Synthesis of Heat Exchangers Network (HEN)
by Revisiting the Method Based on
2^{nd} Law of Thermodynamics

by

Hoo Shean Chuan

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

(DR. SHUHAIMI MAHADZIR)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

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

HOO SHEAN CHUAN

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ABSTRACT

As the project title implies, this project is basically about synthesizing an optimum heat exchanger network (HEN) by using a new approach which revisits *second law of thermodynamics*. This paper is started with introduction which gives an overview of project background, problem statement, objective, and scope of project.

Then, literature review gives clearly about the theory of the project. The following section touches on methodology of the project. Algorithm of HEN has been displayed in this section. This project requires using simulation tools, such as HYSYS to find out the relationship between total exergy lost and hot stream outlet temperature.

Formulation has been performed to obtain generic function equations for C_p, H_f, S_f, H_{fg}, S_{fg}. In the formulation process, Graph Software is used to choose the best fit trends for all these values with respect to their temperatures.

Generic function equations are then used in the calculation of energy balance and exergy lost. All calculations are computed in a template in Microsoft Excel. $T_{hot\ out}$ and $C_{p\ cold\ out}$ are considered as manipulated variables to decide the lowest exergy lost of the HEN. To solve for the minimum exergy lost of HEN more conveniently, "solver" in Microsoft Excel is used.

Finally, the project is concluded in the last section. Recommendations on procedures are also stated to improve the method. Future works are including the transformation of algorithm into GAMS or other mathematical programming tools.

ACKNOWLEDGEMENT

I would like take this opportunity to acknowledge people who had given immeasurable amount of guidance, ideas, assistance, support and advice throughout the whole period conducting the Final Year Research Project.

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CHAPTER 1
INTRODUCTION

1.1 Background

As a results of constant increase of energy consumption, the need for its rational usage increases too. To save energy, the analysis methods, synthesis and optimization using *second law of thermodynamics* are becoming significantly important. Its application could give good results in power and chemical plants optimization and thus, it is possible to obtain a significant increase of process efficiency.

Traditionally, *mass conservation law* and *first law of thermodynamics* are the basis of energy studies. Then, it is included by means of entropy, which is not feasible because of its non-conservability and absence of any direct and definite physical meaning. The usage of second law is very simplified when the concepts of available work or exergy are introduced. It is closer to the terms of mass and energy, and has a concrete physical meaning. However, it is not conservative yet - meaning that exergy conservation equations can be easily formulated and used, like the ones for mass and energy, which results in an additional set of equations. General acceptance of exergy could lead to a wide usage of *second law of thermodynamics* in all phases of the designing process - synthesis, analysis and optimization (Zivkovic P., 2004).

1.2 Problem Statement

Pinch analysis has been widely used in Heat Exchanger Network (HEN) for minimizing the energy consumption of chemical processes by calculating feasible energy targets (minimum energy consumption) thermodynamically and achieving them by optimizing heat recovery systems, energy supply methods and process operating conditions.

Figure 1.1 shows energy flows, or streams, as a function of heat load (kW) against temperature (°C). This data is combined for all streams in the plant to give composite curves, one for all "hot streams" and one for all "cold streams".

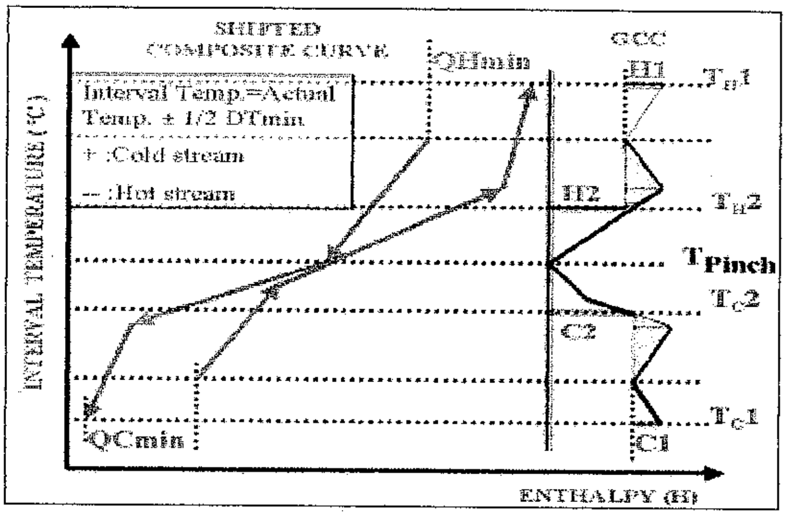

Figure 1.1: Composite curve of temperature versus enthalpy.
(Retrieved from http://www.cheresources.com/pinchtech4.shtml)

Pinch temperature is the point of closest approach between the hot and cold composite curves. The pinch divides the process into two thermodynamically systems. Each is in enthalpy balance when utility targets are applied (B.Linnhoff, 1988). It is where the design is *most constrained*. At this point, determination of ΔT_{min} for an optimum HEN synthesis is questionable. Normally, ΔT_{min} is assumed in pinch analysis before calculating energy consumption. Hence, by finding this point and starting design there, the energy targets can be achieved using heat exchangers to recover heat between hot and cold streams. In practice, during the pinch analysis, often cross-pinch heat exchanges are found between a stream with its temperature above the pinch and one below the pinch. Removal of those heat exchangers by alternative matching make the process reaches its energy target.

1.3 Objective

The main objective of this project is to synthesize optimum HEN by looking for the lowest total exergy lost of all hot and cold streams and also to determine pinch temperature.

1.4 Scopes

This research project is started with analysis on possibility of generating the minimum exergy losses on a HEN which consists of one hot stream and one cold stream. By revisiting *second law of thermodynamics*, it is to find out whether the initial solution of the HEN, generated by pinch design rules and plus and minus principle in the phase of targeting be the only solution with best performance.

The project is also to develop an exergy approach to synthesize an optimum HEN. The scopes include:

(a) Calculating exergy change for a hot stream and a cold stream in a HEN.
(b) Finding out the relation between exergy lost and different temperatures.
(c) Considering the lowest exergy lost in optimum HEN synthesis.
(d) Developing a common HEN algorithm.
(e) Producing a quantitative template of exergy calculation in Microsoft Excel.
(f) Determining ΔT_{min} of HEN at the lowest total exergy lost.

CHAPTER 2
LITERATURE REVIEW

2.1 Exergy Analysis

Exergy analysis combines *first* and *second laws of thermodynamics* to analyze both quantity and quality of energy utilization. Exergy of a system is defined as maximum work obtainable while a process brings the system into equilibrium with surroundings. For processes involving only heat transfer, the exergy change is equal to the thermodynamic availability change. After the system and surroundings reach equilibrium (stable environment), the exergy is zero (Mafi, 2008).

Disregarding kinetic and potential energy changes, the **specific exergy** of a fluid at any cycle state:

$$e = h - h_0 - T_0 (s - s_0)$$

where

T_0 = dead state temperature,

h and s = enthalpy and entropy of the fluid at the specified state

h_0 and s_0 = corresponding properties at the dead state.

Thus, **exergy rate** is the multiplication of specific flow exergy and mass flow rate:

$$E = me$$

As a fluid flow from inlet to outlet, reversible work is given by the exergy change between these two states:

$$e_2 - e_1 = h_2 - h_1 - T_0 (s_2 - s_1)$$

where

Subscript 1 and 2 = inlet and exit state for a flowing fluid

First law of thermodynamics states that energy is never destroyed during a process; it changes from one form to another. During a reversible process, no entropy is generated. In contrast, exergy accounts for the irreversibility of an actual process due to increases in entropy. Exergy destruction in a process involves a temperature change. This destruction is proportional to the entropy increases of the system together with its surroundings. The destroyed exergy has been called **anergy**. For an isothermal process, exergy and energy are interchangeable terms, and there is no anergy.

Exergy destruction during a process can be expressed in terms of the entropy generated as

$$i = T_0 s_{gen}$$

where

s_{gen} = entropy generation.

Friction and *heat transfer* across a finite temperature difference are two main causes for entropy generation. **Heat transfer** is always accompanied by exergy transfer, which is given by

$$e_q = \int \delta q \, (1 - T_0/T)$$

where

δq = differential heat transfer

T = boundary temperature where heat transfer takes place

Heat transfer is assumed to take place with surroundings temperature, T_0. If this heat transfer represents an undesired heat loss, equation above also expresses exergy destruction by heat.

Exergy is a co-property of a system and a reference state. Because of this, exergy is neither a thermodynamic property of matter nor a thermodynamic potential of a system. However, it is the most useful application of these values and is derivable from them mathematically. Determination of exergy was also the first goal of thermodynamics. Both exergy and energy have units of joules. Both are also state functions even though work itself is not.

2.2 Second Law of Thermodynamics

Second law of thermodynamics expresses the universal law of increasing entropy, stating that entropy of an isolated system which is not in equilibrium tend to increase over time, approaching a maximum value at equilibrium. There are many versions of *second law of thermodynamics*, but they all have the same effect, which is to explain the phenomenon of irreversibility in nature.

1. In a system, a process can occur only if it increases the total entropy of the universe. Thus, while a system can undergo some physical process that decreases its own entropy, the entropy of the universe (which includes the system and its surroundings) must increase overall.

2. Heat cannot flow spontaneously from a material at lower temperature to a material at higher temperature. This could be seen from the mathematical definition of entropy, a process in which heat flows from cold to hot have decreasing entropy. This is allowable in a non-isolated system, however only if entropy is created elsewhere, such that the total entropy is constant or increasing, as required by *second law of thermodynamics*.

3. Energy extraction by heat from high temperature energy source and then convert all of the energy into work is not possible. At least some of the energy must be passed on to heat a low temperature energy sink. Thus, a heat engine with 100% efficiency is thermodynamically impossible.

Figure 2.1 depicts three characteristic cases of heat transfer considering stream temperature profiles related to ambient temperature. Temperature profile slopes indicate a flow-heat-capacity difference of the shown flows and that an enthalpy change is related to the heat transfer between streams, Q.

If both the streams are at the temperature above the ambient temperature (**Figure 2.1**), the hot stream approaches T_0; therefore, its availability decreases. The cold stream moves away from T_0, and, accordingly, its availability increases.

In other words, the hot stream transfers both heat and ability to the cold stream. According to the 2nd Law of thermodynamics, when driving forces (in form of a minimal temperature difference between flows ΔT_{min} needed for heat transfer) are bigger than differential, all the processes are thermodynamically irreversible so the availability must be "consumed". It is clear, by the space between the lines in **Figure 2.1 (a)**, that the driving force is bigger than differential. Thus some of the availability in the hot stream is consumed.

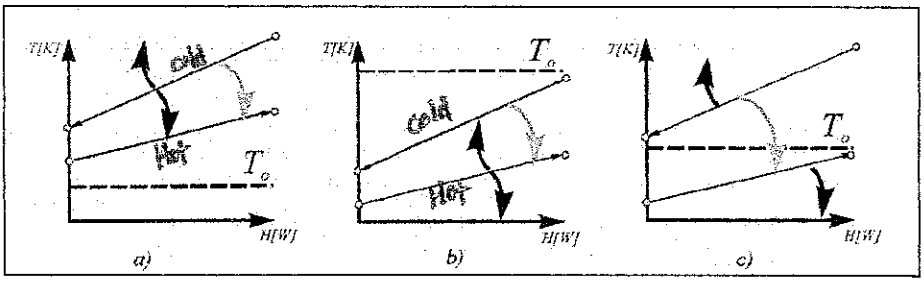

Figure 2.1: Flow availability change analysis in heat transfer processes

The heat transfer process shown in **Figure 2.1 (a)** can be made more thermodynamically reversible by reducing the approximate temperature between 2 streams. However, even with ΔT of zero at the close end, the heat exchange is still not reversible notwithstanding the fact that the infinite heat exchanger is required. Direct heat transfer between 2 streams can be reversible only if the ΔT approaches zero along the entire length of the exchanger, which is represented with identical slopes of T-H lines (identical heat-flow-capacities). In other words, thermodynamic inefficiency increases as the disparity between the heat-flow-capacities increases.

Figure 2.1 (b) depicts heat transfer between the two streams below the ambient temperature. Heat is transferred from the hot stream to the cold stream, as directed by *second law of thermodynamics*. However, it is now the cold stream which approaches the ambient temperature, and therefore decreases in the availability, while the hot stream diverges from the ambient temperature and increases in availability. In heat transfer below ambient, the availability is transferred in the opposite direction from the cold stream to the hot stream.

Figure 2.1 (c) depicts heat transfer between two streams across the ambient temperature. Heat is transferred from hot stream to the cold stream. However, both the streams approach the ambient temperature and accordingly, both streams decrease in availability. Thus, in heat transfer across the ambient, no availability is transferred, but the availability of both streams is consumed. Heat from the ambient could have been used to heat the cold stream. Using the hot stream to heat the cold stream is an unnecessary waste of the temperature's driving force (of availability). The ambient represents a "pinch" temperature. This is from a *second law of thermodynamics* viewpoint, the cornerstone of pinch technology.

The availability analysis leads to another logical question, namely, where does the availability that is not transferred between streams go, that is, how it can be best used. The traditional thermodynamic approach is based on the fact that heat transfer between streams of different heat-flow-capacities cannot be done reversibly, even with an infinite heat exchanger. The reversible work obtainable from the hot stream, or required to heat the cold stream, is

$$W_{rev} = \int (T-T_0)/T \, dQ_H$$

The amount of heat transferred, Q_H from the hot stream is the same as transferred to the cold stream.

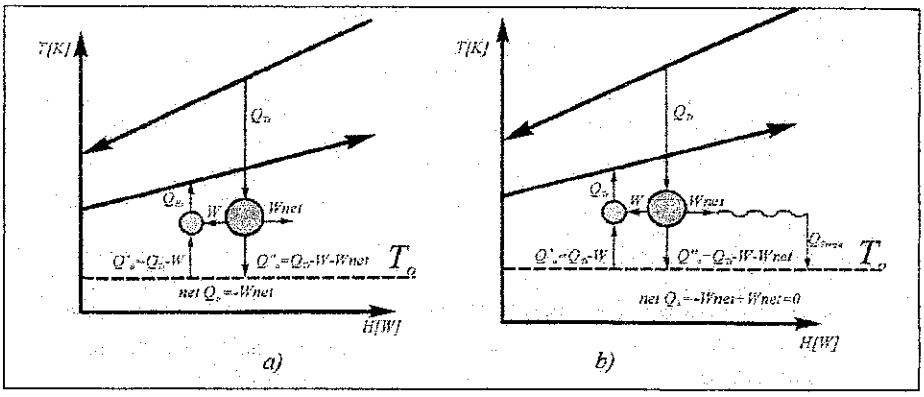

Figure 2.2: Flow availability loss analysis at heat transfer processes

The traditional thermodynamic approach does not take into account the equipment size and cost. The heat exchangers required in reversible heat engines and heat pumps must be infinite in size and are, therefore, infinite in cost. Additionally, it would take an infinite time for heat exchange to occur reversibly. The conclusion this analysis is that it is possible to exchange heat only when there are infinite temperature differences between streams, which causes availability consumption.

Except from the unavoidable availability loss in plants, other losses resulting from the errors observed in the use of the *Second Law of Thermodynamic* can occur. An example is a high pressure steam throttling before being used for heat transfer. No work is produced, and there is no reduction in plant requirements, which increases the cost of the plant.

Heat integration exergetical method represents an interactive method based on the following guidelines for elimination second law errors. The following are simple and common sense second law guidelines were proposed as an aid to detecting, or avoiding, second law errors (Zivkovic P., 2004).

1. Excessive thermodynamic driving forces are not used in process operations.
2. Mixing of streams with differences temperature, pressure or chemical composition is minimized.
3. Don't discard heat at high temperature to the ambient, or to cooling water.
4. Don't heat refrigerated streams with hot streams or with cooling water.

5. When choosing streams for heat exchange, try to match streams where the final temperature of one is close to the initial temperature of the other.
6. When exchanging heat between two streams, the exchange is more efficient if the heat capacities of the streams are similar. If there is a big difference between the two, consider the splitting the stream with the larger heat capacity.
7. Minimize the use of the intermediate heat transfer fluids when exchanging heat between two streams.
8. The more valuable heat (or refrigeration) is, the further its temperature from the ambient is.
9. The economic optimum ΔT at a heat exchanger decreases as the temperature decreases and vice versa.
10. Minimize the throttling of stream, or other gases.
11. The larger the mass flow, the larger the opportunity to save (or to waste) energy.
12. Use simplified exergy consumption calculations as a guide to process modifications.
13. Some second law inefficiencies cannot be avoided unlike others. Concentrate on those which can.

CHAPTER 3
METHODOLOGY

3.1 Basic Heat Exchanger Network (HEN)

The project considers a typical Heat Exchanger Network (HEN). This HEN (**Figure 3.1**) has a heat exchanger, heater and cooler. Water is used as medium fluid in all streams. Literally, hot stream outlet temperature, $T_{hot\ out}$ is always assumed to be same as hot stream target temperature, $T_{hot\ target}$. However, in reality, it is not the case. Thus, a cooler is normally installed to cool the hot stream outlet temperature when it does not reach the target one whereas a heater is used to heat the cold stream outlet temperature when it is apart from the required one. Saturated steam is being used for heating whereas by meeting the industrial requirement, cooling water inlet temperature, $T_{cool\ in}$ is set at 30°C and the outlet temperature, $T_{cool\ out}$ is 40°C.

