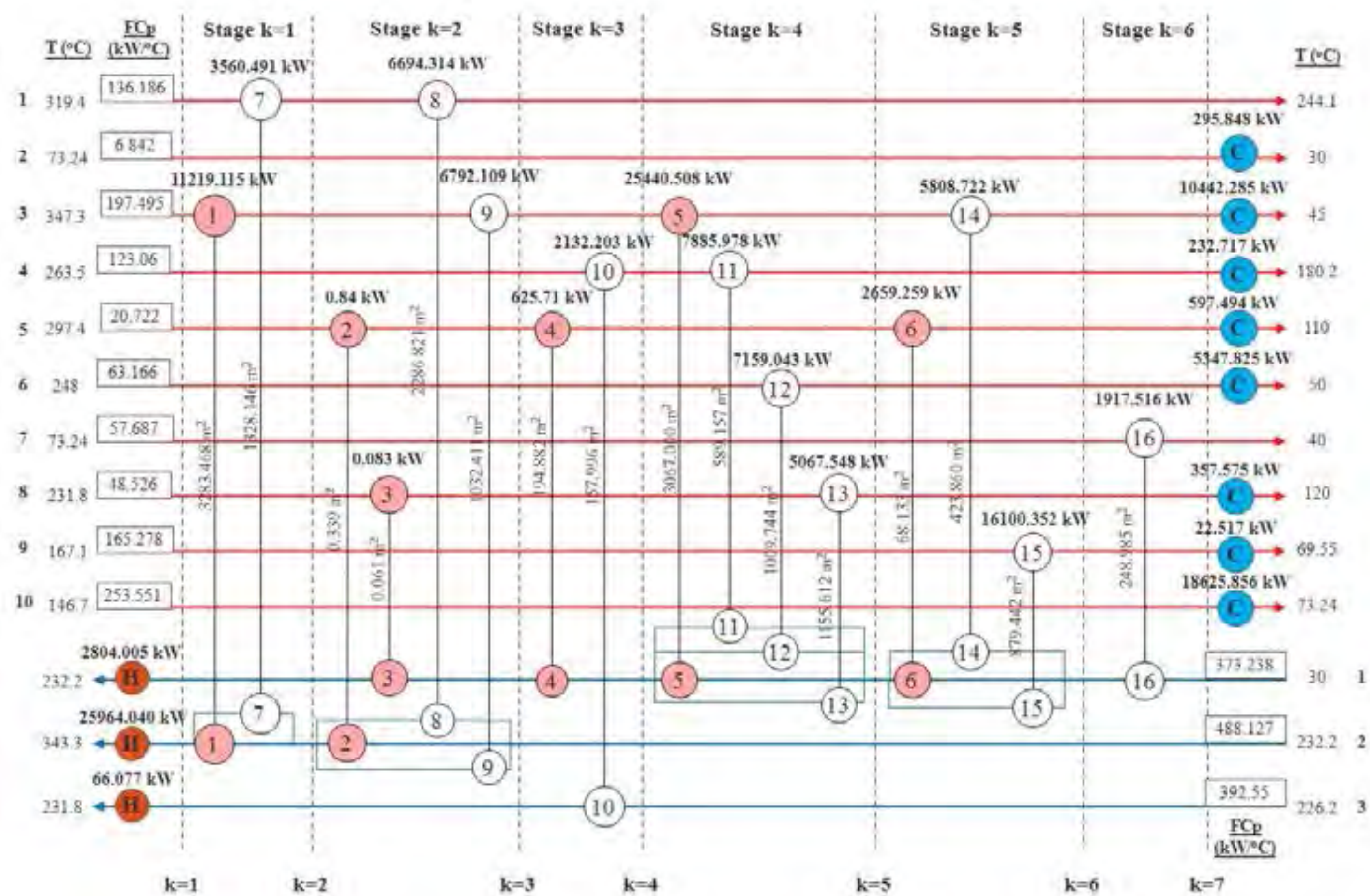

Figure B22 Retrofit case 1 HEN at month 11 of real crude oil preheat train.

