Data Reconciliation and Fouling Analysis in Heat Exchanger Network

by

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Dissertation submitted in partial fulfilment of
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CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

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May 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted on this project, that the original work is my own except as specified in the references and acknowledgement, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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AHMAD NURUDDIN BIN ABDUL AZIZ

ABSTRACT

In refinery, crude preheat train is use to preheat the crude oil with various product and pump around stream from downstream atmospheric until it reaches an optimum temperature for furnace heating. The variables such as temperature and flow rates is measured regularly and used to optimize the energy recovery in the train. However, since all measurement subject to certain error, any optimization exercised will not be accurate. In other to minimize the error, the measured variables are reconciled using data reconciliation technique. Data reconciliation is a mathematical approach which allows some adjustment on the measurement data in Heat Exchanger Network (HEN) to be made by eliminating measurement errors and obtain reconciled estimates of all stream flows, enthalpy and temperatures. This is to ensure that the measurement data satisfy the steady-state mass and energy balances of the crude preheat train. In HEN, Steady-State Data Reconciliation technique is implement. A set of mathematical models are generated in the form of matrices and used to treat the raw measurement data around crude preheat train so that more reliable measurement data are produced. The project started by extracting the data from the Piping and Instrumentation Diagram (P&ID) of the refinery. Then, the properties estimation of the data was done using Petrosim. After that, the Steady-State Data Reconciliation Model is developed in terms of matrices and solved by Matlab software. The results obtained consist of a vector of new adjusted raw data measurement or known as reconciled values. Analysis of the results show that the reconciled enthalpy did satisfied energy balances. However, the recalculated temperatures show huge adjustment compared to measured temperature, up to 12 ^{o}C adjustment (Stream 37). The data obtain is then used in fouling analysis of heat exchanger network. Fouling is an unwanted deposit on heat transfer equipment results in reduced efficiency of heat recovery. Fouling model is developed using the data from heat exchanger specification sheet supplied by the refinery. The model will predict the fouling resistance of heat exchanger at a time. Using the reconciled temperature, the fouling profile a long time for each heat exchanger is developed and the performance of heat exchanger is analysed. It is found that the most fouled heat exchanger is E-1107.

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CHAPTER 1: INTRODUCTION

1.1 Background

In any chemical plant, heat exchanger plays an important part because of the large investment and a number of problems it represents (Gilmour, 1960). The heat exchanger provides the desired temperature of any stream in chemical process such as feed into the reactor, preheat of feed before distillation process or cooling of product before storage. If not, there will be a waste of energy in the process. For example, if the feed preheater to distillation column does not perform as required, the reboiler and cooler will overwork. This mean more energy is needed, thus increase the cost. Therefore, in such case as a crude preheating train in refinery industry where the crude oil is heated by passing it through a network of heat exchangers, analyses can be done to improve the performances.

In chemical process in industry, many variables such as flow rates, temperature, and pressure are continuously measured and recorded for purpose of process control, on–line optimization and process economic evaluation (Romagnoli, J.A., & Sanchez, M.C, 2000). The quality of process data obtained affects the performance and profit gained from the process. Nonetheless, the measurements consist of temperature and flow rates of inlet and outlet of heat exchanger often contain errors, either random error or gross biased error. These means that the process constraints, a common functional model represented by conservation equation are not exactly satisfied (Romagnoli, J.A., & Sanchez, M.C, 2000).

Therefore, it is a common practise in chemical plants nowadays to implement a method to treat the data measured which is known as data reconciliation. Data reconciliation estimate the data of process variable by using the information contained in the process measurements and models (Narasimhan, S. & Jordache, J., 2000). It will allow adjustment on the data measured so that the treated measurements are consistent with the corresponding balances (Narasimhan, S. & Jordache, J., 2000). °C

Other analytical methods to optimize the heat exchanger performance are fouling analysis. According to (Bott, 1995) fouling is defined as the accumulation of unwanted deposits on the surface of heat exchanger. The foulant could be a crystalline matter, biological material, particulate matter or the product of chemical reactions. The occurrence of fouling depend on how fluid is being handle and their element in combination with the operating parameters such as temperature, flow rate and pressure (Bott, 1995).

Fouling has become an issue in heat exchangers since the first heat exchanger was designed. Fouling cause the total heat transfer coefficient of the heat transfer surface to reduce and therefore reduce the efficiency of energy retrieves. To overcome fouling, industries usually add additives into the process. These additives will act as inhibitor to prevent the scale formation. However, despite the best effort to reduce fouling, still the growth of deposit will occur (Bott, 1995). Therefore, periodic cleaning either chemically or physically will be necessary to clean the scaled deposits.

Therefore, this report will discuss on data reconciliation for measured data from a heat exchanger network with deep focus in crude preheat process in petroleum refinery plant. A mathematical model will be developed and applied to process instrumentation and observable measurements involved in heat exchanger network. Besides that, the fouling analysis wills also being carried out.

1.2 Problem Statement

In chemical plants, the process variables are often measured and their validity is crucial and the same goes to the process in crude preheating process in refinery industry. However, the data measured in heat exchanger network often is compromised by having some unbiased error. This error causes the measurement data to violate the conservation law mass and energy balance. As a result, any optimization practise on the process will not be efficient as the data obtained are not reliable.

Fouling in heat exchanger has become a problem in industry since the first heat exchanger was used. Fouling caused decrease in heat transfer efficiency due to scale formation on the wall of heat exchanger. As a result of this phenomenon, the operational cost of refineries increased. Maintaining optimality in the heat exchanger network becomes a trial and error procedure since lack of tools to access the fouling. This will results in the reduction of plant profit and also reduce the optimality operation of the heat exchanger network.

1.3 Objective

This projects aim to propose a numerical solution technique to be applied to formulate data reconciliation problem specifically for process in heat exchanger network in crude oil preheating in refinery industry. It is also aimed to analyse for the fouling status in each heat exchanger and the fouling profile along time.

1.4 Scope of Study

The project will cover the procedure of data reconciliation on the measurement data in heat exchanger network that operate in crude preheat train in refinery industry. The methods of Steady–state Data reconciliation is chosen and applied to deal with the steady state system present in heat exchanger network.

Besides that, this project will also focus on the fouling analysis of heat exchangers where the fouling resistance of each heat exchanger are determine by developing an appropriate models.

CHAPTER 2: LITERATURE REVIEW

2.1 Data Reconciliation

Measurement data in heat exchanger network such as flow rates, and temperature is not only affected by error in measurement but also by process variability. Thus, the measurement will not consistent with the conservation of mass and energy. This justifies the need of data reconciliation to rectify these errors. Data reconciliation is a technique developed to reduce random error in data measured by makes uses of process model constraint to obtain the estimates of process variable (Narasimhan, S. & Jordache, J., 2000).

Any raw data measured in process, are subject to random and possibly gross error. The term random error refers that neither the sign nor magnitude of the error can be predicted confidently. In other word, if the experiment is repeated with the same instrument and process condition is kept constant, the outcome of the experiment may be different depend on resulted random error. Random error originated by a number of different sources such as power fluctuation, change in ambient condition, analog input filtering and so on (Narasimhan, S. & Jordache, J., 2000). The only possible way to characterize this error is by the use of probability distribution. Gross error is an error subjected to malfunction in measurement instrument. That is to say, if the experiment is repeated with the same instrument under same process condition, the result will subjected to the gross error in same magnitude as the previous one. Data reconciliation will treat the measured data by considering the present of random error only but does not compensate error cause by instrument malfunction.

During the designing stage of any chemical process, not all measurement instruments such as flow and temperature transducer are put on place at each process stream and variables. Thus, not all variables will be determined in the process. Even though it is a norm that unmeasured variables are eliminated from the set of constraint before reconciliation is carried out, some of the unmeasured process variables called observable or determinable unmeasured variables are not inferred in the procedure of data reconciliation. The observable unmeasured variables value will be estimate after the measured variables are reconciled (Crowe, C.M., Garcia Campos, Y.A., & Hrymak, A., 1983). Hence, it is important to classify the process variables before any attempt for reconciliation is done. The process variables can be classified as below.

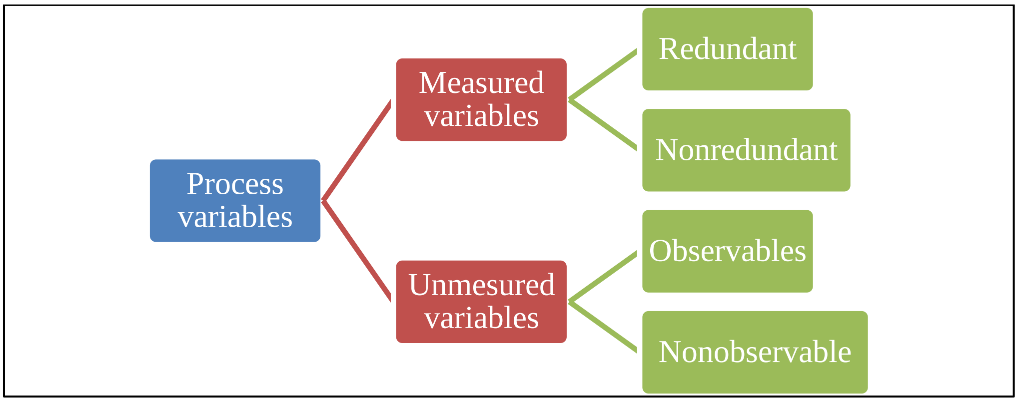

Figure 1: Classification of Process Variable

2.1.1 Linear Steady-State Data Reconciliation

In crude preheat train, the crude stream is usually split and each one of it heated by a various product and pump around stream from downstream atmospheric until it reaches an optimum temperature for furnace heating. To maximize energy recovery, variable such as temperature and flow rate is measured online every few hours. This data then will be used to determine the optimal flows that allow optimum heat energy transfer between streams.