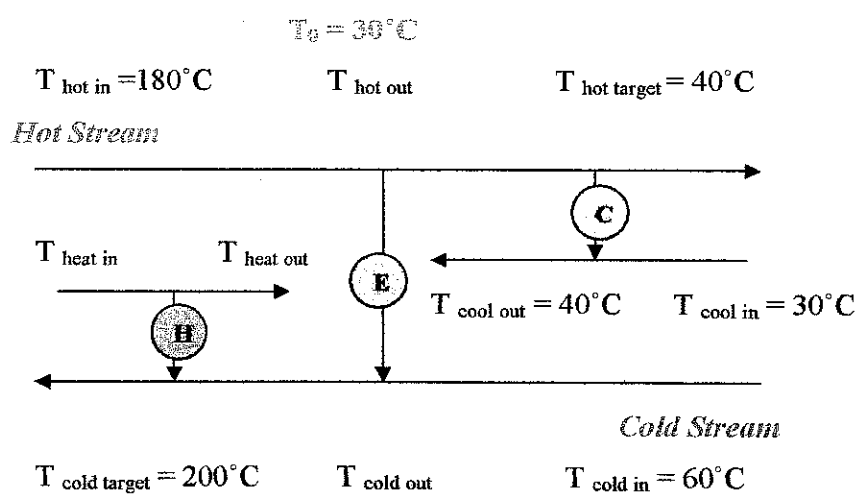

Figure 3.1: A basic HEN with heater and cooler

The exergy generic equation has been used: $Ex = H - T_0S$ where Ex is change of exergy, H is enthalpy, T_0 is ambient temperature and S is entropy. Ambient temperature has been set as 30°C. For saturated steam, latent heat of vaporization, h_{fg} is considered. Exergy for a point should be accounted for its magnitude because exergy has no direction. For heat transfer, change of exergy is mostly considered. Change of exergy, ΔEx for the heat exchanger, heater and cooler are calculated for total exergy lost, $\sum Ex_{lost}$ for the HEN.

In this project, Microsoft Excel and HYSYS simulator have been used. Microsoft Excel is used for complex and tedious numerical calculation of total exergy lost for all streams (hot and cold). Besides, Microsoft Excel is also a tool to do a trending on exergy lost with respect to the manipulated hot stream outlet temperature, $T_{hot\ out}$. HYSYS simulator acts as the source data of enthalpy and entropy values. Besides, steam table is also another useful source data for this project.

After calculation, study has been carried out on these trends. An algorithm is then generated. The algorithm is important for writing code in programming, especially GAMS.

3.2 HEN Algorithm

An algorithm is a sequence of finite instructions used for calculation and data processing. It is formally a type of effective method in which a list of well-defined instructions for completing a task will, when given an initial state, proceed through a well-defined series of successive states, eventually terminating in an end-state.

In this project, it is done after calculation of exergy of all streams have been well defined. The algorithm of this project has been shown in **Figure 3.2**.

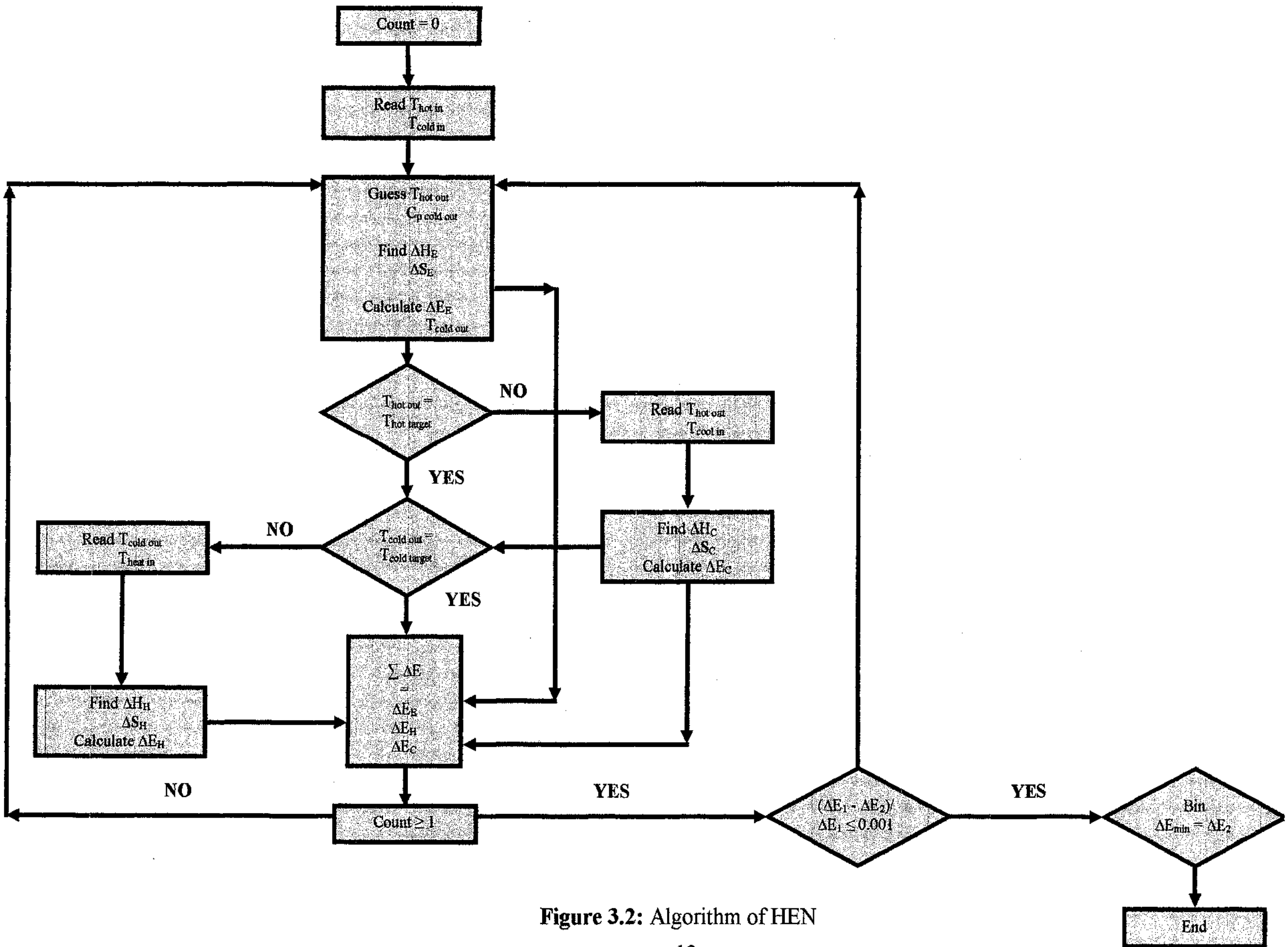

Figure 3.2: Algorithm of HEN

3.3 Model Formulations

A tabulated data retrieved from thermodynamic book is inputted into Graph System to formulate models for specific heat capacity, enthalpy, entropy and latent heat of vaporization with respect to temperatures (refer to **Appendix C**). These trends could be represented by generic equation functions. In other words, when temperatures are given, the four elements (specific heat capacity, enthalpy, entropy and latent heat of vaporization) of the temperatures could be generated in Microsoft Excel by applying the generic equation functions.

Polynomial equation is assumed for all these data (specific heat capacity, enthalpy, entropy and latent heat of vaporization). In the modeling process, R^2 regression line which indicates how fit of the line is concerned in choosing the generic equation functions. Equations with larger R^2 values are used as the generic equation functions. Errors are also calculated to ensure the modeled values are not too far from the tabulated data. Only error less than 5% (equivalent to SSE = 0.005) are accepted (Refer to **Appendix D**). Errors which are more than 5% are not considered for the equation functions. Thus, the generic equation functions are only valid for certain range of temperatures as shown in **Table 3.1**.