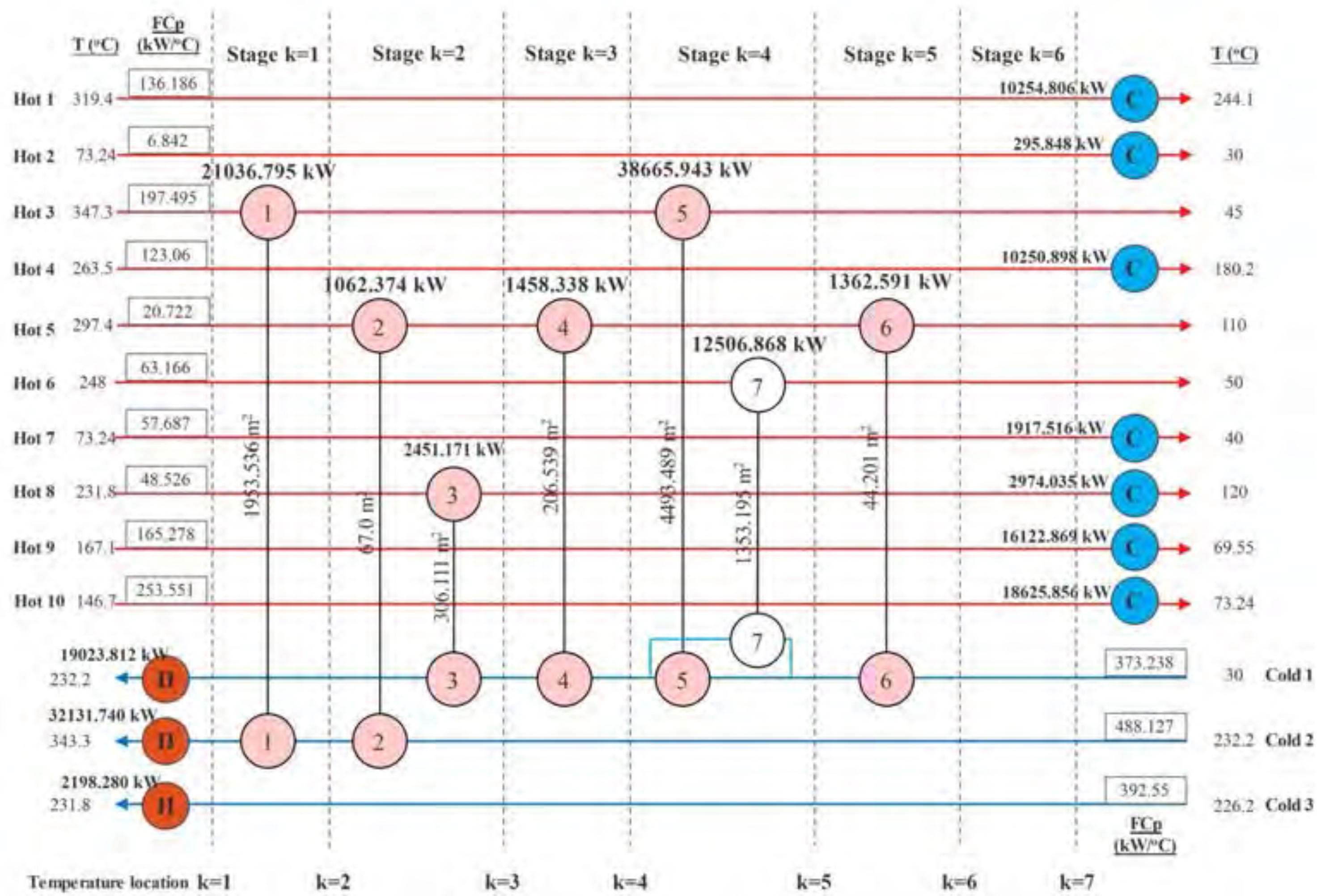

Figure B23 Retrofit case 2 HEN at month 1 of real crude oil preheat train.

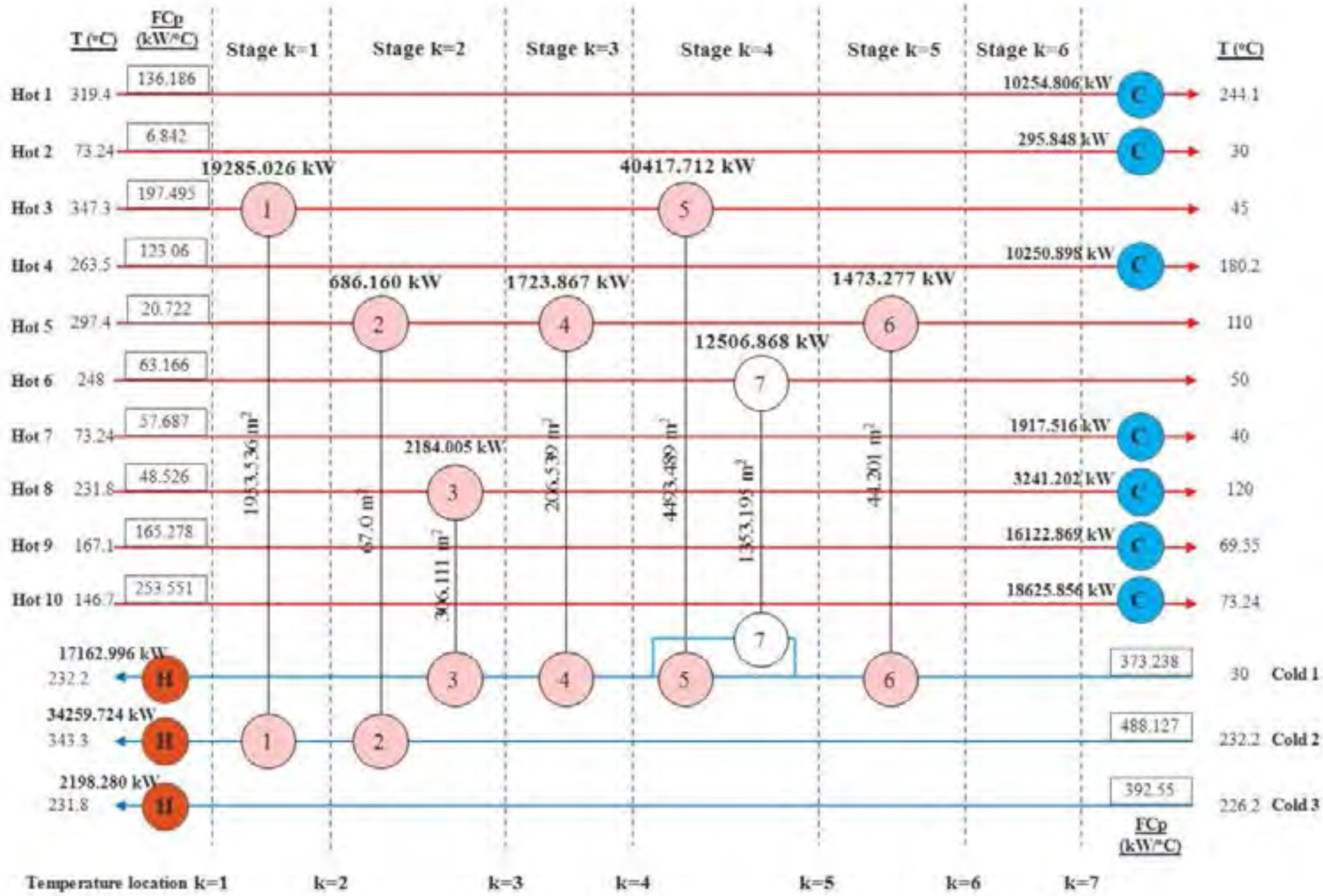

Figure B24 Retrofit case 2 HEN at month 2 of real crude oil preheat train.