Usually, the entire variable is measure in crude preheat train, however it is possible to ignore some measurement and only use the measurement of all stream for determining optimal crude split flow (Narasimhan, S. & Jordache, J., 2000). But, since all measurement containing error, any optimization practise will not necessarily result in predicted gains.

Steady-state data reconciliation is applied to measurement to overcome this problem. The reconciled estimated of all streams variable is obtained that satisfy the flow and enthalpy balances of crude preheat train (Narasimhan, S. & Jordache, J., 2000). The optimization practise using this reconciled value will more accurately represent the actual current performance of heat exchanger. This will allow maximum recovery between cold and hot stream thus minimize the cost for utility.

However, it should be noted, that the steady state process in crude preheat train will subjected to time constant. Since there will always a change in the type and flow of crude being preheat that will affected the value of variable measured along the process, the reconciled value will not be valid all the time. It will take 2 hours for the process to reach a new steady state. The process will let to operate for additional two hours before the new optimization can take place. The measurement made in preceding two hours can then be averaged and used in reconciliation problem (Narasimhan, S. & Jordache, J., 2000).

2.1.2 Linear Steady-State With All Variables Measured

This is a simplest problem faced in data reconciliation with all the process variable is measured in the network and process is in steady-state condition. The assumption was made that there is not systematic error and the measurement data only contain random error.

First, the measurement model is describe as below

$$y = \hat{y} + \varepsilon$$

Where y and $\hat{y}$ is the measured and actual value of variable respectively and ε is the random error for measurement y.

The data reconciliation can be formulated by following constraint weighted least-squares optimization problem stated before. At process steady-state, the reconciled data is obtained by:

Minimizing $$J(\hat{y}) = (y - \hat{y})^T V^{-1} (y - \hat{y})$$

Subject to $$A\hat{y} = 0$$

Equation 1 represents the least-square criterion. V is a (n x n) variance matrix, a type of diagonal matrix that represents the weight. The weight reflects the degree of accuracy of data measured respectively (Noor Azman, 2013). Equation 2 represents the constraint of the process where $A\hat{y}$ is incidence matrix of dimension (m x n) and 0 is a (m x 1) vector whose element is zero. Consider the case when all data variables are measured, the analytical solution or estimates obtained through data reconciliation are given by.

$$\hat{y} = y - VA^T(AVA^T)^{-1}A\hat{y}$$

This equation will serve as a basic equation in all linear steady-state data reconciliation problem.

2.1.3 Linear Steady-State with both Measured and Unmeasured Variables

In real situation, not all flows are measured in plant due to physical or economical consideration. The problem can solve efficiently by using the method call projection matrix introduce by Crowe et al. that are further extended to non-linear problem by Swartz (Noor Azman, 2013). Swartz proposed the used of iteration procedure by applying the QR factorization introduced by Crowe et al. to reconciled data. The step involved is as below.

i) Reconciling flows first

ii) Computing enthalpy for each heat exchanger in the network based on the measured inlet and outlet temperature values.

iii) Reconcile the enthalpy values

iv) Recalculate back the temperature values according to the reconciled value of enthalpy.

In this method, the determinable unmeasured variable will be decomposed before any attempt to reconcile data is done. After all measured data is reconciled, the value unmeasured data is calculated using the reconciled measured value. The incidence matrix is divided into matrices in term of measured and unmeasured variable.

$$A_y\hat{y} + A_z\acute{z} = 0$$

Where A_y correspond to the measured variables while A_z correspond to the unmeasured variables. Now the reconciliation problem can be rewrite as:

Minimizing $$J(\hat{y}) = (y - \hat{y})^T V^{-1} (y - \hat{y})$$

Subject to $$A_y \hat{y} + A_z \acute{z} = 0$$

The reconciliation problem can be solve by eliminate the ź value by pre-multiplying both sides by a projection matrix P such that $PA_z = 0$. Then, the reconciliation problem becomes:

Minimizing $$J(\hat{y}) = (y - \hat{y})^T V^{-1} (y - \hat{y})$$

Subject to $$PA_y \hat{y} = 0$$

The development of projection matrix P is perform by using Q-R factorization of matrix A_z. The statement of the Q-R Theorem by (Johnson et al., 1993) say that if a matrix A_z (m×n), where m≥n, has columns that are linearly independent ($\text{rank}(A_z) = n$), then there is an (m×m) matrix Q with orthonormal column vectors such that $A_z = QR$.

The solution for this reconciliation problem can be given replacing the matrix A by matrix PA_y.

$$\hat{y} = y - V(PA_y)^T((PA_y)V(PA_y)^T)^{-1}(PA)_y\hat{y}$$

To obtain the estimates ź for the variable z, the solution ŷ can be substituted in equation (8) provided that the unmeasured variables are determinable (Noor Azman, 2013).

$$\acute{z} = -\left(A_Z^T A_Z\right)^{-1} A_Z^T (A_y \hat{y})$$

2.1.4 Steady-State Data Reconciliation for Bilinear Systems

In industrial plants, process streams often contain multi component system in other word bilinear system, a type of non-linear system. Such condition cannot be treated using normal linear reconciliation technique. However, bilinear steady-state data reconciliation technique is used to reconcile this bilinear system because it is more efficient than using non-linear programming technique to solve for the non-linear data reconciliation problems. The treatment of bilinear problem procedure is discussed based on a book entitled "Data Processing and Reconciliation for Chemical Process Operation" by Romagnoli, J. A. R., and Sanchez, M. C., (2000).

Component mass and energy balance as well as normalization equations which are the constraints for reconciliation procedure of enthalpy data are written by using the method for bilinear system. Streams are divided into three categories depending on the combination of flow rates (F) and temperature (T) measurements as shown in *Table 1*.

Table 1: Categories of Stream

Category	F	T
1	Measured	Measured
2	Unmeasured	Measured
3	Measured/Unmeasured	Unmeasured

However, this case study will only consider the first two categories

Bilinear Constraint procedure:

a) Component mass/energy balance:

$$B_a f_{ch} + B_2 V d = 0$$

b) Normalization equation

$$E_1 f_{ch} + E_2 V d + E_4 f_m + E_5 f_u = 0$$

Where

f_{ch} : vector of enthalpy flows for stream in Category 1

d : vector of measured temperatures for streams in Category 2

f_M : measured total flow rates

f_u : unmeasured total flow rates

V : diagonal matrix of unmeasured total flow rates of Category 2

The measured variable d is replaced by a consistent measured value with the correction factor ε_d as follow,

$$d = d^{'} + \varepsilon_d$$

A new variable, θ is created which defined as

$$\theta = V_{\varepsilon d}$$

The variable d in the terms that appear in equation (13) and (14) are replaced by

$$B_2Vd = B_2\theta + B_2Vd^{'}$$

$$E_2Vd = E_2\theta + B_{32}Vd^{'}$$

The stream of unmeasured total flow rates of category 2 is to be displayed by introducing B_4 and E_6 as

$$B_2Vd = B_4(d)f_{u2}$$

$$E_2Vd = E_6(d)\ f_{u2}$$

New matrices of B5 and E7 are obtained as follow to group all unmeasured total flow rates by adding zero columns to B4 and E6.

$$B_5(d')f_{u2} = B_4Vd'$$

$$E_7(d')f_{u2} = E_2Vd'$$

The set of energy balances and normalization equation after all the above mentioned modification of the bilinear terms are now written as:

$$\begin{bmatrix} 0 & B_1 & B_2 & B_5 \\ E_4 & E_1 & E_2 & B_8 \end{bmatrix} \begin{bmatrix} f_m \\ f_{ch} \\ \theta \\ f_u \end{bmatrix} = 0 \qquad \text{where, } E_8=E_7+E_5$$

Considering adjustment of total flow rates (ε_f) and enthalpy flows (ε_{fch}), the above equation become

$$[B_{11} \quad B_{22}] \begin{bmatrix} a \\ f_u \end{bmatrix} = 0,$$

Where, $$a = \begin{bmatrix} \varepsilon_{f_m} \\ \varepsilon_{f_{ch}} \\ \theta \end{bmatrix}, B_{11} = \begin{bmatrix} 0 & B_1 & B_2 \\ E_4 & E_1 & E_2 \end{bmatrix}, B_{22} = \begin{bmatrix} B_5 \\ E_8 \end{bmatrix}$$