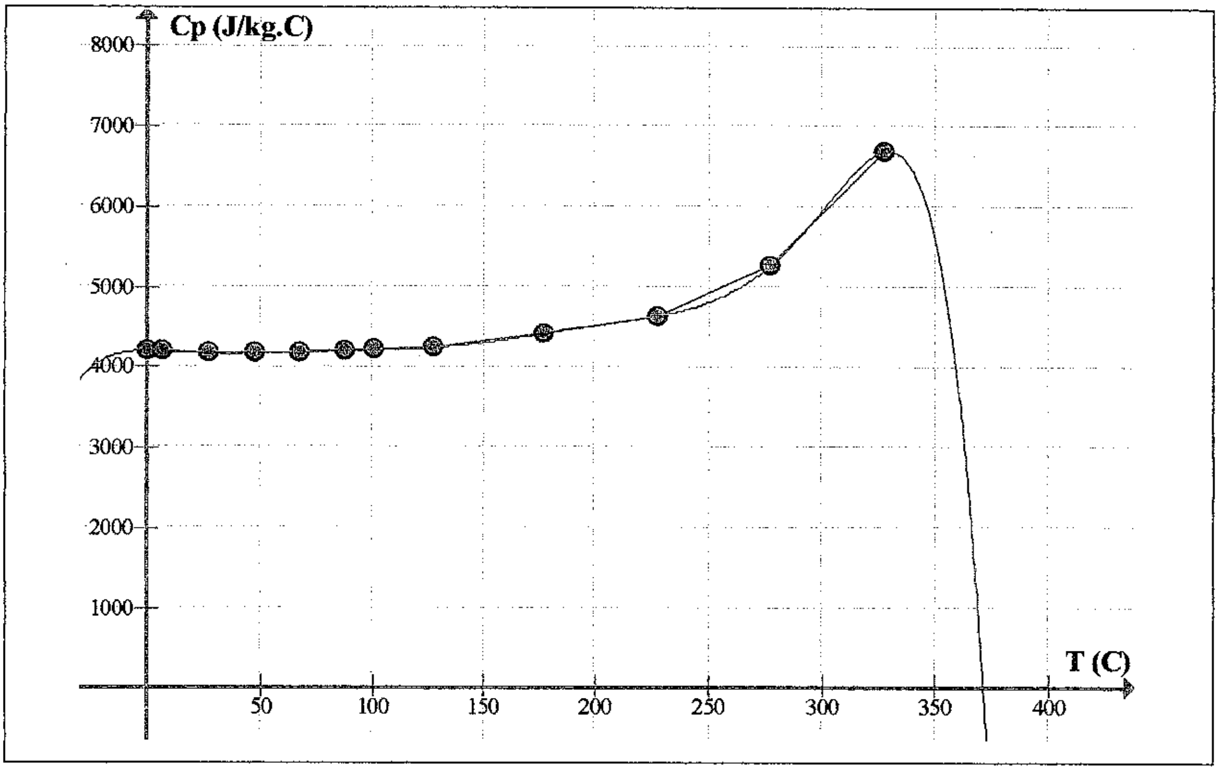

Figure 3.3: Graph of C_p versus T

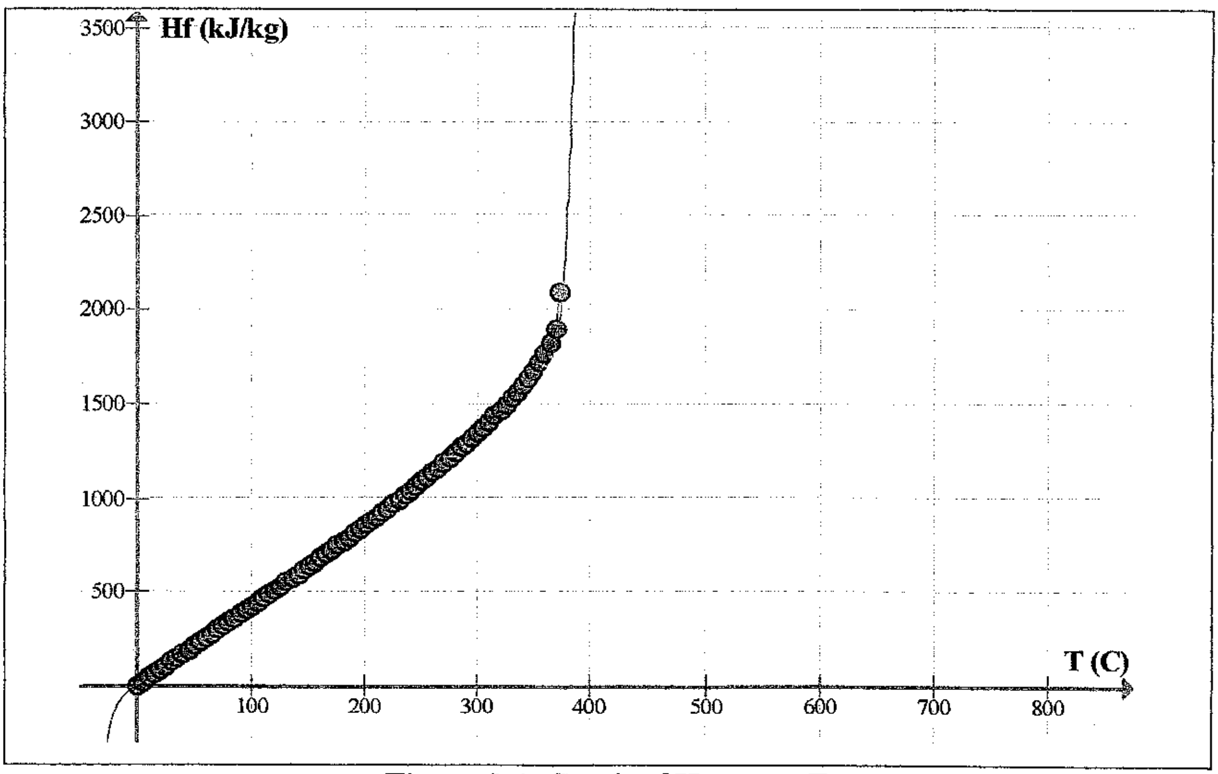

Figure 3.4: Graph of H_f versus T

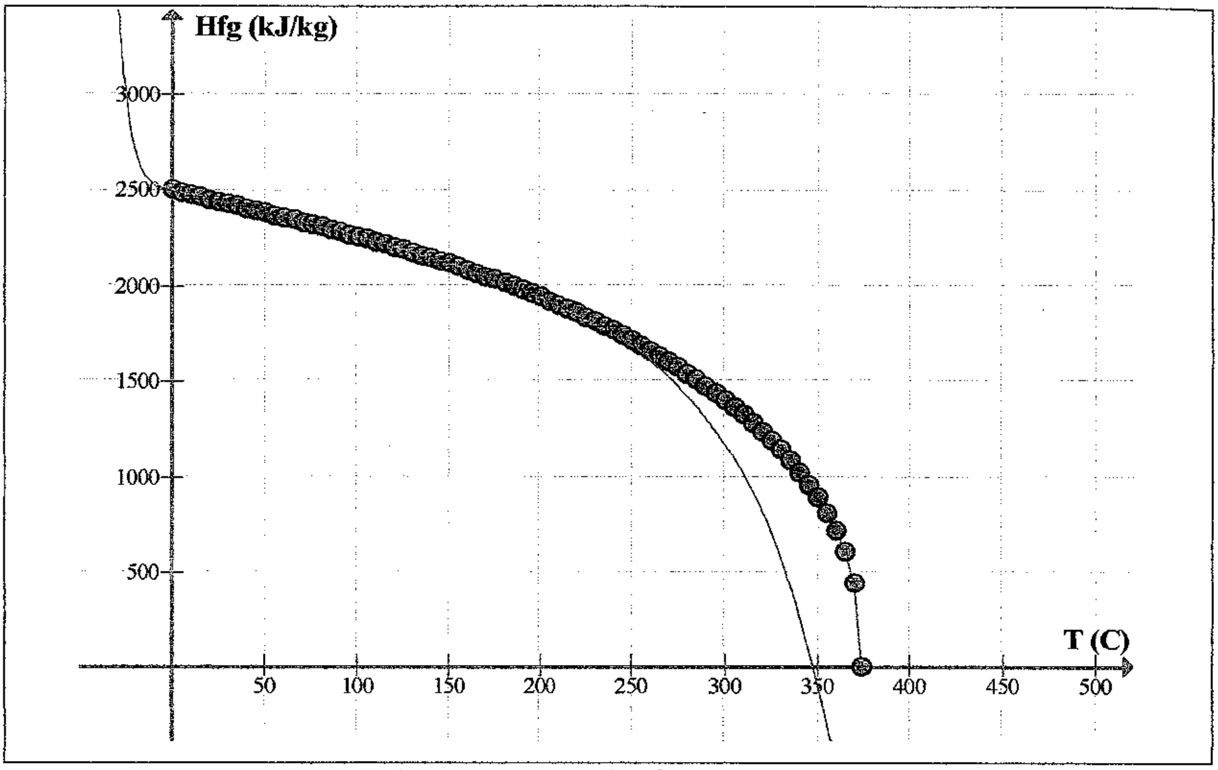

Figure 3.5: Graph of H_{fg} versus T

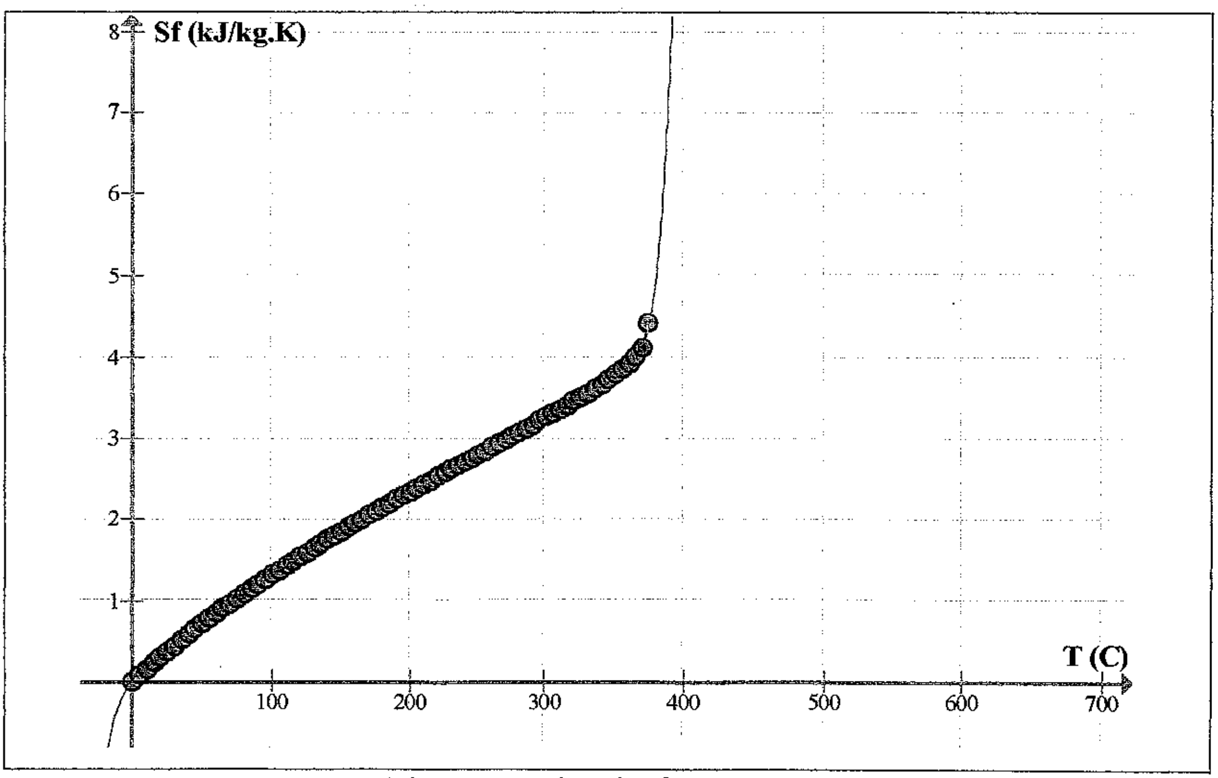

Figure 3.6: Graph of S_f versus T

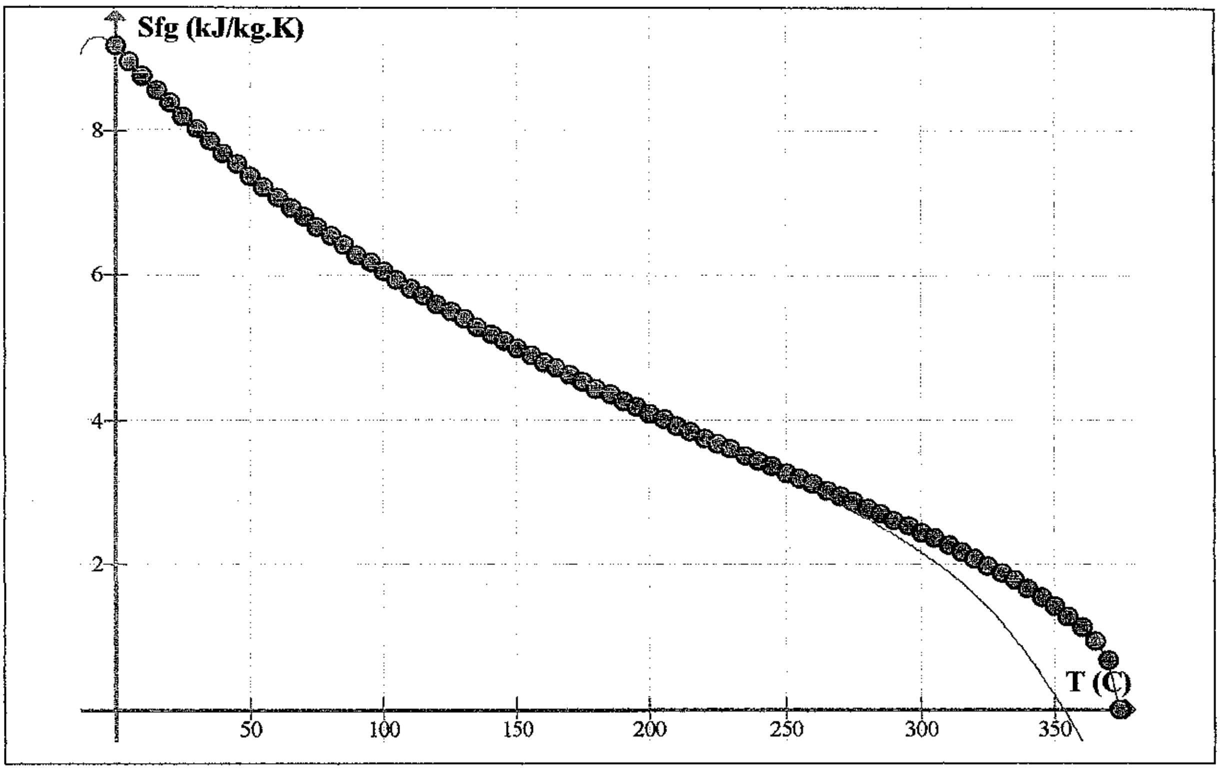

Figure 3.7: Graph of S_{fg} versus T

Table 3.1: Function equations for C_p, H_f, H_{fg}, S_f and S_{fg}

Parameters	**Equations**
C_p	$C_p = -6.031236E\text{-}15T^8 + 0.0000000000068996425T^7 - 0.0000000031335455T^6 + 0.00000072179138T^5 - 0.000088922557T^4 + 0.0056472219T^3 - 0.14828461T^2 + 0.24153542T + 4203.456$ **Range :** 0 - 326.8 °C
H_f	$H_f = 1.7813417E\text{-}30T^{15} - 4.5507602E\text{-}27T^{14} + 5.1978755E\text{-}24T^{13} - 3.502434E\text{-}21T^{12} + 1.5469261E\text{-}18T^{11} - 4.7057934E\text{-}16T^{10} + 1.0082306E\text{-}13T^9 - 1.5288166E\text{-}11T^8 + 1.6247234E\text{-}09T^7 - 1.1795386E\text{-}07T^6 + 5.57788E\text{-}06T^5 - 0.00015750345T^4 + 0.0022106007T^3 - 0.0078641879T^2 + 4.1331407T + 0.13602907$ **Range :** 5 – 373.95 °C
H_{fg}	$H_{fg} = -4.1094412E\text{-}30T^{15} + 1.0493516E\text{-}26T^{14} - 1.1979607E\text{-}23T^{13} + 8.0674378E\text{-}21T^{12} - 3.560743E\text{-}18T^{11} + 1.0822954E\text{-}15T^{10} - 2.3164291E\text{-}13T^9 + 0.000000000035075938T^8 - 0.0000000037202563T^7 + 0.00000026926182T^6 - 0.000012665089T^5 + 0.00035357146T^4 - 0.0047938506T^3 + 0.011529828T^2 - 2.1576794T + 2500.5161$ **Range :** 0.01 – 305 °C
S_f	$S_f = 8.0692604E\text{-}29T^{13} - 1.873405E\text{-}25T^{12} + 1.9228998E\text{-}22T^{11} - 1.1487899E\text{-}19T^{10} + 4.4257812E\text{-}17T^9 - 1.1509791E\text{-}14T^8 + 2.0556459E\text{-}12T^7 - 2.5155834E\text{-}10T^6 + 2.0674002E\text{-}08T^5 - 1.0950787E\text{-}06T^4 + 3.4817898E\text{-}05T^3 - 0.00060780556T^2 + 0.019177244T - 0.0031852377$ **Range :** 5 – 373.95 °C
S_{fg}	$S_{fg} = -1.7119655E\text{-}30T^{14} + 4.2872679E\text{-}27T^{13} - 4.7900571E\text{-}24T^{12} + 3.1493118E\text{-}21T^{11} - 1.3532265E\text{-}18T^{10} + 3.9910587E\text{-}16T^9 - 8.2566824E\text{-}14T^8 + 0.00000000001203202T^7 - 0.000000001222315T^6 + 0.000000084362616T^5 - 0.0000037773132T^4 + 0.00010106076T^3 - 0.0012725445T^2 - 0.034453531T + 9.1516268$ **Range :** 0.01 – 315 °C

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Relation Between Exergy Lost and T $_{hot\ out}$

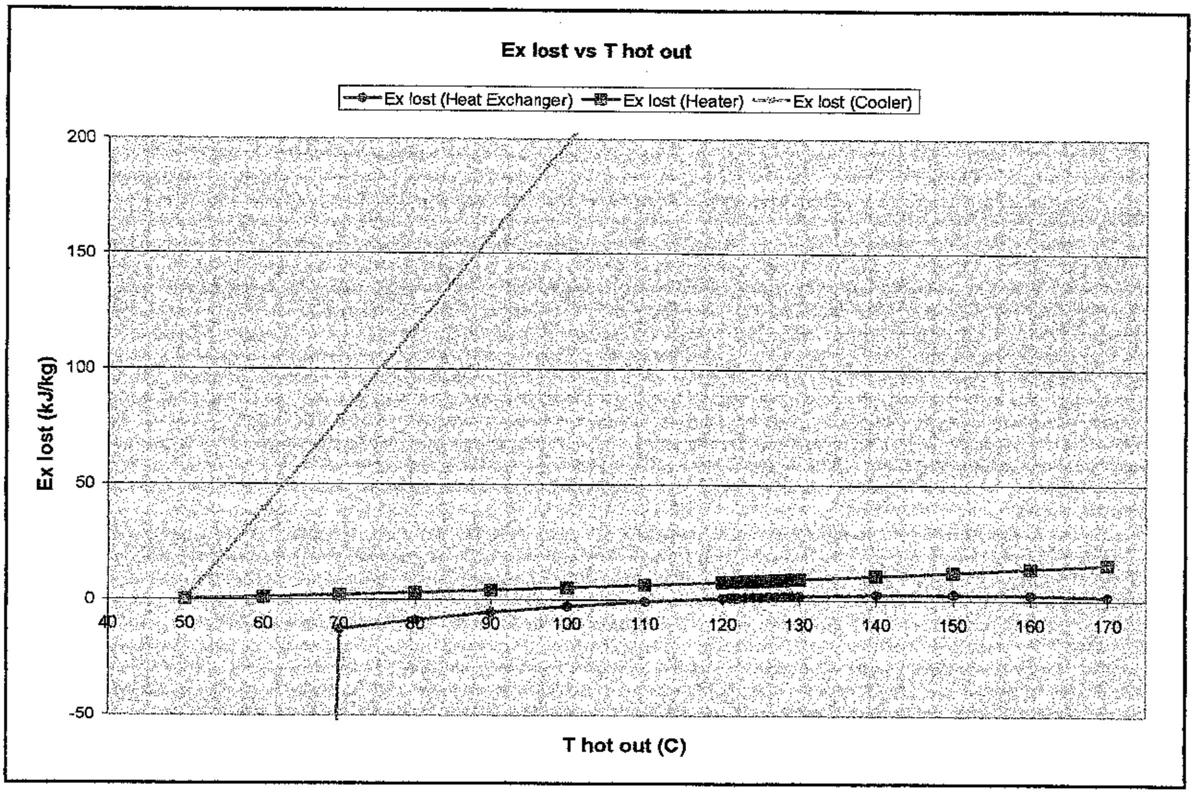

Figure 4.1: Exergy lost for heat exchanger, heater and cooler versus hot stream outlet temperature

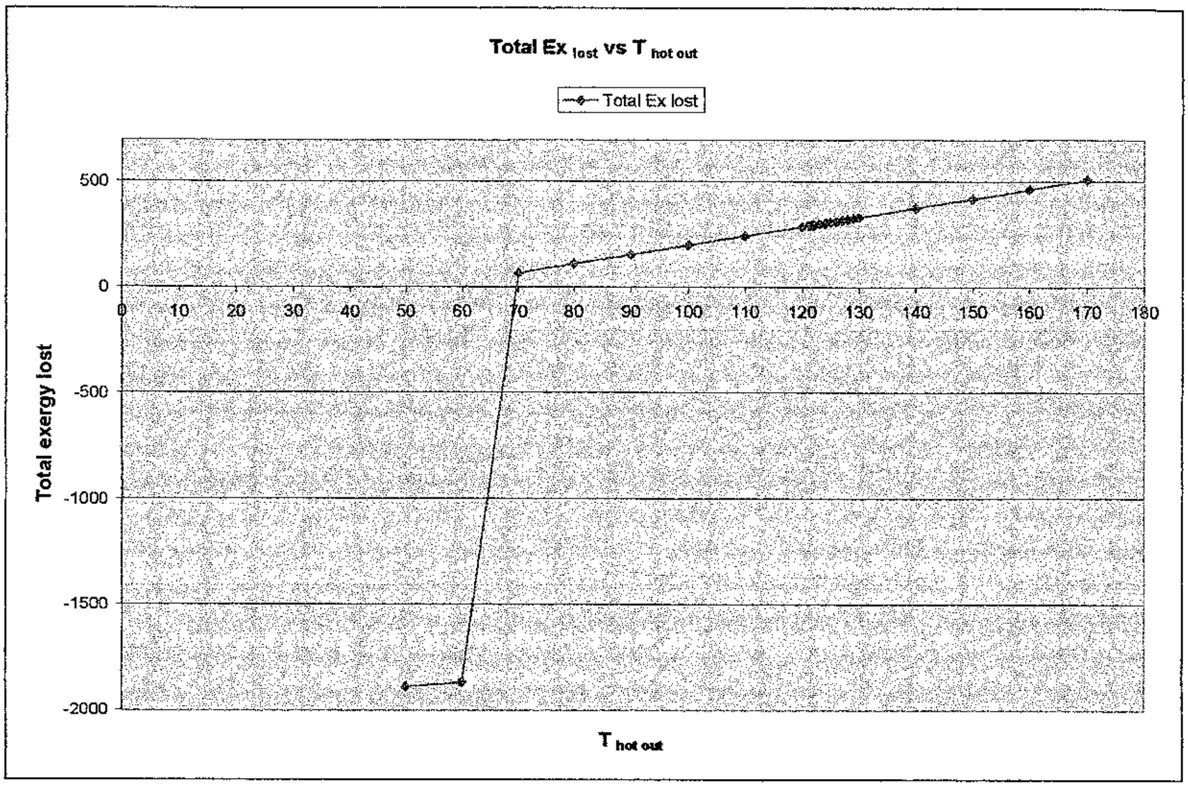

Figure 4.2: Total exergy lost, $\sum Ex_{lost}$ versus hot stream outlet temperature, $T_{hot\ out}$

In the case study, exergy lost for heat exchanger, heater and cooler with respect to the manipulated hot stream outlet temperature, $T_{hot\ out}$ are trended as shown in **Figure 4.1**. For heat exchanger, negative exergy lost, which is impractical, increases from hot stream outlet temperature, $T_{hot\ out}$ = 70°C to no exergy lost at $T_{hot\ out}$ = 115°C. Then, exergy lost increases to the maximum of 0.77 kJ/kg at $T_{hot\ out}$ = 80°C. Beyond that, exergy lost decreases till $T_{hot\ out}$ = 80°C. For both heater and cooler, exergy lost with respect to $T_{hot\ out}$ increases from 50°C to 170°C. Compared to heater, cooler has an extreme increase in exergy lost with respect to $T_{hot\ out}$.

Total exergy lost, $\sum Ex_{lost}$ with respect to the manipulated $T_{hot\ out}$ are trended in **Figure 4.2**. It is observed that total exergy lost, which is negative initially, increases from $T_{hot\ out}$ = 50°C to $T_{hot\ out}$ = 70°C. Beyond $T_{hot\ out}$ = 70°C, $\sum Ex_{lost}$ increases with respect to $T_{hot\ out}$ till $T_{hot\ out}$ = 170°C.

4.2 Simulation in Microsoft Excel

Inputted parameters includes $T_{hot\ in}$, m_{hot}, $T_{hot\ target}$, $T_{cold\ in}$, $T_{cold\ target}$, $T_{cool\ in}$ and $T_{cool\ out}$. These data are given before a HEN design. $T_{hot\ out}$ and $C_{p\ cold\ out}$ are guess parameters. However, values guessed are within their limitation. With both inputted and guessed parameters, several parameters, including $C_{p\ cold\ in}$, $C_{p\ cold\ target}$, m_{cold}, m_{cool}, m_{heat} and $T_{cool\ out}$, can be calculated by using energy balance equation. Sample calculation is shown in **Appendix E-1**.