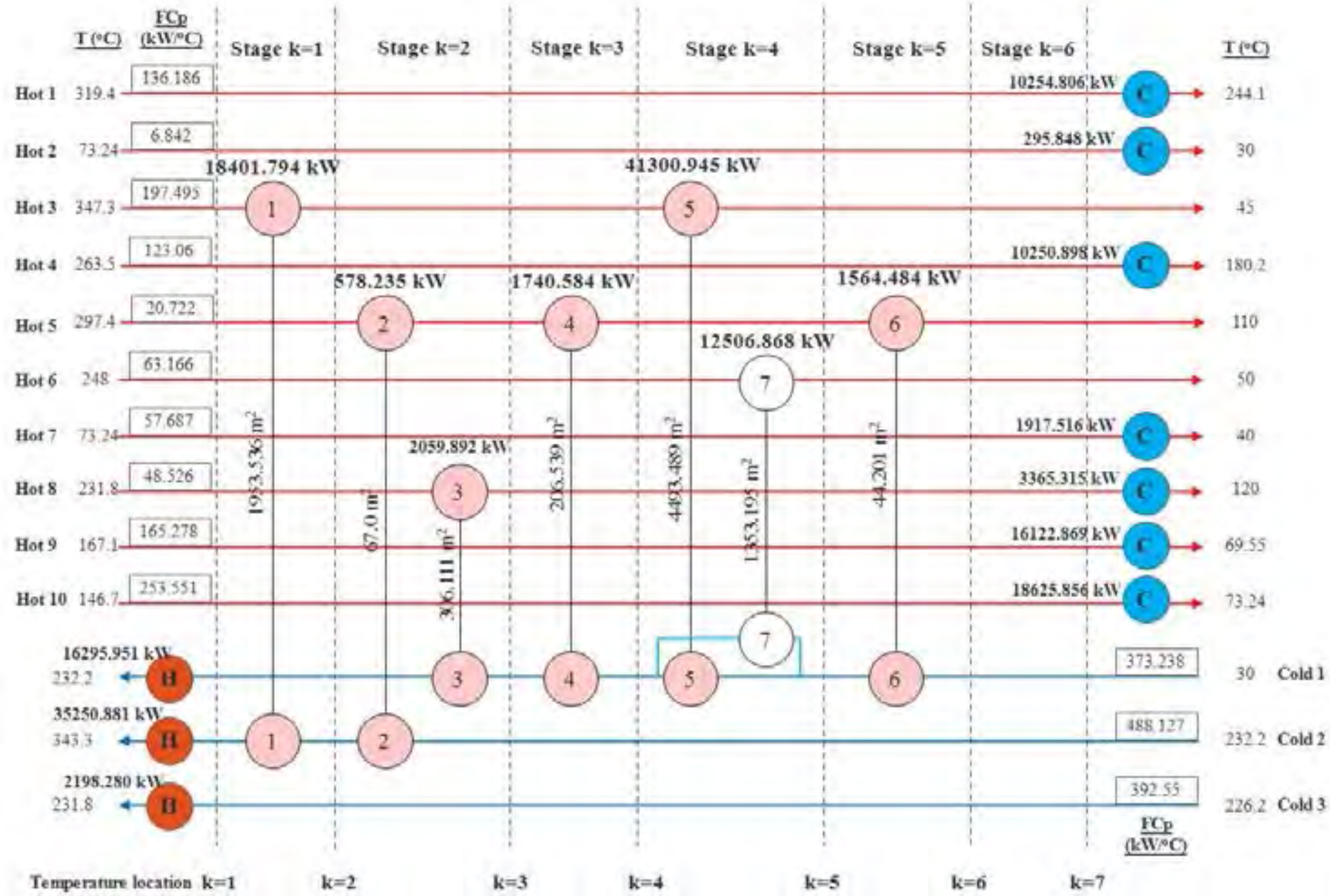

Figure B25 Retrofit case 2 HEN at month 3 of real crude oil preheat train.