Therefore, the general reconciliation problem can be written as:

$$min_{\delta,\theta}(\varepsilon_{f_m}{}^T \Psi_{f_m}{}^{-1} \varepsilon_{f_m} + \varepsilon_{f_m}{}^T \Psi_{f_{ch}}{}^{-1} \varepsilon_{f_{ch}} + \theta^T \Psi_\theta{}^{-1} \theta$$

$$[B_{11} \quad B_{22}] \begin{bmatrix} a \\ f_u \end{bmatrix} = - \begin{bmatrix} 0 & B_1 \\ E_4 & E_1 \end{bmatrix} \begin{bmatrix} f_m \\ f_{ch} \end{bmatrix} = e$$

Σ_{fm}, Ψ_{fch} and Ψ_θ are the weighing matrices for f_m, f_{ch} and θ. Ψ_θ is defined as

$$\Sigma_\theta = V \Sigma_d V$$

2.2 Fouling Analysis

Fouling refer to accumulated of unwanted deposit on the surface of heat exchangers and is heavily depend on the variety of ageing mechanism such as corrosion, fatigue, wear, or pitting and also is closely related to operational condition such as fluid temperature and velocity (Mohamad Zin, 2010) .This deposit reduce the performance of heat exchanger over time compare to “clean condition” during start up (Mohanty, D.K. & Singru, P.M., 2012) and is a conductive resistance that must be consider for in the design heat transfer coefficient. The resistance of heat transfer between two fluids is contribute by the fouling thickness, film heat transfers and the thermal conductivity of the wall.

The common method to described level of fouling thermal resistant (R_f) in heat exchanger is represent by expression below (Mohamad Zin, 2010):

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} + R_f$$

Where,

U = overall heat transfer coefficient

h_1, h_2 = film coefficient of the two heat transfer fluids

R_f = fouling resistance

At steady state conditions, the heat flux, *q'* across a clean surface is given as:

$$q' = U_C \Delta T_{lmtd}$$

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{ln \frac{\Delta T_1}{\Delta T_2}}$$

$$\frac{1}{U_C} = R_{TC} = \frac{1}{h_h} + R_W + \frac{A_h}{A_C h_C}$$

Where,

q'	= heat flux
U_C	= overall heat transfer coefficient during clean condition
ΔT_{lmtd}	= log mean temperature difference
ΔT_1	= temperature difference between hot fluid
ΔT_2	= temperature difference between cold fluid
R_{TC}	= total resistance to heat flow
A_C	= cold fluid side heat transfer area
$\frac{1}{h_h}$	= film resistance of the hot fluid
$\frac{A_h}{A_C h_C}$	= film resistance of cold fluid
R_W	= thermal resistance of the metal wall

The heat flux across a fouled surface is given as:

$$q' = U_D \Delta T_{lmtd}$$

$$\frac{1}{U_D} = R_{TF} = \frac{1}{h_h} + R_W + R_F + \frac{1}{h_C}$$

Where R_F is the resistance of fouling to heat transfers. Thus, the fouling resistance can be express by:

$$R_f = \frac{1}{U_D} - \frac{1}{U_C}$$

In other to determine the fouling resistance in heat exchanger, some physical properties of the fluid are needed such as viscosity, heat capacity, density and thermal conductivity. The process data for flow rate and temperature of the fluids is obtained from the reconciled data. The fouling resistance profile with time of each heat exchanger then will be developed.

CHAPTER 3: METHODOLOGY

3.1 Project Flow Chart

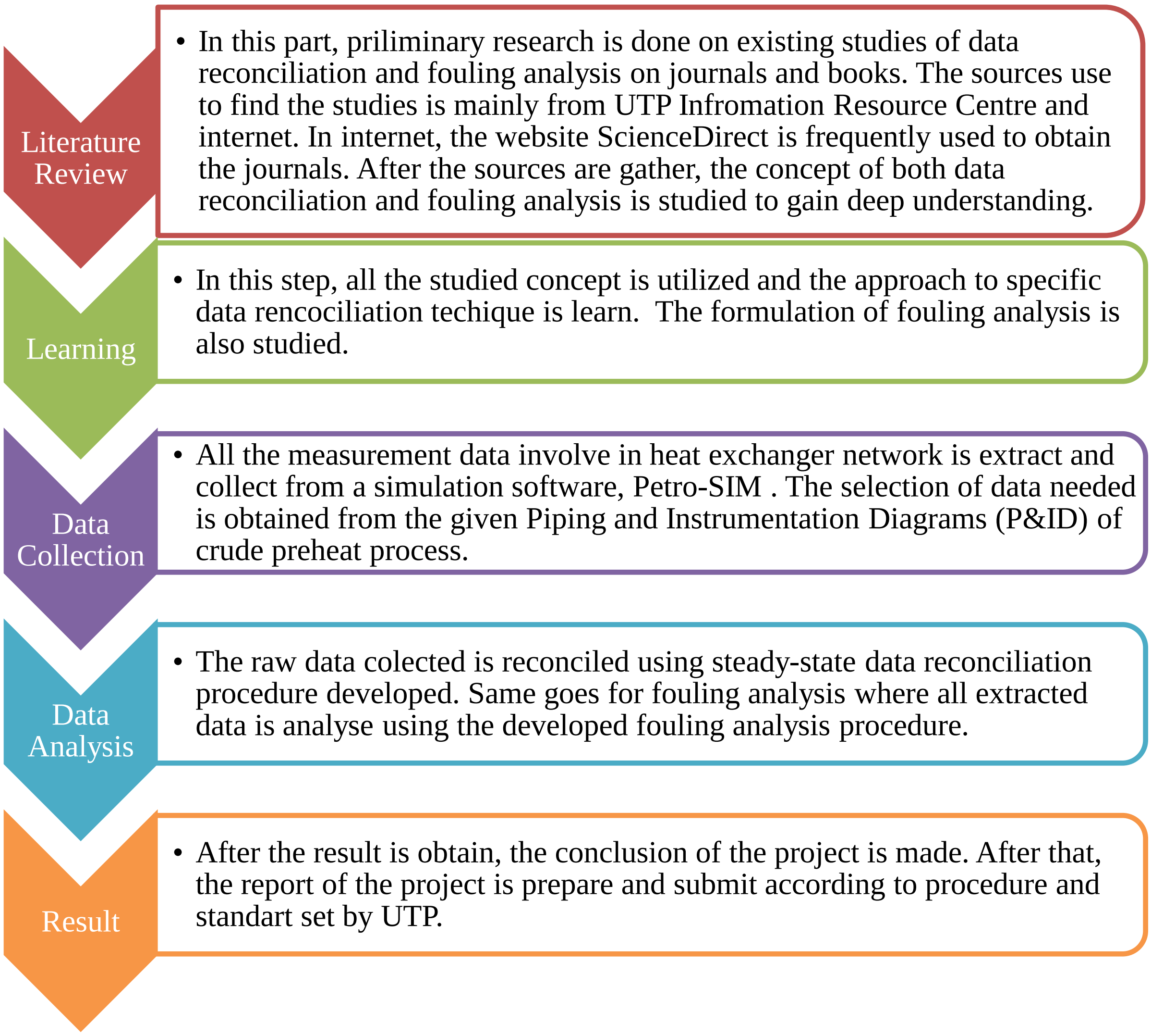

Figure 2: Project Flow Chart

3.2 Gantt Chart and Key Milestone

Table 2: Gant Chart and Key Milestone FYP1

No	Detail Work	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Topic	■	■												
2	Preliminary Research Work			■	■	■									
3	Submission of Extended Proposal Defence						■								
4	Proposal Defence							●							
5	Project Work Continues								■	■	■	■	■		
6	Submission of Interim Draft Report													●	
7	Submission of Interim Report														●

Table 3: Gant Chart and Key Milestone FYP2

No	Detail Work	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project Work Continues	■	■	■	■	■	■	■								
2	Submission of Progress Report								●							
3	Project Work Continues								■	■	■	■	■			
4	Pre-SEDEX											●				
5	Submission of Draft Report												●			
6	Submission of Dissertation													●		

7	Submission of Technical Paper													●		
8	Oral Presentation															●
9	Submission of Dissertation (hard bound)															●

■ Process ● Milestone

3.3 Project Activities

3.3.1 Data Reconciliation

<u>Data Collection</u>

a) Go through the provided PFD for crude preheat train and understand the process.

b) Go through the process flow and identify the heat exchangers involved and parameters associated with the heat exchangers (temperature and flow rate). Identify both measured and unmeasured variables.

c) Extract the stream data of heat exchanger network provided by the refinery such as flow rate and temperature. The properties of the stream such as density, heat capacity and viscosity are simulate using PETROSIM software.

d) All the measurement data will be used for steady-state data reconciliation procedure.