For exergy lost calculation (refer to **Appendix E-2**), model formulations for specific heat capacity, enthalpy, entropy and latent heat of vaporization in previous section are used to calculate the exergy lost for heat exchanger, heater and cooler in Microsoft Excel. However, there are constraints need to be considered in looking for the lowest exergy lost (refer to **Table 4.1**). All inputted, guessed, calculated and resulted parameters are shown in **Table 4.2**.

Table 4.1: Constraints on HEN (1 hot stream and 1 cold stream)

	Constraints
Process Streams	$T_{hot\ out} < T_{hot\ in}$, $T_{hot\ out} >= T_{hot\ target}$ $C_{p\ cold\ out} > C_{p\ cold\ in}$, $C_{p\ cold\ out} <= C_{p\ cold\ target}$
Utilities Streams	$T_{cool\ in} = 30$ °C $T_{cool\ out} = 40$ °C $T_{heat\ in} = T_{heat\ out} >= 0$
Exergies Lost	Ex Lost $_{HE} >= 0$ Ex Lost $_{Heater} >= 0$ Ex Lost $_{Cooler} >= 0$ Total Ex Lost $>= 0$

Table 4.2: Inputted, guessed, calculated and resulted parameters in Excel

	Input				Calculated	
$T_{hot\ in}$	180.00	°C		$C_{p\ cold\ in}$	4184.85	J/kg.°C
m_{hot}	1000.00	kg/s		$C_{p\ cold\ target}$	4523.85	J/kg.°C
$T_{hot\ target}$	40.00	°C		m_{cold}	1525.51	kg/s
$T_{cold\ in}$	60.00	°C		m_{cool}	3703.27	kg/s
$T_{cold\ target}$	200.00	°C		m_{heat}	1499.98	kg/s
$T_{cool\ in}$	30.00	°C		$T_{cold\ out}$	129.69	°C
$T_{cool\ out}$	40.00	°C			Exergy Lost	
				Ex Lost for HE	136.83	kJ/kg
	Guess			Ex Lost for Heater	0.00	kJ/kg
$T_{hot\ out}$	76.92	°C		Ex Lost for Cooler	104.33	kJ/kg
$C_{p\ cold\ out}$	4184.85	J/kg.°C		Total Ex Lost	241.16	kJ/kg

4.3 Minimum Driving Force (ΔT_{min})

Minimum driving force, ΔT_{min} can be determined by the minimum temperature change in composite curve. Both $T_{hot\ out}$ and $T_{cold\ out}$ are important parameters to determine the ΔT_{min}. As shown in **Figure 4.3**, there are two minimum temperature changes which are 103.08 °C and 69.69 °C. For initial solution, smaller value (69.69 °C) is taken as ΔT_{min} for this HEN.

Table 4.3: Determination of ΔT_{min} with $T_{hot\ out}$ and $T_{cold\ out}$

Streams	Upper T	Lower T
Hot	180.00	129.69
Cold	76.92	60.00
H (kJ/kg)	762.75	251.19
ΔT_{min}	103.08	69.69

However, ΔT_{min} could be determined by considering the temperature difference between 129.69 °C and 76.92 °C as shown in **Figure 4.3**. The difference is 52.77 °C which is smaller than 103.08 °C and 69.69 °C. Thus, by considering the lowest value, the ΔT_{min} is 52.77 °C.

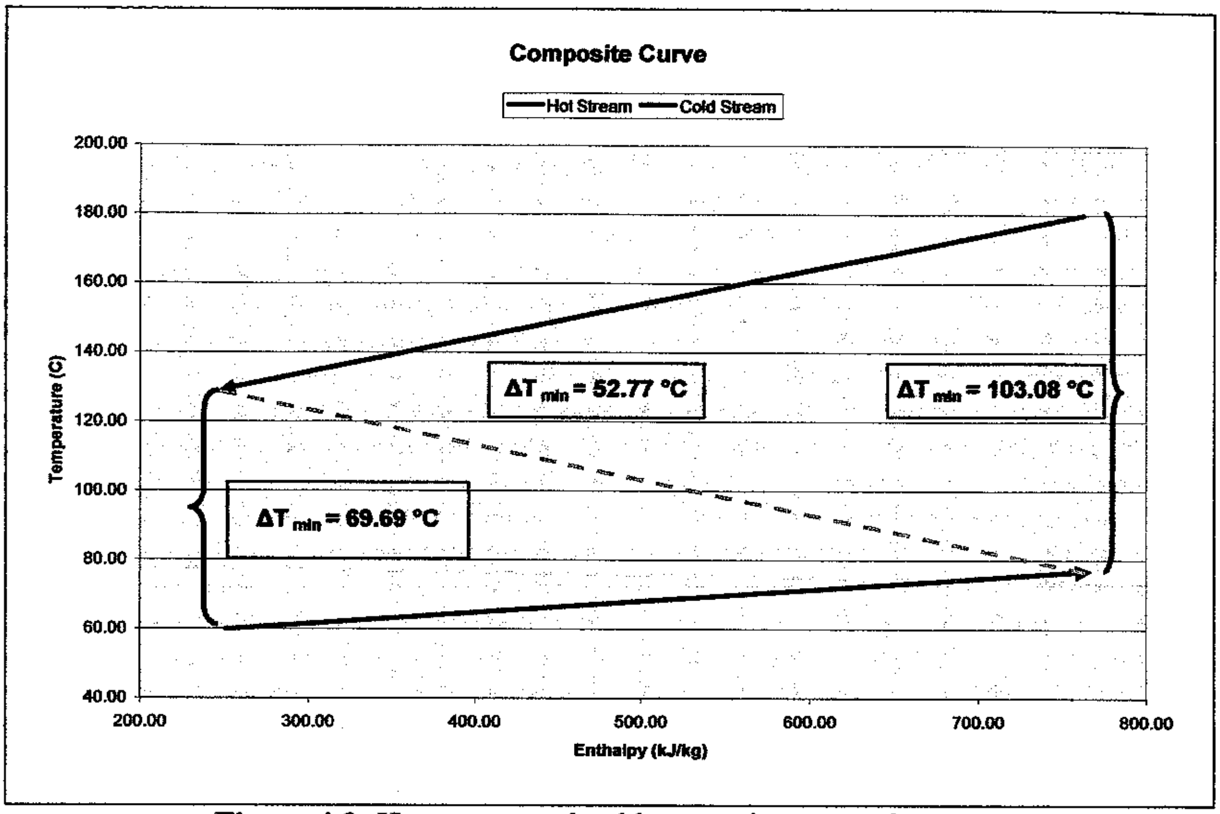

Figure 4.3: Hot stream and cold stream in composite curve

CHAPTER 5
CONCLUSION AND RECOMMENDATION

In conclusion, the progress of the project is within the time scheduled. A case study is conducted on a HEN which consists of one hot stream and one cold stream. The job scope includes finding out the relationship between the total exergy lost with respect to the manipulated hot stream outlet temperature, $T_{hot\ out}$ and $C_{p\ cold\ out}$. Algorithm of the HEN (one hot stream and one cold stream) is generated to be the basis of building a general template in Microsoft Excel. Generic function equations for all streams are also determined.

In model formulation, graph software is used for model formulation. The least errors are preferred. The preferred model formulas are then generated the lowest total exergy lost in HEN. With that, the minimum driving force, ΔT_{min} are also determined.

In the future, the project can be continued with validating the exergy analysis approach in current literature review. The ΔT_{min} of case studies in literature review will be compared with the one created in this new approach. The HEN will be more complicated with more hot streams and more cold streams. Besides, this project could include transforming the algorithm into codes in GAMS in the future.

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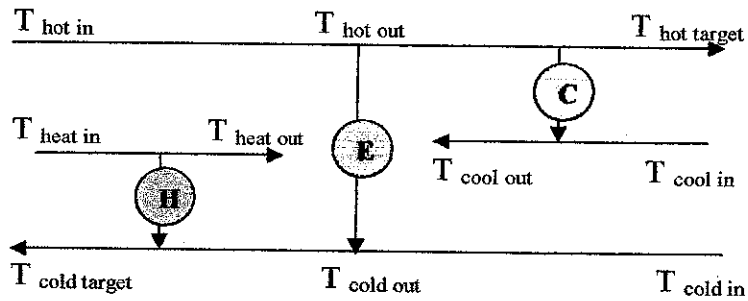
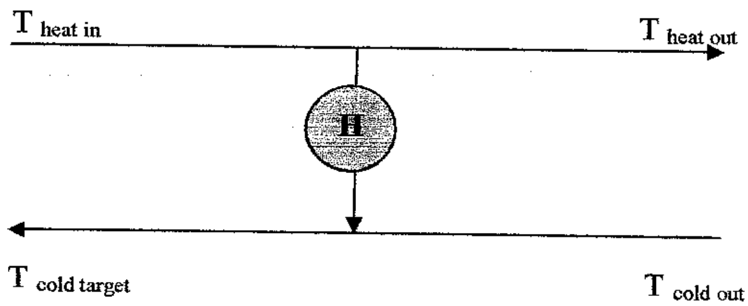
APPENDIX A

DIAGRAMS

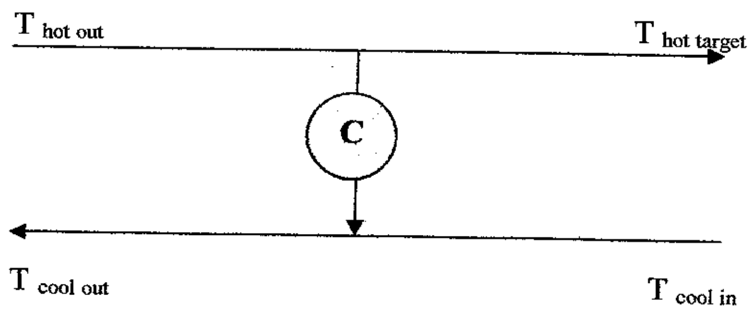
Heat Exchanger Network (HEN)



Heater



Cooler



APPENDIX B

MODELS

Exergy General Equation

$$Ex = H - T_0S$$

Hot Stream

$$\Delta Ex_{hot} = \Delta H_{hot} - T_0\Delta S_{hot}$$

$$\Delta H_{hot} = H_{hot\ in} - H_{hot\ out}$$

$$\Delta S_{hot} = S_{hot\ in} - S_{hot\ out}$$

$$\Delta Ex_{hot} = (H_{hot\ in} - H_{hot\ out}) - T_0 (S_{hot\ in} - S_{hot\ out})$$

Cold Stream

$$\Delta Ex_{cold} = \Delta H_{cold} - T_0\Delta S_{cold}$$

$$\Delta H_{cold} = H_{cold\ out} - H_{cold\ in}$$

$$\Delta S_{cold} = S_{cold\ out} - S_{cold\ in}$$

$$\Delta Ex_{cold} = (H_{cold\ out} - H_{cold\ in}) - T_0 (S_{cold\ out} - S_{cold\ in})$$

Exergy Lost

$$\Delta Ex_{lost} = \Delta Ex_{hot} - \Delta Ex_{cold}$$

$$\Delta Ex_{lost} = [(H_{hot\ in} - H_{hot\ out}) - T_0 (S_{hot\ in} - S_{hot\ out})] - [(H_{cold\ out} - H_{cold\ in}) - T_0 (S_{cold\ out} - S_{cold\ in})]$$

$$\Delta Ex_{lost} = [(H_{hot\ in} - H_{hot\ out}) - T_0 (S_{hot\ in} - S_{hot\ out})] + [(H_{cold\ in} - H_{cold\ out}) - T_0 (S_{cold\ in} - S_{cold\ out})]$$

Total Exergy Lost

$$\sum Ex_{lost} = \Delta Ex_{lost\ E} + \Delta Ex_{lost\ C} + \Delta Ex_{lost\ H}$$

APPENDIX C

THERMODYNAMICS PROPERTIES FOR WATER

Table C1: Heat capacity, C_p for water

T (K)	T (°C)	C_p (J/kg.°C)
273.2	0	4205
280	6.8	4197
300	26.8	4177
320	46.8	4176
340	66.8	4187
360	86.8	4204
373.2	100	4220
400	126.8	4241
450	176.8	4419
500	226.8	4647
550	276.8	5272
600	326.8	6691

Table C2: Enthalpy for saturated water, H_f for water

T (°C)	h_f (kJ/kg)	T (°C)	h_f (kJ/kg)
0.0100	0.0010	190.0000	807.4300
5.0000	21.0200	195.0000	829.7800
10.0000	42.0220	200.0000	852.2600
15.0000	62.9820	205.0000	874.8700
20.0000	83.9150	210.0000	897.6100
25.0000	104.8300	215.0000	920.5000
30.0000	125.7400	220.0000	943.5500
35.0000	146.6400	225.0000	966.7600
40.0000	167.5300	230.0000	990.1400
45.0000	188.4400	235.0000	1013.7000
50.0000	209.3400	240.0000	1037.5000
55.0000	230.2600	245.0000	1061.5000
60.0000	251.1800	250.0000	1085.7000
65.0000	272.1200	255.0000	1110.1000
70.0000	293.0700	260.0000	1134.8000
75.0000	314.0300	265.0000	1159.8000
80.0000	335.0200	270.0000	1185.1000
85.0000	356.0200	275.0000	1210.7000
90.0000	377.0400	280.0000	1236.7000
95.0000	398.0900	285.0000	1263.1000
100.0000	419.1700	290.0000	1289.8000
105.0000	440.2800	295.0000	1317.1000
110.0000	461.4200	300.0000	1344.8000
115.0000	482.5900	305.0000	1373.1000
120.0000	503.8100	310.0000	1402.0000
125.0000	525.0700	315.0000	1431.6000
130.0000	546.3800	320.0000	1462.0000
135.0000	567.7500	325.0000	1493.4000
140.0000	589.1600	330.0000	1525.8000
145.0000	610.6400	335.0000	1559.4000
150.0000	632.1800	340.0000	1594.6000
155.0000	653.7900	345.0000	1631.7000
160.0000	675.4700	350.0000	1671.2000
165.0000	697.2400	355.0000	1714.0000
170.0000	719.0800	360.0000	1761.5000
175.0000	741.0200	365.0000	1817.2000
180.0000	763.0500	370.0000	1891.2000
185.0000	785.1900	373.9500	2084.3000

Table C3: Heat of evaporation, h_{fg} for water

T (°C)	h_{fg} (kJ/kg)	T (°C)	h_{fg} (kJ/kg)
0.0100	2500.9000	190.0000	1977.9000
5.0000	2489.1000	195.0000	1959.0000
10.0000	2477.2000	200.0000	1939.8000
15.0000	2465.4000	205.0000	1920.0000
20.0000	2453.5000	210.0000	1899.7000
25.0000	2441.7000	215.0000	1878.8000
30.0000	2429.8000	220.0000	1857.4000
35.0000	2417.9000	225.0000	1835.4000
40.0000	2406.0000	230.0000	1812.8000
45.0000	2394.0000	235.0000	1789.5000
50.0000	2382.0000	240.0000	1765.5000
55.0000	2369.8000	245.0000	1740.8000
60.0000	2357.7000	250.0000	1715.3000
65.0000	2345.4000	255.0000	1689.0000
70.0000	2333.0000	260.0000	1661.8000
75.0000	2320.6000	265.0000	1633.7000
80.0000	2308.0000	270.0000	1604.6000
85.0000	2295.3000	275.0000	1574.5000
90.0000	2282.5000	280.0000	1543.2000
95.0000	2269.6000	285.0000	1510.7000
100.0000	2256.4000	290.0000	1476.9000
105.0000	2243.1000	295.0000	1441.6000
110.0000	2229.7000	300.0000	1404.8000
115.0000	2216.0000	305.0000	1366.3000
120.0000	2202.1000	310.0000	1325.9000
125.0000	2188.1000	315.0000	1283.4000
130.0000	2173.7000	320.0000	1238.5000
135.0000	2159.1000	325.0000	1191.0000
140.0000	2144.3000	330.0000	1140.3000
145.0000	2129.2000	335.0000	1086.0000
150.0000	2113.8000	340.0000	1027.4000
155.0000	2098.0000	345.0000	963.4000
160.0000	2082.0000	350.0000	892.7000
165.0000	2065.6000	355.0000	812.9000
170.0000	2048.8000	360.0000	720.1000
175.0000	2031.7000	365.0000	605.5000
180.0000	2014.2000	370.0000	443.1000
185.0000	1996.2000	373.9500	0.0000