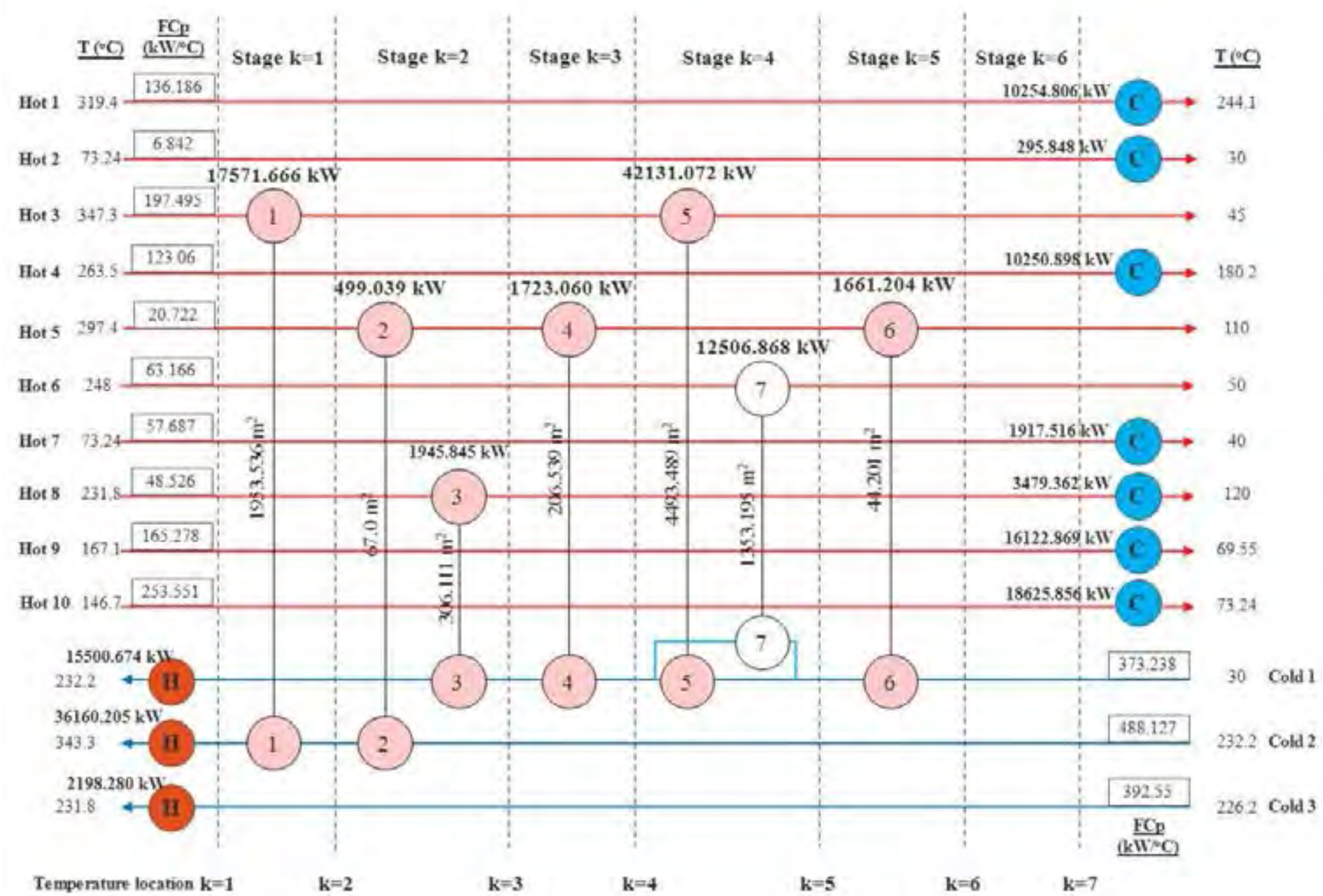

Figure B26 Retrofit case 2 HEN at month 4 of real crude oil preheat train.

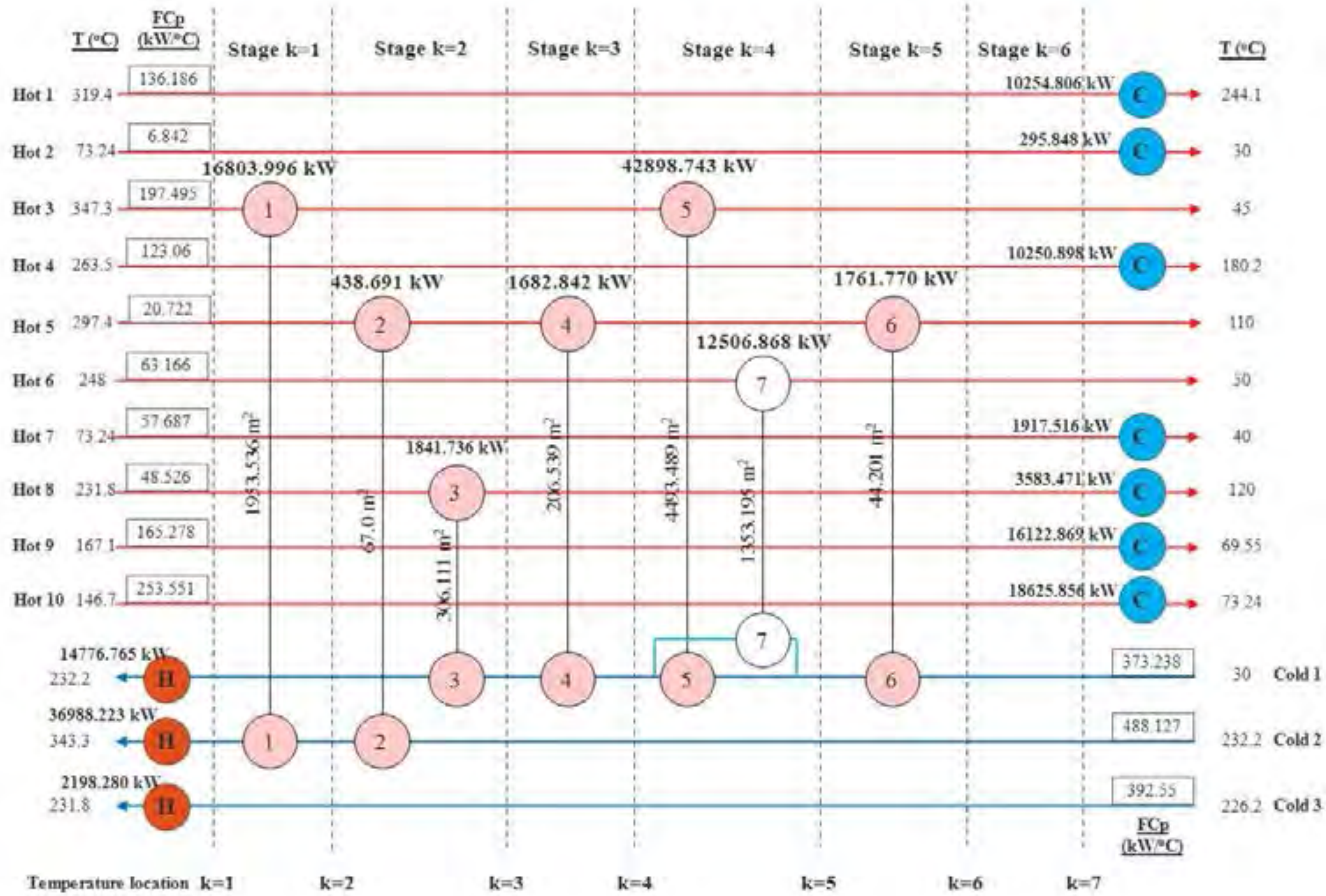

Figure B27 Retrofit case 2 HEN at month 5 of real crude oil preheat train.