<u>Steady-State Data Reconciliation Procedure</u>

The proposed bilinear steady-state data reconciliation model approach is applied to the raw measurements data of HEN.

a) Calculation of specific enthalpy:

b) From the available data of heat capacity, Cp for all the hot streams and crude and also the value of temperature, specific enthalpy, H is calculated by the equation of,

$$H = C_P T$$

c) Calculation of enthalpy:

   i. Value of enthalpy for both hot and cold streams for each heat exchanger unit are calculated by using the equation of

$$Q = FC_P T$$

d) Data reconciliation specific enthalpy to satisfy energy balance or enthalpy balance:

   i. Apply the bilinear steady-state data reconciliation mathematical model to all of the flow rates measurement and calculated enthalpy data to reconcile data measurement on flow rates and enthalpy for the HEN.

   ii. The result of reconciled values enthalpy is well tabulated for comparison with the raw data of calculated value of enthalpy.

e) Recalculation of temperatures:

   i. From the reconciled values of enthalpy, recalculate back the value of inlet and outlet temperatures for each of heat exchanger unit.

3.3.2 Fouling Analysis

a) Reconciled data and properties estimated from previous experiment are used in fouling analysis.
b) The fouling calculation model is develop using Microsoft Excel.
c) The result obtain from above calculation is then used to developed a fouling profile with time for each heat exchanger and the performance of each heat exchanger is analysed.

3.4 Tools and Software

Throughout the flow of the project the tools and equipments required are as follow:

a) Microsoft Excel – Heat Exchanger Network Data recording and fouling analysis

b) MATLAB – Solving matrix form of mathematical model to produce reconciled data.

c) PETROSIM – Simulation software to generate properties of crude oil and products streams.

CHAPTER 4: RESULT AND DISCUSSION

4.1 Data Reconciliation

4.1.1 Data Gathering

Properties Estimation

In any refinery, the variables such as temperature, flow rates and pressure are often measured for optimization purpose. However, these measured variables were not enough in other for data reconciliation technique and fouling analysis to be implemented. Properties such as density (ρ), heat capacity (Cp), and viscosity (μ) is needed. Therefore, to estimate these unknown properties, a simulation software Petro-SIM was used. This software will estimate those properties using the data available.

The properties estimates will be divided into two sections which are the crude properties and products properties. The crude properties estimates is depended on the crude blend composition and operating condition while product properties estimates is depend on the operating condition only. Using the Oil Manager database available in Petro-SIM the properties of the crude oil was predicted based on its crude blend composition.

Heat Exchanger Network (HEN) Representative of Crude Preheat Train

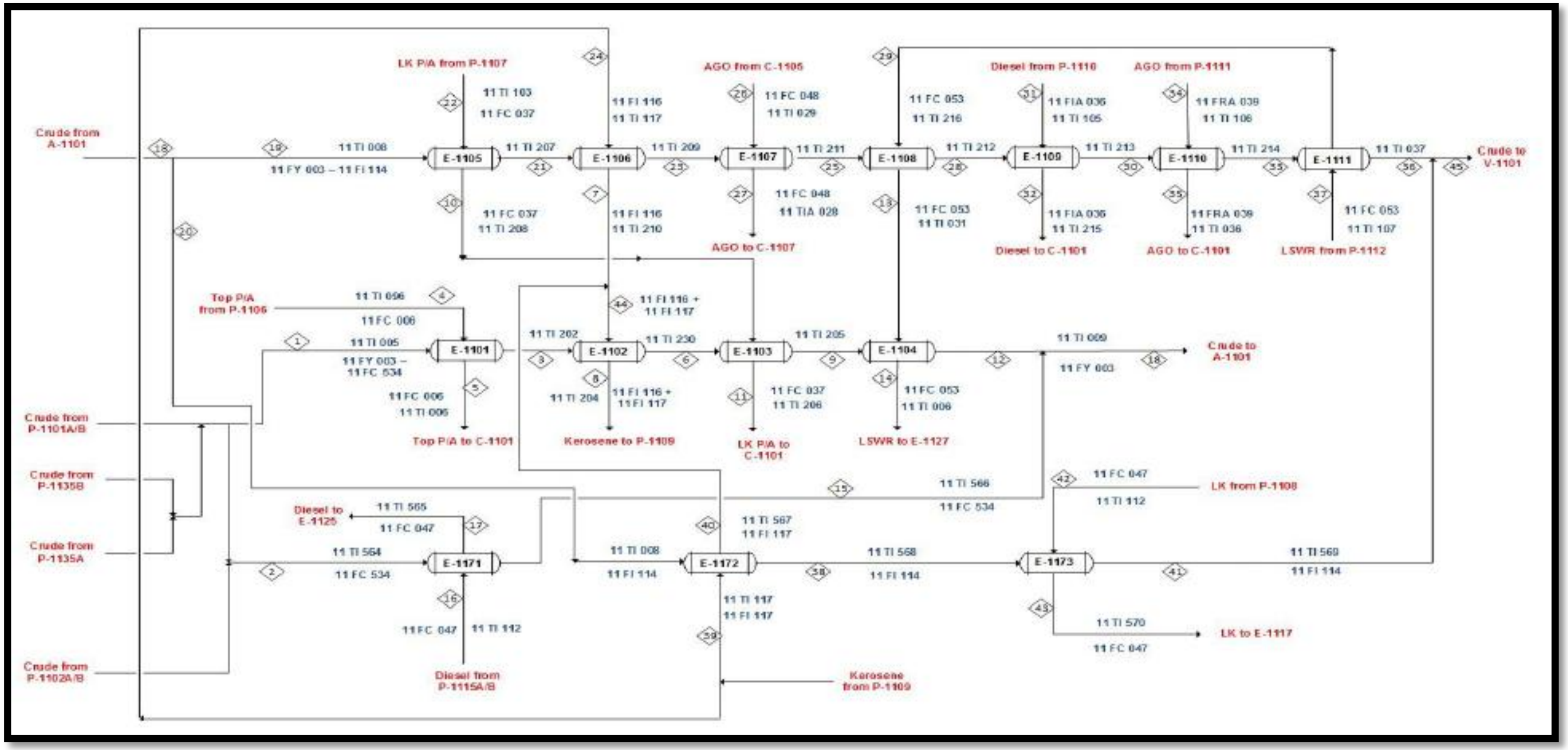

Figure 3: Heat Exchanger Network in Crude Preheating Process

Figure 2 above shows the whole system of heat exchanger network involves in the project. A total of 14 heat exchanger units in parallel and series with a total number of 44 process streams are involved. All the raw measurement data available as well as the determinable unmeasured data of temperatures and flow rates are treated by the steady-state data reconciliation model.

Heat Exchanger Network Data Measurement

All the raw measurement data tags extracted from Piping and Instrumentation Diagrams (P&ID) of crude preheating process that includes the inlet and outlet flow rates and temperatures of both cold and hot streams in all the heat exchanger unit is shown below.

Table 4: Heat Exchanger Network Data Measurement

Stream No	Flow Rate Tags	Temperature Tags
1	11 FY 003-11 FC 534	11 TI 005
2	11 FC 534	11 TI 564
3	-	11 TI 202
4	11 FC 006	11 TI 096
5	-	11 TI 201
6	-	11 TI 230
7	-	11 TI 210
8	-	11 TI 204
9	-	11 TI 205
10	-	11 TI 208
11	-	11 TI 206
12	-	-
13	-	11 TI 031
14	-	11 TI 006
15	-	11 TI 566
16	-	11 TI 112
17	-	11 TI 565

18	-	11 TI 009
19	11 FY 003-11 FI 114	11 TI 008
20	11 FI 114	11 TI 008
21	-	11 TI 207
22	11 FC 037	11 TI 103
23	-	11 TI 209
24	11 FI 116	11 TI 117
25	-	11 TI 211
26	11 FC 048	11 TI 029
27	-	11 TI 028
28	-	11 TI 212
29	-	11 TI 216
30	-	11 TI 213
31	-	11 TI 105
32	11 FI 036	11 TI 215
33	-	11 TI 214
34	11 FC 035	11 TI 106
35	-	11 TI 036
36	-	11 TI 037
37	-	11 TI 107
38	-	11 TI 568
39	11 FI 117	11 TI 117
40	-	11 TI 567
41	-	11 TI 569
42	11 FC 047	11 TI 112
43	-	11 TI 570
44	-	-

4.1.2 Classification of Heat Exchanger Network Measurement Data

Using the extracted data in tag numbers, all the raw measurement data for both flow rate and temperature in HEN in real value have been collected from a refinery plant. The raw data then will be classified as follows:

a) Measured Variables:
   - Redundant (over measured): A measured process variable that can also be computed from the balance equations and the rest of the measured variables
   - Non-redundant (just measured): A measured variable that cannot be computed from the balance equations and the rest of the measured variables.

b) Unmeasured Variables
   - Determinable: An unmeasured variable is determinable if it can be evaluated from the available measurements using balance equations.
   - Indeterminable: An unmeasured variable is indeterminable if cannot be evaluated from the available measurements using balance equations.