Table C4: Entropy for saturated liquid, S_f for water

T (°C)	s_f (kJ/kg.K)	T (°C)	s_f (kJ/kg.K)
0.0100	0.0000	190.0000	2.2355
5.0000	0.0763	195.0000	2.2831
10.0000	0.1511	200.0000	2.3305
15.0000	0.2245	205.0000	2.3776
20.0000	0.2965	210.0000	2.4245
25.0000	0.3672	215.0000	2.4712
30.0000	0.4368	220.0000	2.5176
35.0000	0.5051	225.0000	2.5639
40.0000	0.5724	230.0000	2.6100
45.0000	0.6386	235.0000	2.6560
50.0000	0.7038	240.0000	2.7018
55.0000	0.7680	245.0000	2.7476
60.0000	0.8313	250.0000	2.7933
65.0000	0.8937	255.0000	2.8390
70.0000	0.9551	260.0000	2.8847
75.0000	1.0158	265.0000	2.9304
80.0000	1.0756	270.0000	2.9762
85.0000	1.1346	275.0000	3.0221
90.0000	1.1929	280.0000	3.0681
95.0000	1.2504	285.0000	3.1144
100.0000	1.3072	290.0000	3.1608
105.0000	1.3634	295.0000	3.2076
110.0000	1.4188	300.0000	3.2548
115.0000	1.4737	305.0000	3.3024
120.0000	1.5279	310.0000	3.3506
125.0000	1.5816	315.0000	3.3994
130.0000	1.6346	320.0000	3.4491
135.0000	1.6872	325.0000	3.4998
140.0000	1.7392	330.0000	3.5516
145.0000	1.7908	335.0000	3.6050
150.0000	1.8418	340.0000	3.6602
155.0000	1.8924	345.0000	3.7179
160.0000	1.9426	350.0000	3.7788
165.0000	1.9923	355.0000	3.8442
170.0000	2.0417	360.0000	3.9165
175.0000	2.0906	365.0000	4.0004
180.0000	2.1392	370.0000	4.1119
185.0000	2.1875	373.9500	4.4070

Table C5: Entropy of evaporation, S_{fg} for water

T (°C)	s_{fg} (kJ/kg.K)	T (°C)	s_{fg} (kJ/kg.K)
0.0100	9.1556	190.0000	4.2705
5.0000	8.9487	195.0000	4.1847
10.0000	8.7488	200.0000	4.0997
15.0000	8.5559	205.0000	4.0154
20.0000	8.3696	210.0000	3.9318
25.0000	8.1895	215.0000	3.8489
30.0000	8.0152	220.0000	3.7664
35.0000	7.8466	225.0000	3.6844
40.0000	7.6832	230.0000	3.6028
45.0000	7.5247	235.0000	3.5216
50.0000	7.3710	240.0000	3.4405
55.0000	7.2218	245.0000	3.3596
60.0000	7.0769	250.0000	3.2788
65.0000	6.9360	255.0000	3.1979
70.0000	6.7989	260.0000	3.1169
75.0000	6.6655	265.0000	3.0358
80.0000	6.5355	270.0000	2.9542
85.0000	6.4089	275.0000	2.8723
90.0000	6.2853	280.0000	2.7898
95.0000	6.1647	285.0000	2.7066
100.0000	6.0470	290.0000	2.6225
105.0000	5.9319	295.0000	2.5374
110.0000	5.8193	300.0000	2.4511
115.0000	5.7092	305.0000	2.3633
120.0000	5.6013	310.0000	2.2737
125.0000	5.4956	315.0000	2.1821
130.0000	5.3919	320.0000	2.0881
135.0000	5.2901	325.0000	1.9911
140.0000	5.1901	330.0000	1.8906
145.0000	5.0919	335.0000	1.7857
150.0000	4.9953	340.0000	1.6756
155.0000	4.9002	345.0000	1.5585
160.0000	4.8066	350.0000	1.4326
165.0000	4.7143	355.0000	1.2942
170.0000	4.6233	360.0000	1.1373
175.0000	4.5335	365.0000	0.9489
180.0000	4.4448	370.0000	0.6890
185.0000	4.3572	373.9500	0.0000

APPENDIX D

MODEL FORMULATIONS

Heat Capacity, C_p

Microsoft Excel (C_p)

Poly 2	SSE	Poly 3	SSE	Poly 4	SSE	Poly 5	SSE	Poly 6	SSE
4333.10	0.00	4155.80	0.00	4216.10	0.00	4203.50	0.00	4202.90	0.00
4292.13	0.00	4176.14	0.00	4196.26	0.00	4196.95	0.00	4197.39	0.00
4192.33	0.00	4215.33	0.00	4164.89	0.00	4182.64	0.00	4183.34	0.00
4123.41	0.00	4231.23	0.00	4161.50	0.00	4180.54	0.00	4178.37	0.00
4085.36	0.00	4233.43	0.00	4173.25	0.00	4194.58	0.00	4185.43	0.00
4078.20	0.00	4231.54	0.00	4190.76	0.00	4226.65	0.00	4203.12	0.00
4090.39	0.00	4232.71	0.00	4202.45	0.00	4258.02	0.00	4218.52	0.00
4156.52	0.00	4253.87	0.00	4222.79	0.00	4346.82	0.00	4250.51	0.00
4428.11	0.00	4429.73	0.00	4262.91	0.00	4607.61	0.00	4261.83	0.00
4892.70	0.00	4910.00	0.00	4411.94	0.00	5040.29	0.01	4137.91	0.01
5550.29	0.00	5844.66	0.01	4914.76	0.00	5809.70	0.01	3875.49	0.07
6400.89	0.00	7383.73	0.01	6151.22	0.01	7270.86	0.01	3616.52	0.21

Graph Software (C_p)

Poly 7	SSE	Poly 8	SSE	%
4210.08	0.00	**4203.46**	**0.00**	**0.000%**
4189.65	0.00	**4199.84**	**0.00**	**0.000%**
4176.05	0.00	**4175.14**	**0.00**	**0.000%**
4183.01	0.00	**4174.64**	**0.00**	**0.000%**
4189.20	0.00	**4190.82**	**0.00**	**0.000%**
4197.94	0.00	**4205.61**	**0.00**	**0.000%**
4209.68	0.00	**4213.75**	**0.00**	**0.000%**
4256.19	0.00	**4244.36**	**0.00**	**0.000%**
4412.04	0.00	**4418.20**	**0.00**	**0.000%**
4649.78	0.00	**4647.23**	**0.00**	**0.000%**
5271.31	0.00	**5271.98**	**0.00**	**0.000%**
6691.08	0.00	**6691.07**	**0.00**	**0.000%**

Polynomial Equations (C_p)

Poly	Equations	R^2
2	$C_p = 0.0386T^2 - 6.2871T + 4333.1$	0.9508
3	$C_p = 0.0002T^3 - 0.0452T^2 + 3.2891T + 4155.8$	0.9937
4	$C_p = 9E\text{-}07T^4 - 0.0004T^3 + 0.0629T^2 - 3.3265T + 4216.1$	0.9995
5	$C_p = 2E\text{-}09T^5 - 1E\text{-}06T^4 + 0.0002T^3 + 0.0034T^2 - 0.9948T + 4203.5$	0.9998
6	$C_p = -2E\text{-}12T^6 + 4E\text{-}09T^5 - 2E\text{-}06T^4 + 0.0003T^3 - 0.0043T^2 - 0.7938T + 4202.9$	0.9998
7	$C_p = -3.2271612E\text{-}13T^7+0.00000000034892067T^6-0.00000014475671T^5+0.000029499857T^4-0.0030762227T^3+0.16565294T^2-3.9978098T+4210.0844$	0.9999
8	$\mathbf{C_p = -6.031236E\text{-}15T^8+0.0000000000068996425T^7-0.0000000031335455T^6+0.00000072179138T^5-0.000088922557T^4+0.0056472219T^3-0.14828461T^2+0.24153542T+4203.456}$	**1.0000**

Liquid Enthalpy, H_f

Microsoft Excel (H_f)

Poly 2	SSE	Poly 3	SSE	Poly 4	SSE	Poly 5	SSE	Poly 6	SSE
41.59	1.73E+09	-24.10	5.81E+08	17.61	3.10E+08	-13.50	1.82E+08	10.94	1.20E+08
57.25	2.97	2.07	0.81	32.66	0.31	14.00	0.11	24.74	0.03
73.18	0.55	27.81	0.11	48.61	0.02	40.07	0.00	40.77	0.00
89.33	0.17	53.09	0.02	65.38	0.00	64.87	0.00	58.56	0.00
105.70	0.07	77.93	0.01	82.90	0.00	88.59	0.00	77.73	0.01
122.30	0.03	102.35	0.00	101.11	0.00	111.39	0.00	97.94	0.00
139.13	0.01	126.39	0.00	119.96	0.00	133.43	0.00	118.90	0.00
156.18	0.00	150.05	0.00	139.40	0.00	154.88	0.00	140.35	0.00
173.45	0.00	173.37	0.00	159.39	0.00	175.86	0.00	162.10	0.00
190.95	0.00	196.36	0.00	179.86	0.00	196.50	0.00	183.96	0.00
208.68	0.00	219.04	0.00	200.80	0.00	216.90	0.00	205.81	0.00
226.62	0.00	241.45	0.00	222.15	0.00	237.17	0.00	227.52	0.00
244.80	0.00	263.60	0.00	243.87	0.00	257.39	0.00	249.02	0.00
263.20	0.00	285.52	0.00	265.95	0.00	277.65	0.00	270.25	0.00
281.82	0.00	307.22	0.00	288.34	0.00	298.00	0.00	291.19	0.00
300.67	0.00	328.74	0.00	311.02	0.00	318.51	0.00	311.82	0.00
319.75	0.00	350.08	0.00	333.96	0.00	339.23	0.00	332.14	0.00
339.05	0.00	371.28	0.00	357.15	0.00	360.18	0.00	352.20	0.00
358.57	0.00	392.36	0.00	380.57	0.00	381.40	0.00	372.01	0.00
378.32	0.00	413.34	0.00	404.19	0.00	402.91	0.00	391.63	0.00
398.30	0.00	434.24	0.00	428.02	0.00	424.73	0.00	411.14	0.00
418.49	0.00	455.08	0.00	452.03	0.00	446.84	0.00	430.58	0.00
438.92	0.00	475.90	0.00	476.23	0.00	469.26	0.00	450.05	0.00
459.57	0.00	496.70	0.00	500.62	0.00	491.97	0.00	469.63	0.00
480.44	0.00	517.52	0.00	525.18	0.00	514.95	0.00	489.41	0.00
501.54	0.00	538.37	0.00	549.92	0.00	538.17	0.00	509.47	0.00
522.87	0.00	559.28	0.00	574.86	0.00	561.62	0.00	529.93	0.00

544.42	0.00	580.26	0.00	600.00	0.00	585.25	0.00	550.86	0.00
566.19	0.00	601.36	0.00	625.35	0.00	609.02	0.00	572.37	0.00
588.19	0.00	622.57	0.00	650.92	0.00	632.89	0.00	594.56	0.00
610.42	0.00	643.93	0.00	676.74	0.00	656.80	0.00	617.53	0.00
632.86	0.00	665.47	0.00	702.82	0.01	680.71	0.00	641.35	0.00
655.54	0.00	687.19	0.00	729.19	0.01	704.55	0.00	666.14	0.00
678.44	0.00	709.13	0.00	755.88	0.01	728.27	0.00	691.98	0.00
701.56	0.00	731.31	0.00	782.92	0.01	751.79	0.00	718.96	0.00
724.91	0.00	753.75	0.00	810.33	0.01	775.05	0.00	747.16	0.00
748.49	0.00	776.47	0.00	838.16	0.01	797.99	0.00	776.67	0.00
772.29	0.00	799.50	0.00	866.45	0.01	820.52	0.00	807.56	0.00
796.31	0.00	822.85	0.00	895.23	0.01	842.59	0.00	839.92	0.00
820.56	0.00	846.55	0.00	924.55	0.01	864.11	0.00	873.83	0.00
845.04	0.00	870.63	0.00	954.46	0.01	885.01	0.00	909.36	0.00
869.73	0.00	895.10	0.00	985.01	0.02	905.21	0.00	946.58	0.01
894.66	0.00	919.99	0.00	1016.25	0.02	924.64	0.00	985.57	0.01
919.81	0.00	945.32	0.00	1048.25	0.02	943.23	0.00	1026.40	0.01
945.18	0.00	971.11	0.00	1081.06	0.02	960.91	0.00	1069.17	0.02
970.78	0.00	997.38	0.00	1114.74	0.02	977.59	0.00	1113.93	0.02
996.61	0.00	1024.17	0.00	1149.36	0.03	993.20	0.00	1160.79	0.03
1022.66	0.00	1051.48	0.00	1184.99	0.03	1007.69	0.00	1209.82	0.04
1048.93	0.00	1079.35	0.00	1221.71	0.03	1020.98	0.00	1261.13	0.05
1075.43	0.00	1107.79	0.00	1259.57	0.03	1033.01	0.00	1314.82	0.06
1102.16	0.00	1136.82	0.00	1298.68	0.04	1043.71	0.00	1371.00	0.07
1129.10	0.00	1166.48	0.00	1339.10	0.04	1053.03	0.00	1429.79	0.08
1156.28	0.00	1196.78	0.00	1380.91	0.05	1060.91	0.00	1491.35	0.10
1183.68	0.00	1227.75	0.00	1424.22	0.05	1067.31	0.01	1555.81	0.12
1211.30	0.00	1259.40	0.00	1469.10	0.06	1072.17	0.01	1623.36	0.14
1239.15	0.00	1291.77	0.00	1515.65	0.06	1075.46	0.01	1694.17	0.16
1267.23	0.00	1324.86	0.01	1563.96	0.07	1077.15	0.02	1768.47	0.18
1295.53	0.00	1358.71	0.01	1614.14	0.08	1077.19	0.02	1846.48	0.21
1324.05	0.00	1393.34	0.01	1666.29	0.09	1075.57	0.03	1928.47	0.25
1352.80	0.00	1428.77	0.01	1720.50	0.09	1072.27	0.03	2014.73	0.28
1381.78	0.00	1465.02	0.01	1776.90	0.10	1067.29	0.04	2105.58	0.32
1410.97	0.00	1502.11	0.01	1835.58	0.11	1060.60	0.05	2201.37	0.36
1440.40	0.00	1540.08	0.01	1896.67	0.12	1052.23	0.06	2302.51	0.41
1470.05	0.00	1578.93	0.01	1960.29	0.14	1042.18	0.07	2409.43	0.47
1499.92	0.00	1618.70	0.01	2026.54	0.15	1030.47	0.09	2522.61	0.53
1530.02	0.00	1659.40	0.01	2095.55	0.16	1017.12	0.10	2642.56	0.59
1560.35	0.00	1701.06	0.01	2167.46	0.18	1002.19	0.12	2769.88	0.66
1590.90	0.00	1743.69	0.01	2242.39	0.19	985.71	0.14	2905.18	0.74
1621.67	0.00	1787.34	0.01	2320.47	0.21	967.74	0.15	3049.16	0.83
1652.67	0.00	1832.00	0.02	2401.83	0.22	948.35	0.18	3202.57	0.93
1683.90	0.00	1877.71	0.02	2486.62	0.24	927.61	0.20	3366.22	1.03
1715.34	0.00	1924.50	0.02	2574.97	0.25	905.62	0.22	3540.99	1.14
1747.02	0.00	1972.37	0.01	2667.03	0.26	882.47	0.25	3727.83	1.25
1778.92	0.00	2021.36	0.01	2762.95	0.27	858.28	0.28	3927.80	1.35
1811.04	0.00	2071.49	0.01	2862.88	0.26	833.16	0.31	4141.99	1.42
1836.58	0.01	2111.91	0.00	2944.75	0.17	812.75	0.37	4322.04	1.15

Graph Software (H_f)

Poly 15	SSE	%	Poly 15	SSE	%
0.18	31102.74	31102.74	807.69	0.00	0.00
20.80	0.00	0.00	830.63	0.00	0.00
41.77	0.00	0.00	853.83	0.00	0.00
62.99	0.00	0.00	877.25	0.00	0.00
84.17	0.00	0.00	900.82	0.00	0.00
105.17	0.00	0.00	924.45	0.00	0.00
125.95	0.00	0.00	948.10	0.00	0.00
146.61	0.00	0.00	971.73	0.00	0.00
167.28	0.00	0.00	995.36	0.00	0.00
188.04	0.00	0.00	1019.02	0.00	0.00
208.96	0.00	0.00	1042.82	0.00	0.00
230.03	0.00	0.00	1066.86	0.00	0.00
251.19	0.00	0.00	1091.29	0.00	0.00
272.37	0.00	0.00	1116.25	0.00	0.00
293.50	0.00	0.00	1141.82	0.00	0.00
314.54	0.00	0.00	1168.06	0.00	0.00
335.46	0.00	0.00	1194.95	0.00	0.00
356.29	0.00	0.00	1222.38	0.00	0.00
377.07	0.00	0.00	1250.17	0.00	0.00
397.85	0.00	0.00	1278.09	0.00	0.00
418.70	0.00	0.00	1305.89	0.00	0.00
439.67	0.00	0.00	1333.35	0.00	0.00
460.81	0.00	0.00	1360.38	0.00	0.00
482.11	0.00	0.00	1387.00	0.00	0.00
503.56	0.00	0.00	1413.44	0.00	0.00
525.13	0.00	0.00	1440.09	0.00	0.00
546.77	0.00	0.00	1467.44	0.00	0.00
568.43	0.00	0.00	1495.95	0.00	0.00
590.05	0.00	0.00	1525.79	0.00	0.00
611.61	0.00	0.00	1556.68	0.00	0.00
633.10	0.00	0.00	1587.63	0.00	0.00
654.53	0.00	0.00	1616.99	0.00	0.00
675.94	0.00	0.00	1642.96	0.00	0.00
697.40	0.00	0.00	1664.96	0.00	0.00
718.98	0.00	0.00	1686.69	0.00	0.00
740.74	0.00	0.00	1721.51	0.00	0.00
762.75	0.00	0.00	1801.82	0.00	0.00
785.06	0.00	0.00	1939.36	0.00	0.00