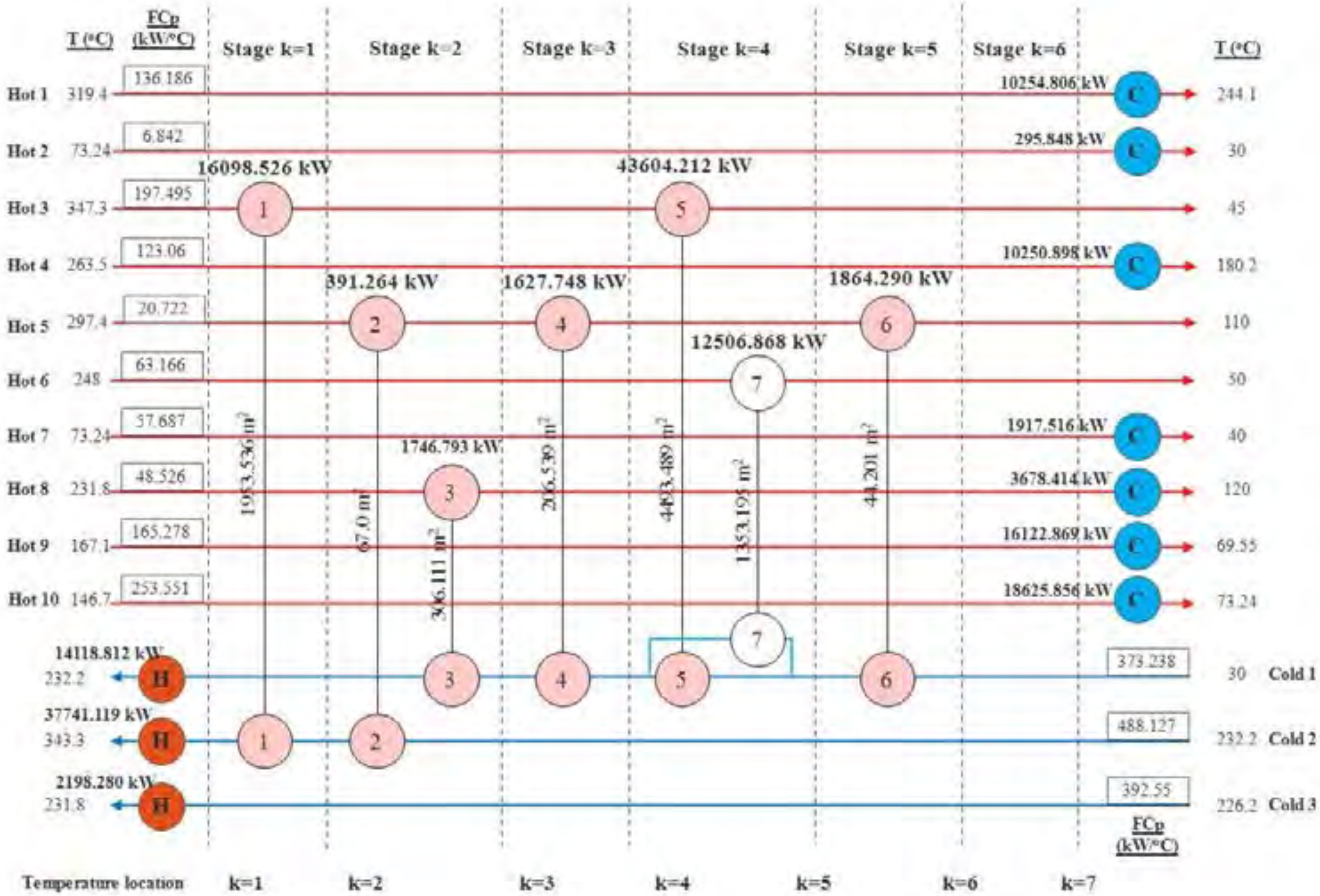

Figure B28 Retrofit case 2 HEN at month 6 of real crude oil preheat train.