I. Flow rate data

The flow rate data is classified into two categories which is non-redundant measured variables" and "determinable unmeasured variables"

a) Non-redundant measured variables:

There are 15 measured variables of flow rate as follow

$F_1, F_2, F_3, F_{14}, F_{16,} F_{18}, F_{19}, F_{20}, F_{22}, F_{26}, F_{32}, F_{34}, F_{39}, F_{42}$

Originally, the data extracted from the plant is in m^3/h. for the purpose of data reconciliation, they are converted into kg/hr unit by multiplying with the value of density of crude and product streams involve around each heat exchanger unit. This crude and product streams property is obtained from simulation by using PETROSIM software from refinery plant.

b) Determinable unmeasured variables:

There are 29 determinable unmeasured variables of flow rate and are listed as follow

F_3, F_5, F_6, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13}, F_{15}, F_{17}, F_{21}, F_{23}, F_{25}, F_{27}, F_{28}, F_{29}, F_{30}, F_{31}, F_{33}, F_{35}, F_{36}, F_{37}, F_{38}, F_{40}, F_{41}, F_{43}, F_{44}

The value of determinable unmeasured variables will be estimated from the value of non-redundant measured variables with the assumption that the inlet flow rate of both hot and cold streams are the same with their outlet flow rates. They are determined as follow

- $F_3 = F_6 = F_9 = F_{12} = \boldsymbol{F_1}$
- $F_5 = \boldsymbol{F_4}$
- $F_7 = \boldsymbol{F_{24}}$
- $F_8 = F_{44} = F_7 + F_{40} = \boldsymbol{F_{24} + F_{39}}$
- $F_{11} = F_{10} = \boldsymbol{F_{22}}$
- $F_{13} = F_{29} = F_{37} = \boldsymbol{F_{14}}$
- $F_{15} = \boldsymbol{F_2}$
- $F_{17} = \boldsymbol{F_{16}}$
- $F_{21} = F_{23} = F_{25} = F_{28} = F_{30} = F_{33} = F_{36} = \boldsymbol{F_{19}}$
- $F_{38} = F_{41} = \boldsymbol{F_{20}}$
- $F_{40} = \boldsymbol{F_{39}}$
- $F_{43} = \boldsymbol{F_{42}}$
- $F_{35} = \boldsymbol{F_{34}}$
- $F_{31} = \boldsymbol{F_{32}}$
- $F_{27} = \boldsymbol{F_{26}}$

II. Temperature Data

a) Non-redundant measured variables:

From a total of 44 data measurement for temperatures, 42 data are classified as measured variable as shown below.

$T_1, T_2, T_3, T_4, T_5, T_7, T_8, T_9, T_{10}, T_{11}, T_{13}, T_{14}, T_{15}, T_{16}, T_{17}, T_{18}, T_{19}, T_{20}, T_{21}, T_{22},$

$T_{23}, T_{24}, T_{25}, T_{26}, T_{27}, T_{28}, T_{29}, T_{30}, T_{31}, T_{32}, T_{33}, T_{34}, T_{35}, T_{36}, T_{37}, T_{38}, T_{39}, T_{40}, T_{41},$

T_{42}, T_{43}

b) Determinable unmeasured variables of temperature:

T_{12} *and* T_{44}

There are determine as follow

$$T_{12} = \frac{(F_{12} + F_{15})(C_{P18}T_{18}) - F_{15}C_{P15}T_{15}}{F_{12}C_{P12}}$$

$$T_{44} = \frac{(F_{40}C_{P40}T_{40}) + (F_7C_{P7}T_7)}{(F_{24}C_{P7} + F_{40}C_{P40})}$$

The value used to calculate the determinable unmeasured variables of temperature will be obtained from the reconciled value estimated value of temperatures resulting from the treatment of all the measured raw measurement data of flow rates and calculated enthalpies by using the Steady-State Data Reconciliation Model in terms of matrices.

4.1.3 Steady-State Data Reconciliation Model

The mathematical model involve in Steady-State Data Reconciliation for HEN are developed in a set of matrices.

Analytical solution

The analytical solution or final model of steady-state data reconciliation in order to treat all the measurement data around heat exchanger network of crude preheating process is developed as follow.

$$\hat{y} = y - VA^T(AVA^T)^{-1}Ay$$

where $\hat{y}$: Vector of reconciled value of flow rate and calculated enthalpy

y : Vector of raw measurement value of flow rate and calculated enthalpy

A: Incidence Matrix

V: Covariance Matrix

a) Assumption

From the variable classification, all the observable variable of flow rate is a non-redundant. Therefore, in this problem, only the energy balance is consider to be the constraint for the data reconciliation procedure.

b) Raw Measurement Data Vector Matrix ŷ:

The raw measurement matrix ŷ is consist of 42 enthalpy obtained by multiplying the temperature with flow rate and heat capacity. The matric of ŷ is generated as below:

$$Q_i = F_i Cp_i T_i$$

ŷ= [43x1]

ŷ= [Q_1 Q_2 Q_3 Q_4 Q_5 Q_6 Q_7 Q_8 Q_9 Q_{10} Q_{11} Q_{13} Q_{14} Q_{15} Q_{16} Q_{17} Q_{18} Q_{19} Q_{20} Q_{21} Q_{22} Q_{23} Q_{24} Q_{25} Q_{26} Q_{27} Q_{28} Q_{29} Q_{30} Q_{31} Q_{32} Q_{33} Q_{34} Q_{35} Q_{36} Q_{37} Q_{38} Q_{39} Q_{40} Q_{41} Q_{42} Q_{43}]

c) Incidence Matrix A:

A= [15x42]

The elements involved in this matrix consist of the values of 1 and 0. The rows represent the number of node available in the model while the columns represent the number of variables involved in the model. Node refers to a point where the heat balancing occurs. For example, in a heat exchanger; energy is balancing where energy receive by cold stream must be equal to energy loses by hot stream. In this model, there are 14 nodes and 42 variables have been identified. The complete incidence matrix is shown in appendix I.

d) Covariance Matrix V:

Covariance matrix represents the weight of adjustment made to the raw data. It contains information about the accuracy of the measurements and the correlation between them (Narasimhan, S. & Jordache, J., 2000). The information about the standard deviation of the error committed by the difference instruments is needed in other for this approach to be used. Using direct method, the covariance matrix can be estimated from a sample of measurement made in a time window. The estimate can be obtained using equation below.

$$V = \frac{1}{N-1}\sum_{i=1}^{N}(y_i - \tilde{y})(y_i - \tilde{y})^T$$

Where $\tilde{y}$ is the sample mean given by

$$\tilde{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$$

The important requirement to estimate V using direct method is that the true value for all variables should be fixed during the time interval in which the above measurements are made. To meet this requirement, a set of measurement consist of reading per minute for each measurement of flow and temperature for duration of 2 hours is obtained from the refinery. The data to be used in estimation is carefully chosen such that when the variance is estimate, the value of variances falls between the selected ranges.

Since this project deal with the enthalpy balance, the variance of enthalpy needs to be estimates. The variance of enthalpy is estimates using the value of variance of flow rate and temperature and its calculation are show below.

Variance of enthalpy:

Variance for the calculated enthalpy for each heat exchanger unit is obtained by calculation using Taylor's series and is given as follow.

$$Var(enthalpy) \approx (T*)^2 Var(F) + (F*)^2 Var(T)$$

Where, *Var (enthalpy)*: Variance of enthalpy

Var (F)	: Variance of flow rate
Var (T)	: Variance of temperature
*T**	: Average temperature measurement
*F**	: Average flow rate measurement

A [42x42] diagonal covariance matrix for enthalpy is generated as shown in Appendix I. The elements involved in the Covariance Matrix V consist of value of variance enthalpy. The rest are the large values of 0 in number.

e) Reconcile Data in Vector Matrix

MATLAB software was used to generate a matrix of $VA^T(AVA^T)^{-1}A$ using the matrices generated above. This matrix then become a constant value and is transferred to Excel file where the vectors of raw measurement data for various days are reconciled using equation $\hat{y} = y - VA^T(AVA^T)^{-1}Ay$. The solution of the model is the vector ŷ in the form of 42 by 1 vector matrix. The vector matrix of ŷ correspond to the reconciled values of calculated enthalpy.

4.1.4 Data Analysis

<u>Model validation</u>

The process of data analysis based on the results obtained from the reconciled values of enthalpy is done by comparing the obtained reconciled data with the raw measurement data and relate them with the law of energy balance.

From the results obtained, the new reconciled data by using the implementation of Steady-State Data Reconciliation model should satisfy energy balance equations involved in heat exchanger network system. The energy balance equation should be satisfied by the value of reconciled enthalpy where the energy obtained by the cold streams is the same with energy loss by the hot streams in each heat exchanger unit.

Based on the obtained results from the treatment of calculated enthalpies by the Steady-State Data Reconciliation model, the reconciled values of enthalpy did satisfy the energy balance equations around each heat exchanger unit where the energy obtained in the form of heat obtained by the cold streams is the same with heat loss by the hot streams in each heat exchanger unit.