Polynomial Equations (H_f)

Poly	Equations	R^2
2	$H_f = 0.0045T^2 + 3.1174T + 41.555$	0.9951
3	$H_f = 3E\text{-}05T^3 - 0.0101T^2 + 5.2939T - 24.151$	0.9976
4	$H_f = 2E\text{-}07T^4 - 9E\text{-}05T^3 + 0.0188T^2 + 2.9244T + 17.578$	0.9985
5	$H_f = 1E\text{-}09T^5 - 1E\text{-}06T^4 + 0.0003T^3 - 0.0339T^2 + 5.6728T - 13.554$	0.9990
6	$H_f = 1E\text{-}11T^6 - 1E\text{-}08T^5 + 4E\text{-}06T^4 - 0.0007T^3 + 0.0539T^2 + 2.5122T + 10.915$	0.9993
15	$\mathbf{H_f = 1.7813417E\text{-}30T^{15} - 4.5507602E\text{-}27T^{14} + 5.1978755E\text{-}24T^{13} - 3.502434E\text{-}21T^{12} + 1.5469261E\text{-}18T^{11} - 4.7057934E\text{-}16T^{10} + 1.0082306E\text{-}13T^{9} - 1.5288166E\text{-}11T^{8} + 1.6247234E\text{-}09T^{7} - 1.1795386E\text{-}07T^{6} + 5.57788E\text{-}06T^{5} - 0.00015750345T^{4} + 0.0022106007T^{3} - 0.0078641879T^{2} + 4.1331407T + 0.13602907}$	**1.0000**

Heat of Vaporization, H_{fg}

Microsoft Excel (H_{fg})

Poly 2	SSE	Poly 3	SSE	Poly 4	SSE	Poly 5	SSE	Poly 6	SSE
2381.11	0.00	2563.35	0.00	2456.11	0.00	2535.14	0.00	2474.22	0.00
2384.87	0.00	2537.97	0.00	2459.33	0.00	2506.72	0.00	2479.98	0.00
2387.90	0.00	2513.77	0.00	2460.27	0.00	2482.01	0.00	2480.28	0.00
2390.19	0.00	2490.76	0.00	2459.08	0.00	2460.59	0.00	2476.15	0.00
2391.73	0.00	2468.89	0.00	2455.87	0.00	2442.01	0.00	2468.53	0.00
2392.54	0.00	2448.09	0.00	2450.79	0.00	2425.84	0.00	2458.23	0.00
2392.61	0.00	2428.32	0.00	2443.95	0.00	2411.68	0.00	2445.98	0.00
2391.94	0.00	2409.53	0.00	2435.47	0.00	2399.15	0.00	2432.37	0.00
2390.53	0.00	2391.66	0.00	2425.46	0.00	2387.90	0.00	2417.93	0.00
2388.38	0.00	2374.65	0.00	2414.04	0.00	2377.59	0.00	2403.11	0.00
2385.49	0.00	2358.47	0.00	2401.29	0.00	2367.92	0.00	2388.29	0.00
2381.85	0.00	2343.05	0.00	2387.30	0.00	2358.59	0.00	2373.76	0.00
2377.48	0.00	2328.34	0.00	2372.18	0.00	2349.33	0.00	2359.78	0.00
2372.37	0.00	2314.30	0.00	2355.99	0.00	2339.89	0.00	2346.58	0.00
2366.52	0.00	2300.86	0.00	2338.82	0.00	2330.03	0.00	2334.30	0.00
2359.93	0.00	2287.97	0.00	2320.72	0.00	2319.53	0.00	2323.10	0.00
2352.60	0.00	2275.59	0.00	2301.77	0.00	2308.18	0.00	2313.09	0.00
2344.52	0.00	2263.66	0.00	2282.02	0.00	2295.78	0.00	2304.35	0.00
2335.71	0.00	2252.13	0.00	2261.53	0.00	2282.14	0.00	2296.97	0.00
2326.16	0.00	2240.94	0.00	2240.33	0.00	2267.11	0.00	2291.01	0.00
2315.87	0.00	2230.04	0.00	2218.47	0.00	2250.51	0.00	2286.56	0.00
2304.84	0.00	2219.38	0.00	2195.98	0.00	2232.19	0.00	2283.68	0.00
2293.07	0.00	2208.91	0.00	2172.88	0.00	2212.01	0.00	2282.44	0.00
2280.56	0.00	2198.58	0.00	2149.21	0.00	2189.81	0.00	2282.95	0.00
2267.30	0.00	2188.33	0.00	2124.96	0.00	2165.48	0.00	2285.31	0.00
2253.31	0.00	2178.11	0.00	2100.16	0.00	2138.88	0.00	2289.64	0.00
2238.58	0.00	2167.86	0.00	2074.80	0.00	2109.88	0.00	2296.10	0.00
2223.11	0.00	2157.54	0.00	2048.88	0.00	2078.35	0.00	2304.86	0.00
2206.90	0.00	2147.10	0.00	2022.39	0.00	2044.17	0.00	2316.13	0.01
2189.95	0.00	2136.47	0.00	1995.33	0.00	2007.21	0.00	2330.14	0.01
2172.26	0.00	2125.61	0.00	1967.66	0.00	1967.35	0.00	2347.15	0.01
2153.82	0.00	2114.47	0.00	1939.35	0.01	1924.46	0.01	2367.46	0.02
2134.65	0.00	2102.98	0.00	1910.39	0.01	1878.40	0.01	2391.43	0.02
2114.74	0.00	2091.11	0.00	1880.72	0.01	1829.04	0.01	2419.41	0.03
2094.09	0.00	2078.80	0.00	1850.31	0.01	1776.23	0.02	2451.82	0.04
2072.70	0.00	2065.99	0.00	1819.09	0.01	1719.82	0.02	2489.10	0.05
2050.57	0.00	2052.63	0.00	1787.02	0.01	1659.65	0.03	2531.75	0.07
2027.69	0.00	2038.68	0.00	1754.03	0.01	1595.55	0.04	2580.27	0.09
2004.08	0.00	2024.07	0.00	1720.06	0.02	1527.34	0.05	2635.24	0.11
1979.73	0.00	2008.75	0.00	1685.02	0.02	1454.83	0.07	2697.25	0.14
1954.64	0.00	1992.68	0.00	1648.84	0.02	1377.82	0.08	2766.92	0.18
1928.81	0.00	1975.80	0.00	1611.43	0.03	1296.09	0.11	2844.91	0.23
1902.24	0.00	1958.05	0.00	1572.69	0.03	1209.40	0.13	2931.92	0.30
1874.93	0.00	1939.39	0.00	1532.54	0.03	1117.51	0.16	3028.65	0.37

1846.87	0.00	1919.77	0.00	1490.85	0.04	1020.15	0.20	3135.85	0.47
1818.08	0.00	1899.12	0.00	1447.53	0.04	917.04	0.25	3254.29	0.60
1788.55	0.00	1877.40	0.00	1402.45	0.05	807.87	0.31	3384.74	0.75
1758.28	0.00	1854.56	0.00	1355.49	0.06	692.32	0.38	3528.00	0.94
1727.27	0.00	1830.54	0.00	1306.52	0.07	570.04	0.46	3684.89	1.18
1695.52	0.00	1805.28	0.00	1255.42	0.08	440.66	0.56	3856.20	1.48
1663.03	0.00	1778.75	0.00	1202.03	0.09	303.79	0.68	4042.76	1.84
1629.79	0.00	1750.88	0.00	1146.20	0.10	159.01	0.82	4245.37	2.29
1595.82	0.00	1721.62	0.00	1087.80	0.12	5.87	0.99	4464.83	2.85
1561.11	0.00	1690.93	0.00	1026.65	0.14	-156.09	1.20	4701.93	3.53
1525.66	0.00	1658.74	0.00	962.60	0.16	-327.38	1.45	4957.44	4.37
1489.47	0.00	1625.00	0.00	895.46	0.19	-508.52	1.75	5232.08	5.40
1452.54	0.00	1589.67	0.00	825.07	0.22	-700.08	2.11	5526.56	6.66
1414.86	0.00	1552.69	0.00	751.24	0.25	-902.66	2.55	5841.54	8.22
1376.45	0.00	1514.01	0.00	673.79	0.30	-1116.87	3.08	6177.63	10.13
1337.30	0.01	1473.57	0.00	592.51	0.35	-1343.37	3.73	6535.38	12.49
1297.41	0.01	1431.32	0.00	507.21	0.41	-1582.87	4.52	6915.28	15.39
1256.78	0.01	1387.21	0.00	417.68	0.48	-1836.09	5.49	7317.74	18.97
1215.41	0.01	1341.19	0.00	323.70	0.57	-2103.80	6.69	7743.10	23.42
1173.30	0.01	1293.21	0.00	225.07	0.68	-2386.82	8.18	8191.59	28.97
1130.44	0.01	1243.21	0.00	121.54	0.81	-2685.98	10.04	8663.35	35.94
1086.85	0.01	1191.14	0.00	12.90	0.98	-3002.17	12.40	9158.42	44.75
1042.52	0.01	1136.94	0.00	-101.10	1.19	-3336.33	15.41	9676.69	56.04
997.45	0.01	1080.57	0.00	-220.70	1.45	-3689.44	19.34	10217.94	70.71
951.64	0.01	1021.98	0.00	-346.15	1.79	-4062.49	24.54	10781.80	90.14
905.09	0.00	961.10	0.00	-477.69	2.24	-4456.57	31.65	11367.76	116.63
857.80	0.00	897.89	0.00	-615.61	2.85	-4872.78	41.71	11975.12	154.12
809.76	0.00	832.30	0.00	-760.15	3.74	-5312.27	56.78	12603.01	210.36
760.99	0.00	764.26	0.00	-911.59	5.13	-5776.26	81.39	13250.39	302.79
711.48	0.03	693.74	0.02	-1070.22	7.66	-6265.99	128.79	13916.00	483.24
661.23	0.24	620.68	0.16	-1236.32	14.37	-6782.78	265.94	14598.37	1020.55
621.01	-	561.13	-	-1373.00	-	-7211.06	-	15148.18	-

Graph Software (H_{fg})

Poly 15	SSE	%	Poly 15	SSE	%
2500.49	0.00	0.00	1977.12	0.00	0.00
2489.60	0.00	0.00	1956.73	0.00	0.00
2477.80	0.00	0.00	1935.41	0.00	0.00
2465.36	0.00	0.00	1913.27	0.00	0.00
2452.93	0.00	0.00	1890.42	0.00	0.00
2440.90	0.00	0.00	1866.98	0.00	0.00
2429.32	0.00	0.00	1843.00	0.00	0.00
2417.98	0.00	0.00	1818.48	0.00	0.00
2406.59	0.00	0.00	1793.31	0.00	0.00
2394.91	0.00	0.00	1767.26	0.00	0.00
2382.83	0.00	0.00	1740.00	0.00	0.00
2370.37	0.00	0.00	1711.09	0.00	0.00
2357.65	0.00	0.00	1680.03	0.00	0.00
2344.82	0.00	0.00	1646.31	0.00	0.00
2332.04	0.00	0.00	1609.45	0.00	0.00
2319.42	0.00	0.00	1569.04	0.00	0.00
2306.98	0.00	0.00	1524.83	0.00	0.00
2294.70	0.00	0.00	1476.67	0.00	0.00
2282.46	0.00	0.00	1424.54	0.01	0.01
2270.12	0.00	0.00	1368.48	0.01	0.01
2257.52	0.00	0.00	1308.50	0.01	0.01
2244.55	0.00	0.00	1244.44	0.02	0.02
2231.10	0.00	0.00	1175.81	0.03	0.03
2217.17	0.00	0.00	1101.69	0.04	0.04
2202.76	0.00	0.00	1020.63	0.05	0.05
2187.97	0.00	0.00	930.67	0.08	0.08
2172.89	0.00	0.00	829.50	0.11	0.11
2157.66	0.00	0.00	714.76	0.16	0.16
2142.36	0.00	0.00	584.54	0.24	0.24
2127.07	0.00	0.00	437.88	0.36	0.36
2111.81	0.00	0.00	275.20	0.54	0.54
2096.51	0.00	0.00	98.23	0.81	0.81
2081.10	0.00	0.00	-91.24	1.21	1.21
2065.41	0.00	0.00	-294.65	1.86	1.86
2049.28	0.00	0.00	-523.69	2.98	2.98
2032.53	0.00	0.00	-813.07	5.49	5.49
2014.99	0.00	0.00	-1242.21	14.47	14.47
1996.54	0.00	0.00	-1780.60	-	-

Polynomial Equations (H_{fg})

Poly	Equations	R^2
2	$H_{fg} = -0.0148T^2 + 0.8277T + 2381.1$	0.9967
3	$H_{fg} = -7E\text{-}05T^3 + 0.0258T^2 - 5.2136T + 2563.4$	0.9862
4	$H_{fg} = -4E\text{-}07T^4 + 0.0002T^3 - 0.0486T^2 + 0.8837T + 2456.1$	0.9917
5	$H_{fg} = -3E\text{-}09T^5 + 2E\text{-}06T^4 - 0.0007T^3 + 0.0856T^2 - 6.1069T + 2535.2$	0.9945
6	$H_{fg} = -3E\text{-}11T^6 + 3E\text{-}08T^5 - 1E\text{-}05T^4 + 0.0017T^3 - 0.1336T^2 + 1.7836T + 2474.2$	0.9962
15	$\mathbf{H_{fg} = -4.1094412E\text{-}30T^{15}+1.0493516E\text{-}26T^{14}-1.1979607E\text{-}23T^{13}+8.0674378E\text{-}21T^{12}-3.560743E\text{-}18T^{11}+1.0822954E\text{-}15T^{10}-2.3164291E\text{-}13T^9+0.000000000035075938T^8-0.0000000037202563T^7+0.00000026926182T^6-0.000012665089T^5+0.00035357146T^4-0.0047938506T^3+0.011529828T^2-2.1576794T+2500.5161}$	**0.9998**

Liquid Entropy, S_f

Microsoft Excel (S_f)

Poly 2	SSE	Poly 3	SSE	Poly 4	SSE	Poly 5	SSE	Poly 6	SS
0.11	-	-0.02	-	0.03	-	-0.02	-	0.02	-
0.17	1.46	0.06	0.07	0.09	0.06	0.07	0.02	0.08	0.0
0.23	0.26	0.14	0.01	0.16	0.00	0.15	0.00	0.15	0.0
0.29	0.08	0.21	0.00	0.23	0.00	0.23	0.00	0.22	0.0
0.35	0.03	0.29	0.00	0.29	0.00	0.30	0.00	0.29	0.0
0.40	0.01	0.36	0.00	0.36	0.00	0.38	0.00	0.36	0.0
0.46	0.00	0.44	0.00	0.43	0.00	0.45	0.00	0.43	0.0
0.52	0.00	0.51	0.00	0.49	0.00	0.52	0.00	0.50	0.0
0.58	0.00	0.58	0.00	0.56	0.00	0.58	0.00	0.56	0.0
0.64	0.00	0.65	0.00	0.62	0.00	0.65	0.00	0.63	0.0
0.69	0.00	0.72	0.00	0.69	0.00	0.71	0.00	0.70	0.0
0.75	0.00	0.79	0.00	0.75	0.00	0.77	0.00	0.77	0.0
0.81	0.00	0.86	0.00	0.82	0.00	0.83	0.00	0.83	0.0
0.87	0.00	0.92	0.00	0.88	0.00	0.89	0.00	0.90	0.0
0.92	0.00	0.99	0.00	0.94	0.00	0.95	0.00	0.96	0.0
0.98	0.00	1.05	0.00	1.01	0.00	1.00	0.00	1.02	0.0
1.04	0.00	1.11	0.00	1.07	0.00	1.06	0.00	1.09	0.0
1.09	0.00	1.17	0.00	1.13	0.00	1.11	0.00	1.15	0.0
1.15	0.00	1.24	0.00	1.19	0.00	1.16	0.00	1.20	0.0
1.20	0.00	1.30	0.00	1.25	0.00	1.21	0.00	1.26	0.0
1.26	0.00	1.36	0.00	1.31	0.00	1.26	0.00	1.32	0.0
1.31	0.00	1.41	0.00	1.37	0.00	1.31	0.00	1.37	0.0
1.37	0.00	1.47	0.00	1.42	0.00	1.35	0.00	1.42	0.0
1.42	0.00	1.53	0.00	1.48	0.00	1.40	0.00	1.47	0.0
1.48	0.00	1.59	0.00	1.54	0.00	1.44	0.00	1.52	0.0
1.53	0.00	1.64	0.00	1.59	0.00	1.48	0.00	1.57	0.0
1.59	0.00	1.70	0.00	1.65	0.00	1.52	0.01	1.62	0.0
1.64	0.00	1.75	0.00	1.70	0.00	1.55	0.01	1.66	0.0
1.70	0.00	1.81	0.00	1.75	0.00	1.59	0.01	1.70	0.0
1.75	0.00	1.86	0.00	1.80	0.00	1.62	0.01	1.74	0.0
1.80	0.00	1.91	0.00	1.85	0.00	1.65	0.01	1.77	0.0
1.86	0.00	1.97	0.00	1.90	0.00	1.67	0.01	1.80	0.0
1.91	0.00	2.02	0.00	1.95	0.00	1.69	0.02	1.83	0.0
1.96	0.00	2.07	0.00	2.00	0.00	1.71	0.02	1.85	0.0
2.02	0.00	2.12	0.00	2.05	0.00	1.73	0.02	1.87	0.01
2.07	0.00	2.18	0.00	2.10	0.00	1.74	0.03	1.88	0.01
2.12	0.00	2.23	0.00	2.15	0.00	1.75	0.03	1.89	0.01
2.17	0.00	2.28	0.00	2.19	0.00	1.75	0.04	1.89	0.02
2.23	0.00	2.33	0.00	2.24	0.00	1.75	0.05	1.89	0.02
2.28	0.00	2.38	0.00	2.28	0.00	1.75	0.05	1.88	0.03
2.33	0.00	2.44	0.00	2.33	0.00	1.74	0.06	1.86	0.04
2.38	0.00	2.49	0.00	2.37	0.00	1.73	0.08	1.83	0.05
2.43	0.00	2.54	0.00	2.42	0.00	1.71	0.09	1.79	0.07
2.48	0.00	2.59	0.00	2.46	0.00	1.68	0.10	1.74	0.09