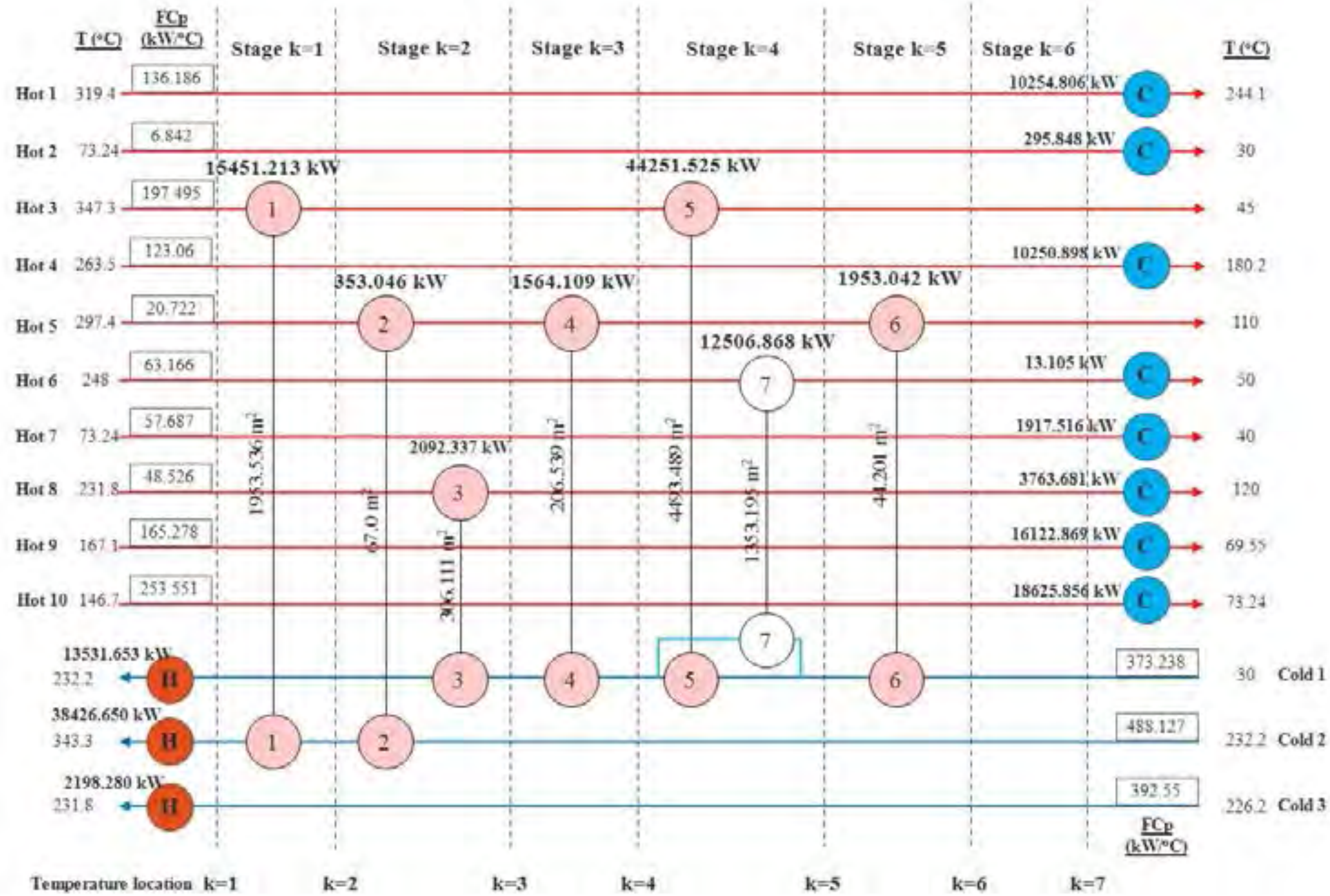

Figure B29 Retrofit case 2 HEN at month 7 of real crude oil preheat train.

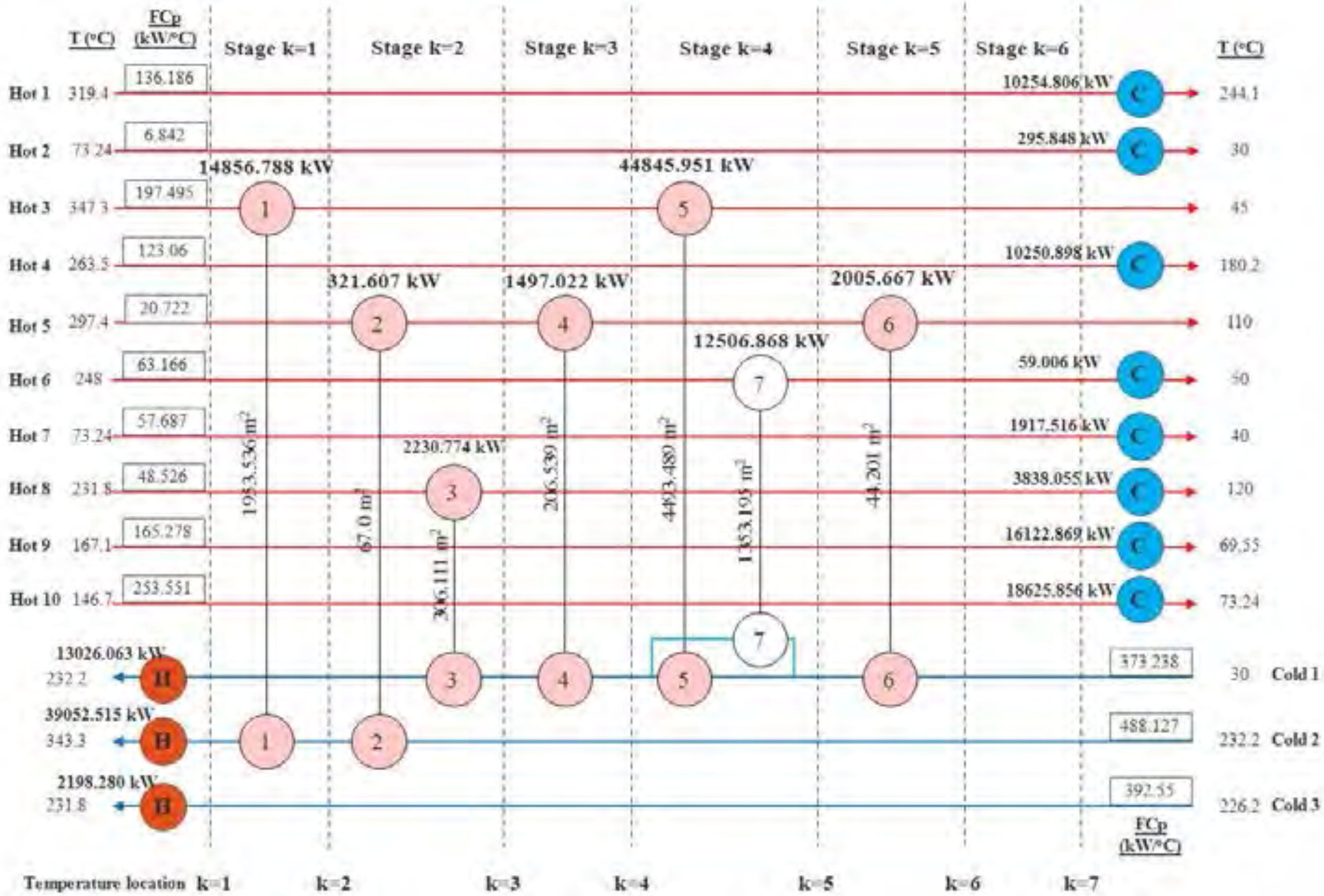

Figure B30 Retrofit case 2 HEN at month 8 of real crude oil preheat train.