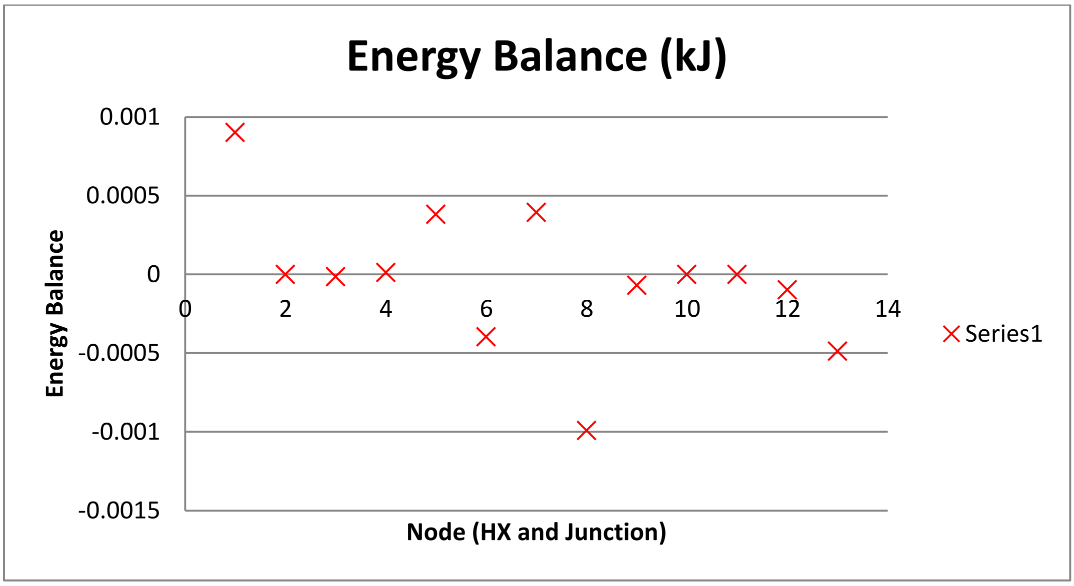

Figure 4: Energy Balance Across Heat Exchangers

From the graph above, the energy balance of each heat exchanger is revolve around zero with the largest variation of $\pm$ 0.001

Apart from that, the difference between reconciled enthalpy and calculated enthalpy is not too large. This is clearly shown through figure 5 below.

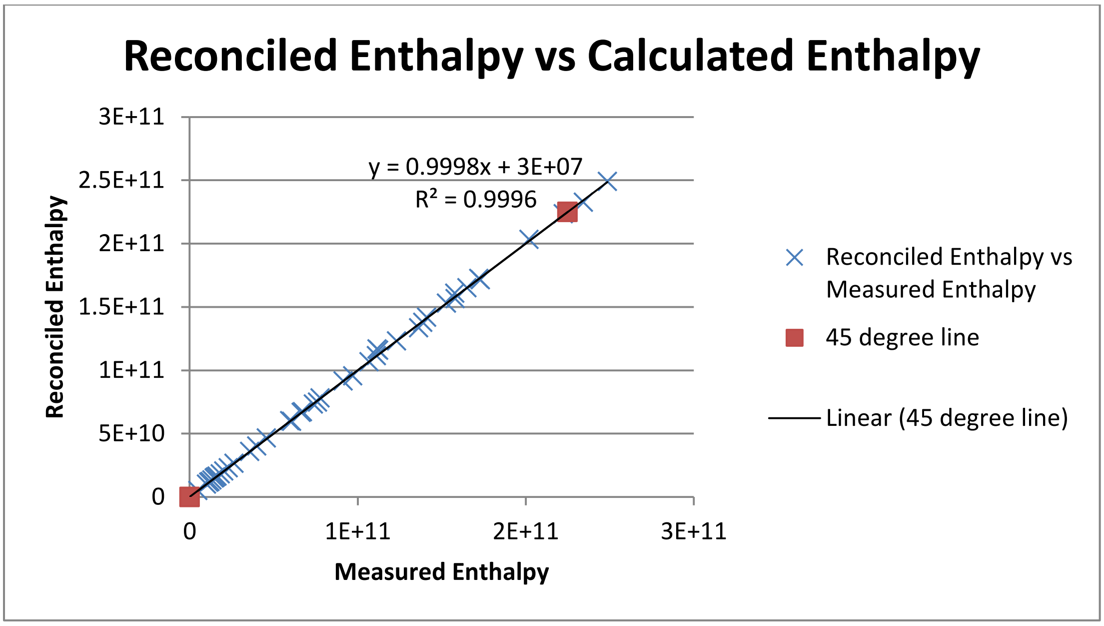

Figure 5: Reconciled Enthalpy against Calculated Enthalpy

The graph show that the plotted points of reconciled enthalpy against calculated enthalpy is not too scattered around the 45^o incline line. This show that the value of reconciled enthalpy does not differ much from their calculated values. These two factors show that the model is valid for temperature estimation.

<u>Temperature estimation</u>

After the enthalpy is reconciled, the next step is to calculate back the value of temperature. The non-observable temperature of stream 12 and 44 is calculated using the reconciled enthalpy. The results of some of the estimated temperature can be referred to appendix II.

Graph below show the temperature changes made to each of the stream's temperature.

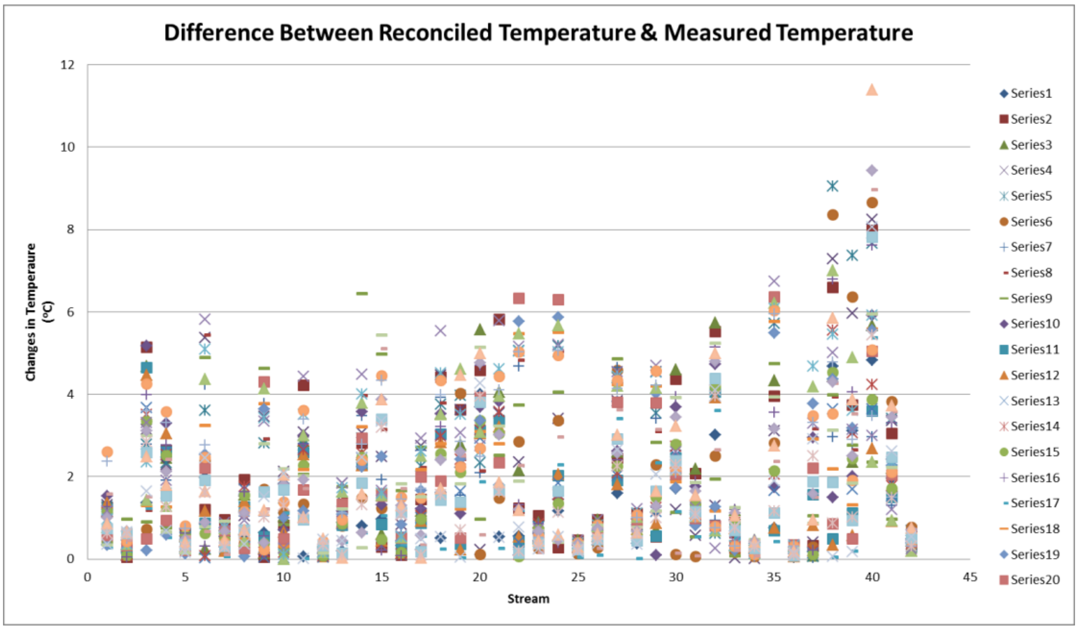

Figure 6: Percentage Different of Reconciled Temperature

The average adjustment of temperature for most of the stream around 5°C. Stream 39, 40, and 41 the high adjustment with stream 41 having and adjustment up to 11.4°C. This might be explained with the effect of estimated properties for crude stream. The PETROSIM software estimated the properties of crude based on the composition of crude blend at respective day. The data is taken based on the average value per hour for each day either form 6.00 am to 6.00 pm. However, the change of crude blend composition can happen at any point in that duration. Therefore, the measurement data obtained is not the right value for respective crude blend composition for each day. The properties estimated is not a correct one, thus cause a huge adjustment in the reconciled data.

E-1173

Besides high adjustment, the reconciled temperatures on streams around E-1173 a certain dates violate thermodynamic feasibility. The violation is summarizing as table below:

Table 5: Temperature Variation in E-1173

Day/Temperature	T_H inlet °C	T_H oulet °C	T_C inlet °C	T_C outlet °C
1/9/2013	175.7	174.13	144.95	147.63
18/9/2013	168.55	168.71	145.59	141.95

As see from the table above, the reconciled temperatures at 1st September 2014 is thermodynamic feasible, where the heat is transfer from the region of high temperature to region of low temperature. However, at 18th September, supposedly hot stream is getting heated from 168.55 ^{o}C to 168.71^{o}C while the crude (cold) stream is getting cooled from 145.59 ^{o}C to 141.95 ^{o}C. Although the reversible role of hot and cold stream is possible depending on the prevailing flows and temperatures, what is unacceptable here is there is a heat transfer from the region of low temperature to high temperature which is thermodynamically infeasible (Narasimhan, S. & Jordache, J., 2000).