2.53	0.00	2.64	0.00	2.50	0.00	1.65	0.12	1.69	0.1
2.58	0.00	2.69	0.00	2.55	0.00	1.61	0.14	1.62	0.1
2.63	0.00	2.75	0.00	2.59	0.00	1.57	0.16	1.53	0.1
2.68	0.00	2.80	0.00	2.63	0.00	1.52	0.18	1.44	0.2
2.73	0.00	2.85	0.00	2.67	0.00	1.46	0.21	1.33	0.2
2.78	0.00	2.90	0.00	2.72	0.00	1.40	0.24	1.21	0.3
2.83	0.00	2.96	0.00	2.76	0.00	1.33	0.27	1.07	0.3
2.88	0.00	3.01	0.00	2.80	0.00	1.26	0.31	0.91	0.4
2.93	0.00	3.06	0.00	2.85	0.00	1.17	0.35	0.74	0.5
2.98	0.00	3.12	0.00	2.89	0.00	1.08	0.40	0.55	0.6
3.03	0.00	3.17	0.00	2.93	0.00	0.98	0.45	0.34	0.7
3.08	0.00	3.23	0.00	2.98	0.00	0.88	0.50	0.11	0.9
3.13	0.00	3.28	0.00	3.02	0.00	0.76	0.57	-0.14	1.0
3.18	0.00	3.34	0.01	3.07	0.00	0.64	0.63	-0.41	1.2
3.22	0.00	3.40	0.01	3.11	0.00	0.51	0.70	-0.71	1.5
3.27	0.00	3.46	0.01	3.16	0.00	0.37	0.78	-1.02	1.7
3.32	0.00	3.52	0.01	3.21	0.00	0.22	0.87	-1.36	2.0
3.37	0.00	3.57	0.01	3.26	0.00	0.06	0.96	-1.73	2.3
3.41	0.00	3.63	0.01	3.31	0.00	-0.10	1.06	-2.12	2.6
3.46	0.00	3.70	0.01	3.36	0.00	-0.27	1.17	-2.54	3.0
3.51	0.00	3.76	0.01	3.41	0.00	-0.46	1.28	-2.98	3.4
3.55	0.00	3.82	0.01	3.47	0.00	-0.65	1.40	-3.45	3.9
3.60	0.00	3.88	0.01	3.52	0.00	-0.85	1.53	-3.94	4.4
3.65	0.00	3.95	0.01	3.58	0.00	-1.06	1.67	-4.47	5.0
3.69	0.00	4.01	0.01	3.64	0.00	-1.27	1.82	-5.02	5.6
3.74	0.00	4.08	0.01	3.70	0.00	-1.50	1.97	-5.60	6.2
3.78	0.00	4.15	0.01	3.76	0.00	-1.73	2.13	-6.21	6.9
3.83	0.00	4.22	0.01	3.83	0.00	-1.97	2.29	-6.84	7.7
3.87	0.00	4.29	0.01	3.90	0.00	-2.22	2.46	-7.51	8.5
3.92	0.00	4.36	0.01	3.97	0.00	-2.48	2.63	-8.20	9.3
3.96	0.00	4.43	0.01	4.04	0.00	-2.75	2.78	-8.91	10.0
4.00	0.01	4.49	0.00	4.10	0.00	-2.96	2.80	-9.50	9.9

Graph Software (S_f)

Poly 13	SSE	%	Poly 13	SSE	%
0.00	-	-	2.24	0.00	0.00%
0.08	0.00	0.42%	2.29	0.00	0.00%
0.15	0.00	0.03%	2.33	0.00	0.00%
0.22	0.00	0.00%	2.38	0.00	0.00%
0.29	0.00	0.01%	2.43	0.00	0.00%
0.36	0.00	0.01%	2.47	0.00	0.00%
0.44	0.00	0.00%	2.52	0.00	0.00%
0.51	0.00	0.00%	2.56	0.00	0.00%
0.57	0.00	0.00%	2.60	0.00	0.00%
0.64	0.00	0.00%	2.65	0.00	0.00%
0.71	0.00	0.00%	2.70	0.00	0.00%
0.77	0.00	0.00%	2.74	0.00	0.00%
0.83	0.00	0.00%	2.79	0.00	0.00%
0.89	0.00	0.00%	2.83	0.00	0.00%
0.95	0.00	0.00%	2.88	0.00	0.00%
1.01	0.00	0.00%	2.93	0.00	0.00%
1.07	0.00	0.00%	2.97	0.00	0.00%
1.13	0.00	0.00%	3.02	0.00	0.00%
1.19	0.00	0.00%	3.07	0.00	0.00%
1.25	0.00	0.00%	3.11	0.00	0.00%
1.31	0.00	0.00%	3.15	0.00	0.00%
1.37	0.00	0.00%	3.20	0.00	0.00%
1.42	0.00	0.00%	3.24	0.00	0.00%
1.48	0.00	0.00%	3.28	0.00	0.00%
1.53	0.00	0.00%	3.33	0.00	0.00%
1.58	0.00	0.00%	3.38	0.00	0.00%
1.64	0.00	0.00%	3.43	0.00	0.00%
1.69	0.00	0.00%	3.48	0.00	0.00%
1.74	0.00	0.00%	3.53	0.00	0.00%
1.79	0.00	0.00%	3.59	0.00	0.00%
1.84	0.00	0.00%	3.65	0.00	0.00%
1.89	0.00	0.00%	3.70	0.00	0.00%
1.94	0.00	0.00%	3.75	0.00	0.01%
1.99	0.00	0.00%	3.80	0.00	0.01%
2.04	0.00	0.00%	3.86	0.00	0.02%
2.09	0.00	0.00%	3.96	0.00	0.01%
2.14	0.00	0.00%	4.12	0.00	0.00%
2.19	0.00	0.00%	4.35	0.00	0.02%

Polynomial Equations (S_f)

Poly	Equations	R^2
2	$S_f = -4E\text{-}06T^2 + 0.0119T + 0.1091$	0.9967
3	$S_f = 5E\text{-}08T^3 - 3E\text{-}05T^2 + 0.0163T - 0.0249$	0.9989
4	$S_f = 2E\text{-}10T^4 - 1E\text{-}07T^3 + 3E\text{-}06T^2 + 0.0133T + 0.0283$	0.9993
5	$S_f = 2E\text{-}12T^5 - 2E\text{-}09T^4 + 5E\text{-}07T^3 - 8E\text{-}05T^2 + 0.0176T - 0.0201$	0.9995
6	$S_f = 2E\text{-}14T^6 - 2E\text{-}11T^5 + 6E\text{-}09T^4 - 9E\text{-}07T^3 + 5E\text{-}05T^2 + 0.0128T + 0.0168$	0.9996
13	$S_f = 8.0692604E\text{-}29T^{13} - 1.873405E\text{-}25T^{12} + 1.9228998E\text{-}22T^{11} - 1.1487899E\text{-}19T^{10} + 4.4257812E\text{-}17T^9 - 1.1509791E\text{-}14T^8 + 2.0556459E\text{-}12T^7 - 2.5155834E\text{-}10T^6 + 2.0674002E\text{-}08T^5 - 1.0950787E\text{-}06T^4 + 3.4817898E\text{-}05T^3 - 0.00060780556T^2 + 0.019177244T - 0.0031852377$	**1.0000**

Fluid Entropy S_{fg}

Microsoft Excel (S_{fg})

Poly 2	SSE	Poly 3	SSE	Poly 4	SSE	Poly 5	SSE	Poly 6	SSE
8.71	0.00	9.18	0.00	9.07	0.00	9.20	0.00	9.11	0.00
8.58	0.00	8.97	0.00	8.90	0.00	8.98	0.00	8.93	0.00
8.45	0.00	8.77	0.00	8.72	0.00	8.76	0.00	8.75	0.00
8.32	0.00	8.57	0.00	8.55	0.00	8.56	0.00	8.57	0.00
8.20	0.00	8.38	0.00	8.38	0.00	8.37	0.00	8.39	0.00
8.07	0.00	8.19	0.00	8.21	0.00	8.19	0.00	8.22	0.00
7.94	0.00	8.01	0.00	8.05	0.00	8.03	0.00	8.04	0.00
7.82	0.00	7.83	0.00	7.89	0.00	7.88	0.00	7.87	0.00
7.69	0.00	7.66	0.00	7.73	0.00	7.73	0.00	7.71	0.00
7.57	0.00	7.48	0.00	7.57	0.00	7.60	0.00	7.55	0.00
7.45	0.00	7.32	0.00	7.42	0.00	7.48	0.00	7.40	0.00
7.33	0.00	7.15	0.00	7.27	0.00	7.37	0.00	7.25	0.00
7.21	0.00	6.99	0.00	7.12	0.00	7.27	0.00	7.12	0.00
7.09	0.00	6.83	0.00	6.98	0.00	7.18	0.00	6.99	0.00
6.97	0.00	6.68	0.00	6.84	0.00	7.10	0.00	6.87	0.00
6.85	0.00	6.53	0.00	6.70	0.00	7.03	0.00	6.76	0.00
6.74	0.00	6.38	0.00	6.56	0.00	6.97	0.00	6.67	0.00
6.62	0.00	6.23	0.00	6.43	0.00	6.92	0.01	6.58	0.00
6.51	0.00	6.09	0.00	6.30	0.00	6.87	0.01	6.50	0.00
6.40	0.00	5.95	0.00	6.18	0.00	6.84	0.01	6.44	0.00
6.28	0.00	5.81	0.00	6.05	0.00	6.81	0.02	6.39	0.00
6.17	0.00	5.67	0.00	5.93	0.00	6.80	0.02	6.36	0.01
6.06	0.00	5.53	0.00	5.81	0.00	6.79	0.03	6.34	0.01
5.95	0.00	5.40	0.00	5.70	0.00	6.80	0.04	6.34	0.01
5.85	0.00	5.27	0.00	5.59	0.00	6.81	0.05	6.36	0.02
5.74	0.00	5.14	0.00	5.48	0.00	6.84	0.06	6.39	0.03
5.63	0.00	5.01	0.01	5.37	0.00	6.87	0.08	6.45	0.04
5.53	0.00	4.88	0.01	5.26	0.00	6.92	0.09	6.52	0.05
5.42	0.00	4.75	0.01	5.16	0.00	6.97	0.12	6.62	0.08
5.32	0.00	4.62	0.01	5.06	0.00	7.04	0.15	6.74	0.10
5.22	0.00	4.50	0.01	4.96	0.00	7.12	0.18	6.89	0.14
5.12	0.00	4.37	0.01	4.87	0.00	7.20	0.22	7.06	0.19
5.02	0.00	4.25	0.01	4.77	0.00	7.30	0.27	7.27	0.26
4.92	0.00	4.12	0.02	4.68	0.00	7.41	0.33	7.50	0.35
4.82	0.00	4.00	0.02	4.59	0.00	7.53	0.40	7.77	0.46
4.72	0.00	3.87	0.02	4.50	0.00	7.67	0.48	8.07	0.61
4.63	0.00	3.74	0.02	4.41	0.00	7.81	0.57	8.41	0.80
4.53	0.00	3.62	0.03	4.33	0.00	7.97	0.69	8.79	1.04
4.44	0.00	3.49	0.03	4.24	0.00	8.14	0.82	9.22	1.34
4.35	0.00	3.37	0.04	4.16	0.00	8.33	0.98	9.68	1.73
4.25	0.00	3.24	0.04	4.07	0.00	8.52	1.16	10.19	2.21
4.16	0.00	3.11	0.05	3.99	0.00	8.73	1.38	10.76	2.82
4.07	0.00	2.98	0.06	3.91	0.00	8.96	1.63	11.37	3.58
3.98	0.00	2.85	0.07	3.83	0.00	9.19	1.93	12.04	4.53

3.90	0.00	2.71	0.08	3.74	0.00	9.44	2.27	12.77	5.71
3.81	0.00	2.58	0.09	3.66	0.00	9.70	2.67	13.56	7.18
3.72	0.00	2.44	0.10	3.58	0.00	9.98	3.13	14.41	9.00
3.64	0.00	2.30	0.12	3.50	0.00	10.27	3.67	15.33	11.24
3.55	0.00	2.16	0.14	3.42	0.00	10.57	4.30	16.32	14.01
3.47	0.00	2.02	0.16	3.33	0.00	10.89	5.03	17.38	17.42
3.39	0.00	1.88	0.18	3.25	0.00	11.22	5.87	18.52	21.62
3.31	0.00	1.73	0.21	3.16	0.00	11.57	6.85	19.75	26.77
3.23	0.00	1.58	0.24	3.07	0.00	11.92	7.98	21.05	33.10
3.15	0.00	1.43	0.28	2.99	0.00	12.29	9.30	22.44	40.86
3.07	0.00	1.27	0.32	2.89	0.00	12.68	10.83	23.92	50.39
2.99	0.00	1.11	0.38	2.80	0.00	13.07	12.61	25.50	62.07
2.92	0.00	0.95	0.43	2.71	0.00	13.48	14.69	27.17	76.40
2.84	0.00	0.79	0.50	2.61	0.00	13.90	17.11	28.95	94.01
2.77	0.00	0.62	0.59	2.51	0.00	14.34	19.95	30.83	115.68
2.70	0.00	0.44	0.68	2.40	0.00	14.78	23.28	32.82	142.40
2.62	0.00	0.27	0.79	2.29	0.00	15.23	27.20	34.91	175.42
2.55	0.01	0.09	0.93	2.18	0.01	15.70	31.85	37.13	216.38
2.48	0.01	-0.10	1.09	2.07	0.01	16.18	37.39	39.46	267.46
2.41	0.01	-0.29	1.28	1.94	0.01	16.66	44.03	41.91	331.46
2.35	0.02	-0.48	1.51	1.82	0.02	17.15	52.06	44.49	412.26
2.28	0.02	-0.68	1.80	1.69	0.02	17.66	61.90	47.19	515.26
2.21	0.03	-0.88	2.15	1.55	0.03	18.16	74.10	50.02	648.08
2.15	0.04	-1.09	2.59	1.41	0.04	18.68	89.51	52.99	822.10
2.08	0.06	-1.30	3.16	1.27	0.06	19.20	109.39	56.09	1054.46
2.02	0.09	-1.52	3.90	1.11	0.08	19.73	135.88	59.33	1373.86
1.96	0.13	-1.74	4.91	0.95	0.11	20.25	172.60	62.70	1829.22
1.90	0.22	-1.97	6.37	0.79	0.15	20.78	226.79	66.23	2517.10
1.84	0.38	-2.21	8.64	0.61	0.21	21.32	314.81	69.89	3654.56
1.78	0.76	-2.45	12.80	0.43	0.30	21.85	485.08	73.70	5878.38
1.72	2.24	-2.69	24.09	0.24	0.42	22.38	990.94	77.66	12480.12
1.68	-	-2.89	-	0.09	-	22.80	-	80.89	-

Graph Software (S_{fg})