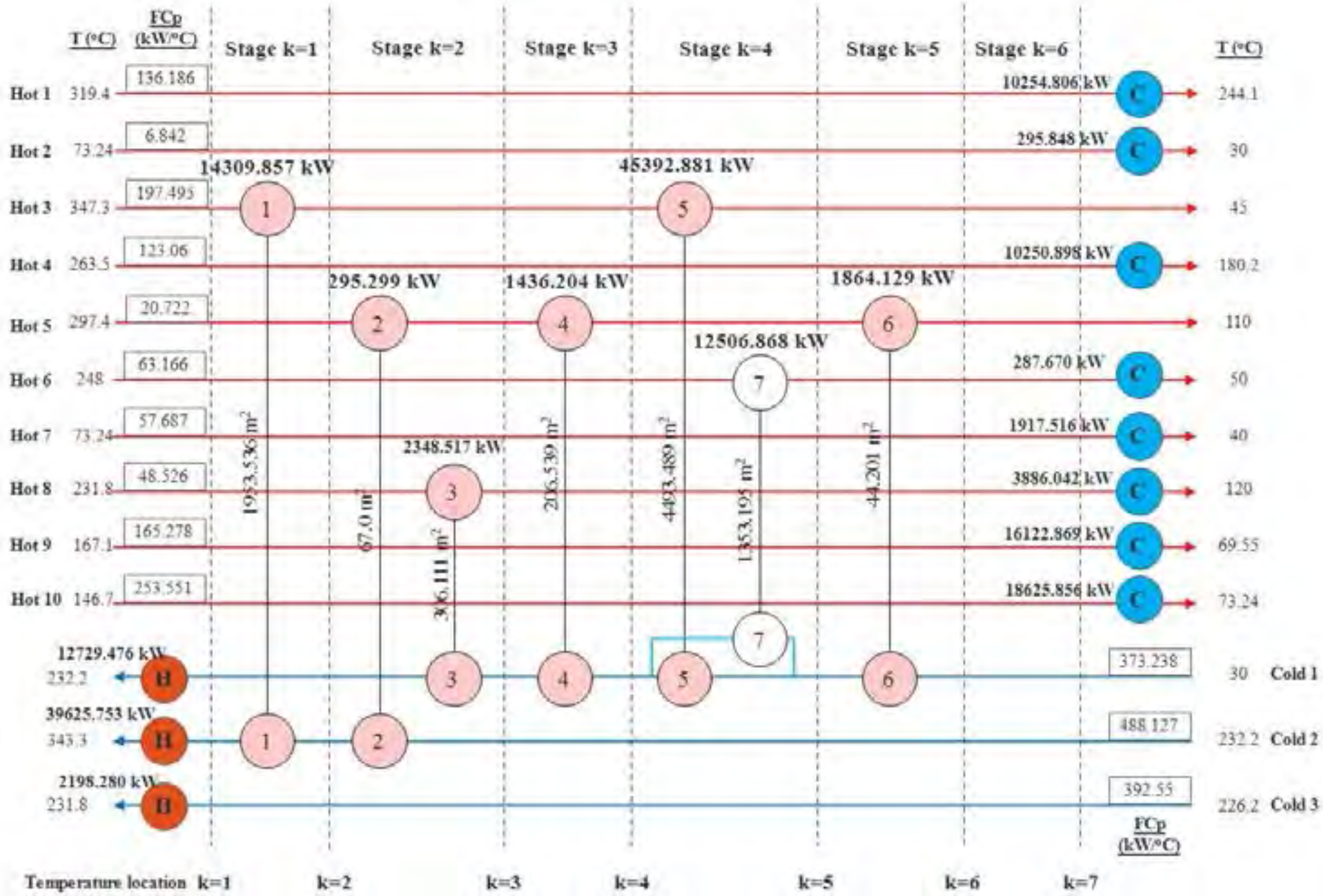

Figure B31 Retrofit case 2 HEN at month 9 of real crude oil preheat train.