4.2 Fouling Analysis

The reconciled temperature is reconciliation procedure above is used in the fouling calculation. There are 14 in total heat exchangers in the network:

a. E-1101
b. E-1102
c. E-1103
d. E-1104
e. E-1105
f. E-1106
g. E1107
h. E-1108
i. E-1109
j. E-1110
k. E-1111
l. E-1112
m. E-1171 (new)
n. E-1172 (new)
o. E-1173 (new)

The unprocessed crude will go through the heat exchanger from E-1101 to E-1172 in a tube side except for the E-1104, E-1108 and E-1111, crude will flow in shell side. All the heat exchanger is a shell and tube heat exchanger except for E-1173. E-1173 is a Compabloc heat exchanger; a type of plate heat exchanger. Therefore, its calculation will different from other. The products that were used to preheat the crude are shown in the table below:

Table 6: Stream in Heat Exchangers

Heat Exchanger	Shell Side	Tube Side	Type
E-1101	Top P/A	Crude	Shell and tube
E-1102	Kerosene	Crude	Shell and tube

E-1103	Light Kero	Crude	Shell and tube
E-1104	Crude	LSWR	Shell and tube
E-1105	Light Kero	Crude	Shell and tube
E-1106	Kerosene	Crude	Shell and tube
E-1107	Diesel	Crude	Shell and tube
E-1108	Crude	LSWR	Shell and tube
E-1109	Diesel P/A	Crude	Shell and tube
E-1110	AGO P/A	Crude	Shell and tube
E-1111	Cride	LSWR	Shell and tube
E-1171	Diesel	Crude	Shell and tube
E-1172	Kerosene	Crude	Shell and tube
E-1173	Light Kero	Crude	Compabloc

4.2.1 Analysis of Heat Exchanger Performance

The fouling models for all heat exchanger have been done by previous projects except for the newly installed heat exchangers of E-1171, E-1172 and E-1173. Therefore, the fouling model for the 3 heat exchanger is carried out.

Fouling Model Development

The rate of heat transfer across the tube wall between product and crude stream is given by

$$Q = U_a A F \Delta T_{LM}$$

Where

Q = Heat transfer, W

U_A = Overall heat transfer coefficient, W/m^2. ^{o}C

A = Heat Transfer Area, m^2

$LMTD = \Delta T_{LM}$ = Log Mean Temperature Difference in ^{o}C = $\frac{(T_i - t_2)(T_2 - t_1)}{ln\left[\frac{(T_1 - t_2)}{(T_2 - t_1)}\right]}$

T = Hot fluid Temperature

t = Cold Fluid Temperature

F = LMTD correction factor

1 = inlet

2 = outlet

Value of F is calculated using the relation given by Bowman et al. (1940). The calculation is given as below

$$P = \frac{T_{c2} - T_{c1}}{T_{h2} - T_{c1}} \qquad R = \frac{T_{h1} - T_{h2}}{T_{c2} - T_{c1}}$$

$$X = \frac{1 - \left(\frac{RP-1}{P-1}\right)^{\frac{1}{N}}}{R - \left(\frac{RP-1}{P-1}\right)^{\frac{1}{N}}}$$

$$F = \frac{\left(\frac{\sqrt{R^2+1}}{R-1}\right) ln\left(\frac{1-X}{1-RX}\right)}{\left(\frac{\frac{2}{X} - 1 - R + \sqrt{R^2+1}}{\frac{2}{X} - 1 - R - \sqrt{R^2+1}}\right)}$$

Where

T_{c1} = Inlet temperature of cold streams, ^oC

T_{c2} = Outlet temperature of cold streams, ^oC

T_{h1} = Inlet temperature of hot streams, ^oC

T_{h2} = Outlet temperature of hot streams, ^oC

N = Number of shell pass

F = LMTD correction factor

The heat transfer can also be calculated using the energy balance on the hot or cold stream and given as below (Biyanto, R.T. & Ramasamy, M., 2012).

$$Q = m_c Cp_c \Delta T_c = m_h Cp_h \Delta T_h$$

Where

m = mass flow rate, kg/hr

Cp = heat capacity, W/kg. °C

ΔT = Temperture difference, °C

c = Cold fluid

h = Hot Fluid

Tube Side Film Heat Transfer Coefficient

The designed film heat transfer coefficient for tube side is calculated using the equation obtain from Smith (2005) with the assumption that $\mu / \mu_W = 1$

$$h_t = K_{hT} v_T^{0.8}$$

Where

h_T = tube side heat transfer coefficient, W/m^2 .°C

K_{hT} $= 0.023 \left(\frac{k}{d_i}\right) Pr^{1/3} \left(\frac{d_i \rho}{\mu}\right)^{0.8}$

k = fluid thermal conductivity, W/mk

Pr = Prandtl number

$= \frac{C_p \mu}{k}$

Cp = fluid heat capacity, J/kg. °C

The film heat transfer coefficient on the tube side under various process conditions is calculated as a correction at design condition (Mohamad Zin, 2010).

$$\frac{h_{ta}}{h_{td}} = \left(\frac{V_a\rho_a}{V_d\rho_d}\right)^{0.8} \left(\frac{\mu_a}{\mu_d}\right)^{-0.4} \left(\frac{c_{pa}}{c_{pd}}\right)^{0.4} \left(\frac{k_a}{k_d}\right)^{0.6}$$

Shell side heat transfer coefficient

The calculation for shell side heat transfer coefficient is more complex compare to tube side where many parameter are involve. One of the most used methods for estimation shell-side heat transfer coefficient for the vertical segmental baffle shells is the Bell-Delaware method. The simplified version of this calculation is taken from (Smith, 2005). At turbulence condition,

$$h_s = \frac{0.24 F_{hn} F_{hw} F_{hb} F_{hL} \rho^{0.64} C_P^{1/3} k^{2/3} v_s^{0.64}}{\mu^{0.307} d_0^{0.36}}$$

Where,

h_s = shell side heat transfer coefficient, W/m^2 .^{o}C

d_o = tube outer diameter, m

F_{hn} = correction factor to allow for the effect of the number rows crossed

F_{hw} = the window correction factor.

F_{hb} = the bypass stream correction factor.

F_{hL} = the leakage correction factor.

v_s = shell side velocity, m/s

The value of correction factors are chosen based on the guideline provide by Sinnot (2005).

The shell side heat transfer coefficient at various process conditions is calculated as the correction from the design conditions. E-1171 and E-1172 use segmental baffles. h_{as} for heat exchanger using segmental baffles is calculate by:

$$\frac{h_{sa}}{h_{sd}} = \left(\frac{V_a \rho_a}{V_d \rho_d}\right)^{0.7} \left(\frac{\mu_a}{\mu_d}\right)^{-0.32} \left(\frac{c_{pa}}{c_{pd}}\right)^{1/3} \left(\frac{k_a}{k_d}\right)^{2/3}$$

Overall heat transfer coefficient under clean conditions is given by subtracting the fouling effects from equations above.

Overall Heat Transfer Coefficient

At clean condition, overall heat transfer coefficient, U_c is calculated using expression below:

$$\frac{1}{U_c} = \frac{d_o}{d_i h_i} + \frac{d_o R_{fi}}{d_i} + \frac{d_o ln\left(\frac{d_o}{d_i}\right)}{2k_w} + R_{f,o} + \frac{1}{h_o}$$

At fouled condition, overall heat transfer coefficient, U_a is calculated using expression below:

$$Q = U_a A F \Delta T_{LM}$$

Plate Heat Exchanger E-1173 (Compabloc)

The film heat transfer coefficients for E-1173 could not be calculated due to lack of information available such as the distance between plates and size of the plates. As for now, the calculation of overall heat transfer coefficient at fouled condition is calculated using expression below

$$Q = U_a A F \Delta T_{LM}$$

At clean condition, since this heat exchanger is still new, the value of overall heat transfer coefficient is taken as per design which is 999 W/m2. ^{o}C.

Fouling Resistance

The fouling resistance is calculated by the difference between the actual (fouled) and clean heat transfer resistances and is given by:

$$R_f = \frac{1}{U_a} + \frac{1}{U_c}$$

Fouling Analysis

In fouling analysis, a set of calculation was done to determine the fouling status in a heat exchanger. The fouling model for the new heat exchanger E-1171 to E-1173 is calculate using the already developed model for other heat exchanger with the adjustment in several parameter specific to the heat exchanger. The fouling resistance is then obtained and analysed.