Poly 14	SSE	%	Poly 14	SSE	%
9.15	0.00	0.00%	4.27	0.00	0.00%
8.96	0.00	0.00%	4.18	0.00	0.00%
8.75	0.00	0.00%	4.09	0.00	0.00%
8.55	0.00	0.00%	4.00	0.00	0.00%
8.36	0.00	0.00%	3.92	0.00	0.00%
8.19	0.00	0.00%	3.83	0.00	0.00%
8.02	0.00	0.00%	3.75	0.00	0.00%
7.85	0.00	0.00%	3.66	0.00	0.00%
7.69	0.00	0.00%	3.58	0.00	0.00%
7.53	0.00	0.00%	3.50	0.00	0.00%
7.37	0.00	0.00%	3.42	0.00	0.00%
7.22	0.00	0.00%	3.33	0.00	0.01%
7.07	0.00	0.00%	3.25	0.00	0.01%
6.93	0.00	0.00%	3.16	0.00	0.02%
6.79	0.00	0.00%	3.06	0.00	0.03%
6.66	0.00	0.00%	2.97	0.00	0.05%
6.53	0.00	0.00%	2.86	0.00	0.09%
6.41	0.00	0.00%	2.76	0.00	0.16%
6.29	0.00	0.00%	2.65	0.00	0.25%
6.17	0.00	0.00%	2.54	0.00	0.38%
6.05	0.00	0.00%	2.42	0.01	0.57%
5.94	0.00	0.00%	2.31	0.01	0.82%
5.82	0.00	0.00%	2.18	0.01	1.18%
5.71	0.00	0.00%	2.06	0.02	1.69%
5.60	0.00	0.00%	1.92	0.02	2.43%
5.49	0.00	0.00%	1.77	0.04	3.57%
5.39	0.00	0.00%	1.61	0.05	5.35%
5.28	0.00	0.00%	1.42	0.08	8.18%
5.18	0.00	0.00%	1.22	0.13	12.69%
5.09	0.00	0.00%	0.99	0.20	19.79%
4.99	0.00	0.00%	0.75	0.31	30.82%
4.90	0.00	0.00%	0.48	0.48	47.67%
4.81	0.00	0.00%	0.20	0.73	73.46%
4.72	0.00	0.00%	-0.09	1.15	114.75%
4.63	0.00	0.00%	-0.43	1.90	189.61%
4.54	0.00	0.00%	-0.86	3.63	363.42%
4.45	0.00	0.00%	-1.50	10.13	1012.97%
4.36	0.00	0.00%	-2.31	-	-

Polynomial Equations (S_{fg})

Poly	Equations	R^2
2	$S_{fg} = 2E\text{-}05T^2 - 0.0263T + 8.7135$	0.9914
3	$S_{fg} = -2E\text{-}07T^3 + 0.0001T^2 - 0.0417T + 9.177$	0.9985
4	$S_{fg} = -4E\text{-}10T^4 + 1E\text{-}07T^3 + 5E\text{-}05T^2 - 0.0358T + 9.0732$	0.9988
5	$S_{fg} = -5E\text{-}12T^5 + 4E\text{-}09T^4 - 1E\text{-}06T^3 + 0.0003T^2 - 0.0474T + 9.2047$	0.9993
6	$S_{fg} = -4E\text{-}14T^6 + 4E\text{-}11T^5 - 1E\text{-}08T^4 + 2E\text{-}06T^3 - 5E\text{-}05T^2 - 0.0358T + 9.1146$	0.9995
14	$S_{fg} = -1.7119655E\text{-}30T^{14}+4.2872679E\text{-}27T^{13}-4.7900571E\text{-}24T^{12}+3.1493118E\text{-}21T^{11}-1.3532265E\text{-}18T^{10}+3.9910587E\text{-}16T^{9}-8.2566824E\text{-}14T^{8}+0.000000000001203202T^{7}-0.000000001222315T^{6}+0.000000084362616T^{5}-0.0000037773132T^{4}+0.00010106076T^{3}-0.0012725445T^{2}-0.034453531T+9.1516268$	**1.0000**

APPENDIX E

Sample Calculations

E-1 Energy Balance

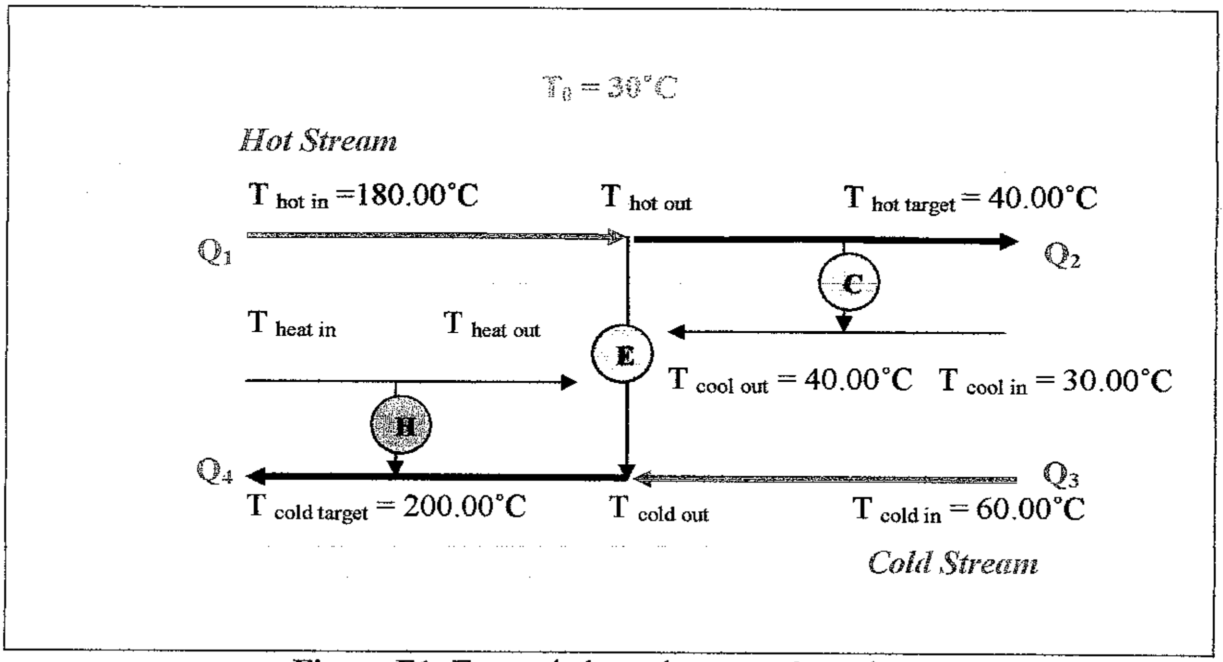


Figure E1: Energy balance between Q_1 and Q_3

Guess $T_{hot\ out} = 76.89°C$

$C_{p\ cold\ out} = 4250.00$ J/kg.°C

$T_{hot\ in} = 180.00°C$, $C_{p\ hot\ in} = 4432.90$ J/kg.°C

$T_{hot\ out} = 76.89°C$, $C_{p\ hot\ out} = 4198.94$ J/kg.°C

$C_{p\ hot\ average} = (C_{p\ hot\ in} + C_{p\ hot\ out})/2 = (4432.90 + 4198.94)/2 = 4315.92$ J/kg.°C

$T_{cold\ in} = 60.00°C$, $C_{p\ cold\ in} = 4184.85$ J/kg.°C

$C_{p\ cold\ out} = 4250.00$ J/kg.°C, $T_{cold\ out} = 129.69°C$

$C_{p\ cold\ average} = (C_{p\ cold\ in} + C_{p\ cold\ out})/2 = (4184.85 + 4250.00)/2 = 4217.43$ J/kg.°C

$m_{hot} = 1000$ kg/s,

$Q_1 = Q_3$,

$$m_{hot}\, C_{p\ hot\ average}\,(T_{hot\ in} - T_{hot\ out}) = m_{cold}\, C_{p\ cold\ average}\,(T_{cold\ out} - T_{cold\ in})$$

$$(1000\ kg/s)(4315.92\ J/kg.°C)(180.00°C - 76.89°C) = m_{cold}\,(4217.43\ J/kg.°C)(129.69°C - 60.00°C)$$

$$\boxed{m_{cold} = 1514.10\ kg/s}$$

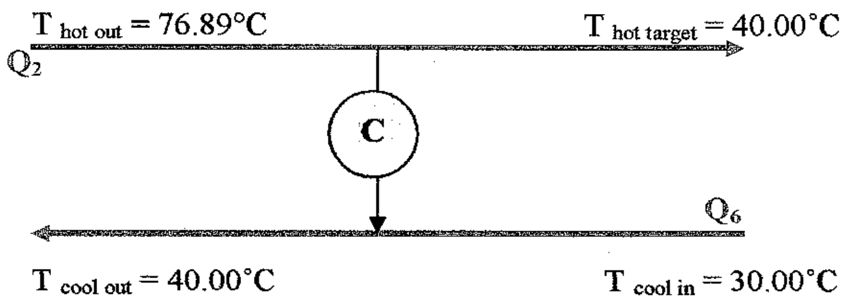


Figure E2: Energy balance between Q_2 and Q_6

$T_{hot\ out} = 76.89°C$, $C_{p\ hot\ out} = 4198.94$ J/kg.°C

$T_{hot\ target} = 40.00°C$, $C_{p\ hot\ target} = 4171.81$ J/kg.°C

$C_{p\ hot\ average} = (C_{p\ hot\ out} + C_{p\ hot\ target})/2 = (4198.94 + 4171.81)/2 = 4185.38$ J/kg.°C

$T_{cool\ in} = 30.00°C$, $C_{p\ cool\ in} = 4173.10$ J/kg.°C

$T_{cool\ out} = 40.00°C$, $C_{p\ cool\ out} = 4171.81$ J/kg.°C

$C_{p\ cold\ average} = (C_{p\ cool\ in} + C_{p\ cool\ out})/2 = (4173.10 + 4171.81)/2 = 4172.46$ J/kg.°C

$Q_2 = Q_6$,

$$m_{hot}\, C_{p\,hot\,average}\,(T_{hot\,out} - T_{hot\,target}) =$$
$$m_{cool}\, C_{p\,cool\,average}\,(T_{cool\,out} - T_{cool\,in})$$
$$(1000\ kg/s)(4185.38\ J/kg.°C)(76.89°C - 40.00°C) =$$
$$m_{cool}\,(4172.46\ J/kg.°C)(40.00°C - 30.00°C)$$

$$\boxed{m_{cool} = 3700.42\ kg/s}$$

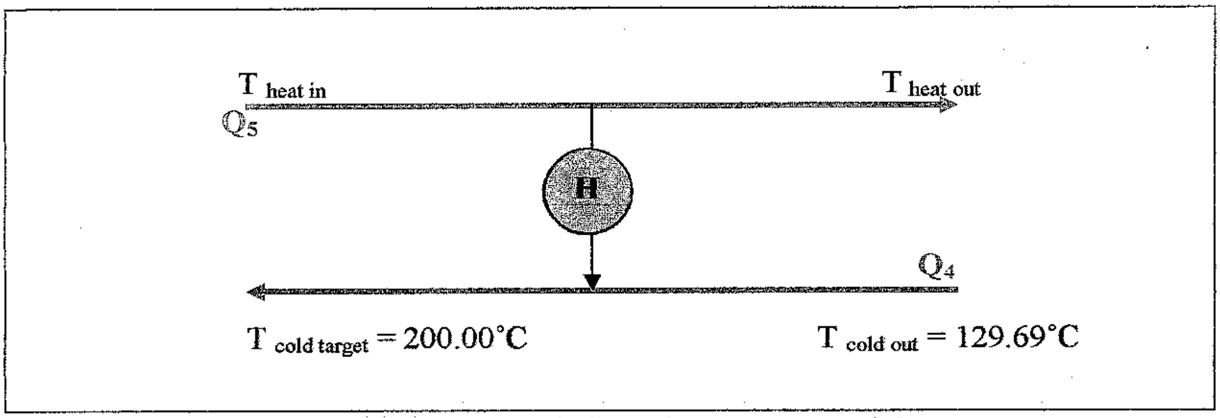


Figure E3: Energy balance between Q_5 and Q_4

$T_{cold\,out} = 129.69°C$, $C_{p\,cold\,out} = 4250.00\ J/kg.°C$

$T_{cold\,target} = 200.00°C$, $C_{p\,cold\,target} = 4523.85\ J/kg.°C$

$C_{p\,cold\,average} = (C_{p\,cold\,out} + C_{p\,cold\,target})/2 = (4250.00 + 4523.85)/2 = 4386.93\ J/kg.°C$

$m_{heat} = 1500.00\ kg/s$, $C_{p\,heat\,average}\,\Delta T_{heat} = H_{fg}$

$Q_5 = Q_4$,

$$m_{cold}\, C_{p\,cold\,average}\,(T_{cold\,out} - T_{cold\,target}) =$$
$$m_{heat}\, C_{p\,heat\,average}\,\Delta T_{heat}$$

$$(1514.10\ kg/s)(4386.93\ J/kg.°C)(200.00°C - 129.69°C) =$$
$$(1500.00\ kg/s)H_{fg}$$

$$H_{fg} = 311344.43 \text{ J/kg} = 311.34 \text{ kJ/kg}$$

$$T_{\text{heat in}} = T_{\text{heat out}} = 338.93\,^{\circ}\text{C}$$

$$S_{fg} = 0.80 \text{ kJ/kg.}^{\circ}\text{C}$$

E-2 Exergy Lost

$T_0 = 30°C$,

$$\text{Ex lost (HE)} = [(H_{f\,\text{hot in}} - H_{f\,\text{hot out}}) - T_0\,(S_{f\,\text{hot in}} - S_{f\,\text{hot out}})] - [(H_{f\,\text{cold out}} - H_{f\,\text{cold in}}) - T_0\,(S_{f\,\text{cold out}} - S_{f\,\text{cold in}})]$$

$T_{\text{hot in}} = 180.00°C$, $H_{f\,\text{hot in}} = 762.75$ kJ/kg, $S_{f\,\text{hot in}} = 2.14$ kJ/kg.°C

$T_{\text{hot out}} = 76.89°C$, $H_{f\,\text{hot out}} = 322.45$ kJ/kg, $S_{f\,\text{hot out}} = 1.04$ kJ/kg.°C

$T_{\text{cold in}} = 60.00°C$, $H_{f\,\text{cold in}} = 251.19$ kJ/kg, $S_{f\,\text{cold in}} = 0.83$ kJ/kg.°C

$T_{\text{cold out}} = 129.69°C$, $H_{f\,\text{cold out}} = 545.42$ kJ/kg, $S_{f\,\text{cold out}} = 1.63$ kJ/kg.°C

$$\begin{aligned}\text{Ex lost (HE)} &= [(762.75 \text{ kJ/kg} - 322.45 \text{ kJ/kg}) - 30\,^{\circ}\text{C}\,(2.14 \text{ kJ/kg.}^{\circ}\text{C} - 1.04 \text{ kJ/kg.}^{\circ}\text{C})] - \\ &\quad [(545.42 \text{ kJ/kg} - 251.19 \text{ kJ/kg}) - 30\,^{\circ}\text{C}\,(1.63 \text{ kJ/kg.}^{\circ}\text{C} - 0.83 \text{ kJ/kg.}^{\circ}\text{C})] \\ &= 137.07 \text{ kJ/kg}\end{aligned}$$

$$\text{Ex lost (Cool)} = [(H_{f\,\text{hot out}} - H_{f\,\text{hot target}}) - T_0\,(S_{f\,\text{hot out}} - S_{f\,\text{hot target}})] - [(H_{f\,\text{cool out}} - H_{f\,\text{cool in}}) - T_0\,(S_{f\,\text{cool out}} - S_{f\,\text{cool in}})]$$

$T_{\text{hot out}} = 76.89°C$, $H_{f\,\text{hot out}} = 322.45$ kJ/kg, $S_{f\,\text{hot out}} = 1.04$ kJ/kg.°C

$T_{\text{hot target}} = 40.00°C$, $H_{f\,\text{hot target}} = 167.28$ kJ/kg, $S_{f\,\text{hot target}} = 0.57$ kJ/kg.°C

$T_{\text{cool in}} = 30.00°C$, $H_{f\,\text{cool in}} = 125.95$ kJ/kg, $S_{f\,\text{cool in}} = 0.44$ kJ/kg.°C

$T_{\text{cool out}} = 40.00°C$, $H_{f\,\text{cool out}} = 167.28$ kJ/kg, $S_{f\,\text{cool out}} = 0.57$ kJ/kg.°C

Ex lost (Cool) = [(322.45 kJ/kg -167.28 kJ/kg) - 30 °C (1.04 kJ/kg.°C – 0.57 kJ/kg.°C)]
– [(167.28 kJ/kg – 125.95 kJ/kg) - 30 °C (0.57 kJ/kg.°C - 0.44 kJ/kg.°C)]
= 103.64 kJ/kg

$$\text{Ex lost (Heat)} = [(H_{\text{heat in}} - H_{\text{heat out}}) - T_0 (S_{\text{heat in}} - S_{\text{heat out}})] - [(H_{f\,\text{cold target}} - H_{f\,\text{cold out}}) - T_0 (S_{f\,\text{cold target}} - S_{f\,\text{cold out}})]$$

$H_{\text{heat in}} - H_{\text{heat out}} = H_{fg} = 311.34$ kJ/kg

$S_{\text{heat in}} - S_{\text{heat out}} = S_{fg} = 0.80$ kJ/kg.°C

$T_{\text{cold out}} = 129.69$°C, $H_{f\,\text{cold out}} = 545.42$ kJ/kg, $S_{f\,\text{cold out}} = 1.63$ kJ/kg.°C

$T_{\text{cold target}} = 200.00$°C, $H_{f\,\text{cold target}} = 853.83$ kJ/kg, $S_{f\,\text{cold target}} = 2.33$ kJ/kg.°C

Ex lost (Heat) = [(311.34 kJ/kg) - 30°C (0.80 kJ/kg.°C)] – [(853.83 kJ/kg – 545.42 kJ/kg) - 30°C (2.33 kJ/kg.°C – 1.63 kJ/kg.°C)]
= 0.00 kJ/kg

Σ Ex lost = Ex lost (HE) + Ex lost (Cool) + Ex lost (Heat)
= 137.07 kJ/kg + 103.64 kJ/kg + 0.00 kJ/kg
= 240.71 kJ/kg