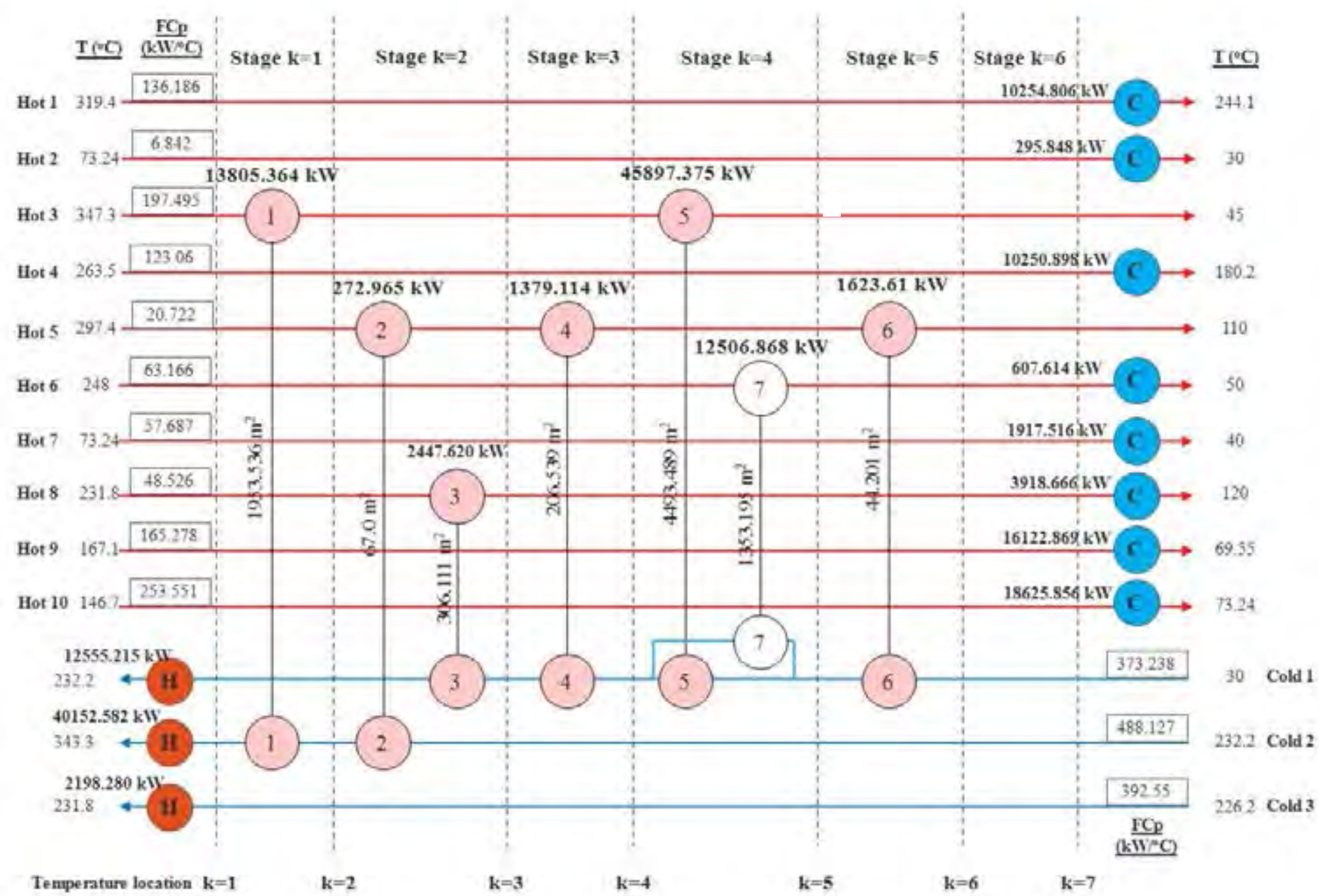

Figure B32 Retrofit case 2 HEN at month 10 of real crude oil preheat train.

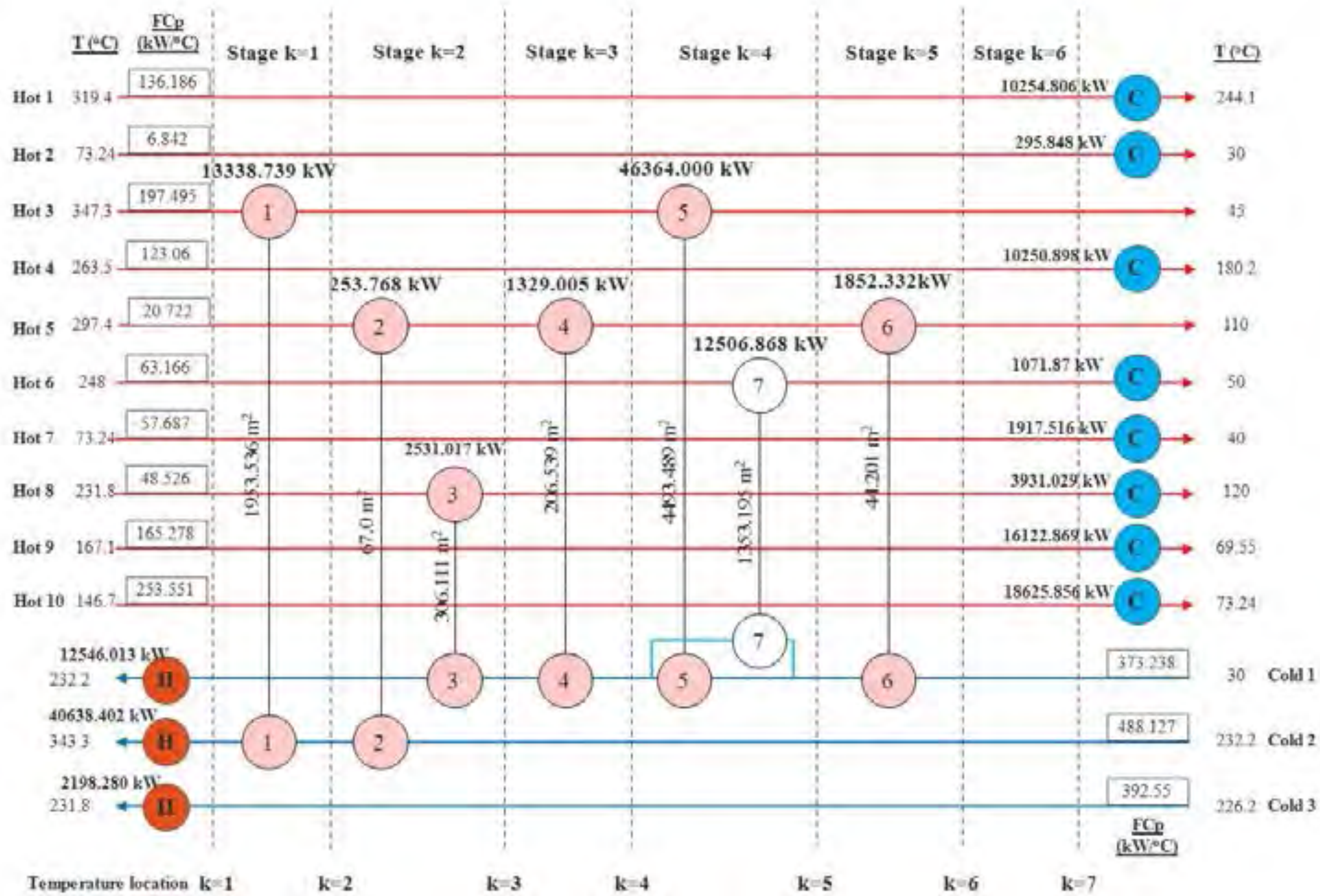

Figure B33 Retrofit case 2 HEN at month 11 of real crude oil preheat train

CURRICULUM VITAE

Name: Mr. Jaturaporn Yanyongsak

Date of Birth: April 12, 1994

Nationality: Thai

University Education:

2012-2016 Bachelor Degree of Engineering, Faculty of Engineering, Silpakorn University, Nakhon Pathom, Thailand

Work Experience:

2015 Position: Green product engineer (Internship)

Company name: *TPBI Co., Ltd., Nakhon Pathom, Thailand.*

Proceedings:

1. Yanyongsak, J.; and Siemanond, K. (2018, Aug 25-29) Heat exchanger network retrofit under fouling effects with cleaning schedule. 21st Conference on Process Integration for Energy Saving and Pollution Reduction - PRES 2018, 25-29 August 2018, Prague, Czech Republic.

Publications:

1. Chanchai Thongpin, Achiraya Muanwong, Jaturaporn Yanyongsak and Pongsakorn Lorphaitoon. Effect of Cloisite15A and Cloisite30B on different ratio of NR/ENR/EVA foam, PACCON 2017.