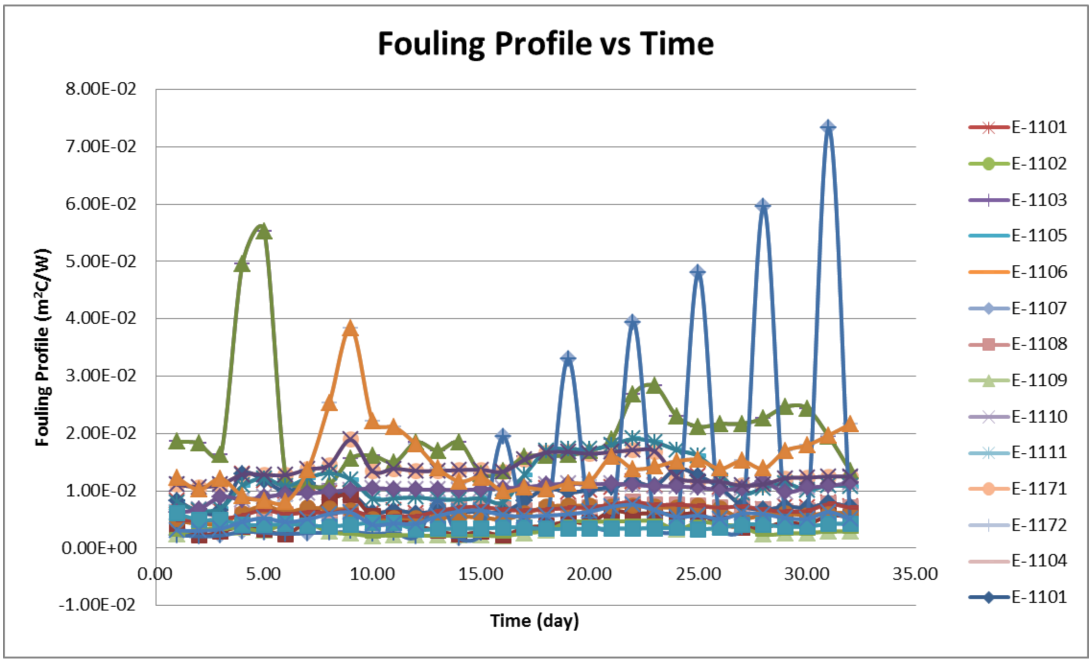

Figure 7: Fouling Profile along Time

From the figure above, E-1107 show a seesaw fouling pattern.. The other heat exchangers show an irregular pattern. As for heat exchanger E-1173, the fouling analysis could not be done due to error in reconciled temperature as stated in previous topic.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

This project is important in other to assess the performance of heat exchanger network in refinery industry. Implementation of data reconciliation technique to treat data measured will reduce the random error in the reading, thus more accurate measurement is obtained. This treated data will then allow optimal performance of heat exchanger network. Using the reconciled data, fouling profile of each heat exchanger a long time is develop. The developed model will enable proper scheduling of heat exchanger cleaning.

The result obtained from the data reconciliation procedure show that the model did obeyed the energy balance of the process. However, the adjustment made into the raw data is high; reach up to 10^{o}C of adjustment (stream 37). The fouling model is successfully developed. It is found that the foulest heat exchanger in the crude preheat train is E-1107. The E-1173 fouling calculation cannot be done due to the reconciled temperatures on streams around E-1173 violate thermodynamic feasibility

It is recommended that, the data measurement is made at the correct time where the crude blend composition starting to change. As for the problem at the temperature measurement at inlet and outlet of hot stream at E-1173, it is recommended to implement the solution suggested by Narasimhan & Jordache (2000). Narasimhan & Jordache (2000) suggest to include the relation between overall heat transfer coefficient (U) and heat load for every heat exchanger and imposing a nonnegativity restriction on U. This will ensure that thermodynamic feasibility is maintained. The calculation of fouling model for E-1173 can be improved by considering the effect of film to heat transfer. For this recommendation, more data on E-1173 are needed such as the distance between plates.

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APPENDICCES

Appendix I

a) Incidence Matrix, A:

[	1	0	-1	1	-1	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
	0	0	1	0	0	-1	1	-1	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	1	0	0	0	;	
	0	0	0	0	0	1	0	0	-1	1	-1
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
	0	0	0	0	0	0	0	0	1	0	0
	1	-1	1	0	0	-1	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
	0	0	0	0	0	0	0	0	0	-1	0
	0	0	0	0	0	0	1	0	-1	1	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
	0	0	0	0	0	0	-1	0	0	0	0
	0	0	0	0	0	0	0	0	1	0	-1
	1	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	

0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1
0	-1	1	-1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0	0	0	0
0	1	0	0	-1	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	-1	1	-1	0	0
0	0	0	0	0	0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	-1	1
-1	0	0	0	0	0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	-1	0	0	0	1	0
0	-1	1	0	0	0	0	0	0	;	
0	1	0	0	0	0	0	0	0	0	0
0	0	-1	1	-1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	-1	1	-1	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	-1	1	-1	]	

b) Covariance Matrix, V:

[	468878452.2		0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	;
0	9747822.591		0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
0	0	641643220.7		0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
0	0	0	1391536791		0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
0	0	0	0	311750626.9		0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
0	0	0	0	0	787563785.2		0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
0	0	0	0	0	0	1914049.523		0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	
0	0	0	0	0	0	0	6029649.482		0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	;	

0 0 0 0 0 0 0 0 397104617.9 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 713796029.7 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0
130467119.5 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
;
0 0 0 0 0 0 0 0 0 0 0
20251809.75 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
47640949.72 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 24370618.71 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 160009939.3 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 53574886.69 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;

0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 101755577.1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 504218244.2 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 5234335.8 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1065139657 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 179002946.3 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0
1507324554 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0
923533.8732 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
1109069319 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;

0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 1459088.461 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 3051527.372 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 616797997.8 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 48007614.5 0 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 794578340.1 0 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 70457584.62 0 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 33566320.38 0 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 444019143 0
0 0 0 0 0 0 0 0 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0

	0	0	0	0	0	0	0	0	0		
	2320036.15		0	0	0	0	0	0	0	0	0
	;										
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	
	886935.8244		0	0	0	0	0	0	0	0	;
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	869274056		0	0	0	0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	20808492.72		0	0	0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	3771356.914		0	0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	8523486.155		0	0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	6263654.972		0	0	0	;	
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	10531082.62		0	0	;	
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 877896.1887 0 ;
0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 177825.6566]

Appendix II

Table of Reconciled Enthalpy and Calculated Enthalpy (sample)

Stream	Calculated Enthalpy kJ	Reconciled Enthalpy kJ
1	4.00E+10	3.98E+10
2	4.90E+09	4.43E+09
3	5.95E+10	6.26E+10
4	1.72E+11	1.98E+11
5	1.53E+11	1.76E+11
6	7.79E+10	8.16E+10
7	1.14E+10	1.21E+10
8	1.33E+10	1.45E+10
9	9.55E+10	9.89E+10
10	1.33E+11	1.52E+11
11	1.16E+11	1.34E+11
13	7.47E+10	6.54E+10
14	4.65E+10	4.76E+10
15	1.82E+10	1.37E+10
16	7.33E+10	7.38E+10
17	6.00E+10	6.45E+10
18	1.42E+11	1.17E+11
19	1.38E+11	1.23E+11
20	1.21E+10	1.2E+10
21	1.61E+11	1.37E+11
22	1.56E+11	1.66E+11
23	1.65E+11	1.41E+11

24	1.55E+10	1.6E+10
25	1.71E+11	1.47E+11
26	1.64E+10	1.67E+10
27	1.00E+10	1.03E+10
28	2.03E+11	1.75E+11
29	1.07E+11	9.32E+10
30	2.23E+11	1.92E+11
31	1.11E+11	1.27E+11
32	9.13E+10	1.09E+11
33	2.33E+11	1.98E+11
34	3.57E+10	2.05E+10
35	2.65E+10	1.44E+10
36	2.49E+11	2.16E+11
37	1.23E+11	1.11E+11
38	1.47E+10	1.49E+10
39	2.29E+10	2.43E+10
40	2.03E+10	2.13E+10
41	1.53E+10	1.53E+10
42	6.71E+10	6.74E+10
43	6.65E+10	6.7E+10

Reconcile Temperature

Stream	Measured Temperature ^oC	Reconciled Temperature ^oC
1	40.06576	39.880476
2	30.33812	30.308941
3	63.17607	56.528283
4	152.2353	149.55624
5	136.0461	138.19447
6	77.4192	84.736473
7	160.573	158.47223
8	80.33152	80.713252
9	95.77521	94.711122

10	169.5603	167.88668
11	147.8649	157.21376
12	Not measured	116.11168
13	226.5281	230.13539
14	159.8582	163.74535
15	113.6348	113.94726
16	166.7947	164.76496
17	133.8235	135.24194
18	119.9173	Not reconciled
19	124.2482	117.80482
20	124.2482	123.10125
21	140.7642	137.32168
22	192.6638	178.03283
23	144.5451	140.63084
24	216.2436	213.48734
25	150.1514	148.49112
26	268.628	265.42203
27	165.4094	166.60434
28	169.1123	177.53124
29	284.3056	273.52962
30	182.7078	187.10799
31	279.0541	264.68292
32	235.784	245.80867
33	189.2231	194.3281
34	334.6441	331.71633
35	233.433	234.94057
36	200.4949	210.99283
37	330.9766	307.62576
38	145.0366	147.52936
39	207.6075	204.58189
40	189.3527	187.85874
41	148.3258	147.39615
42	166.7947	170.70394

43	174.9188	170.73979
44	Not measured	179.14995