ESTIMATION & COMPARISON OF HEAT TRANSFER COEFFICIENT OF CRUDE OIL USING VARIOUS CORRELATIONS

by

Noor Zaheera Binti Noorizam

A project dissertation submitted to the

Chemical Engineering Programme

Universiti Teknologi PETRONAS

In partial fulfillment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(CHEMICAL ENGINEERING)

SEPTEMBER 2011

Universiti Teknologi PETRONAS

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CERTIFICATION OF APPROVAL

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Approved by,

(AP Dr. M. Ramasamy)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2011

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.

NOOR ZAHEERA BINTI NOORIZAM

ABSTRACT

Heat transfer may occur by any one or more of the three basic mechanisms of heat transfer; conduction, convection and radiation but in process industries, the transfer of heat between two fluids is generally done via convective heat transfer.

For example, in oil refinery plant, the most common heat transfer phenomenon is the crude oil/water interchange via heat exchanger.

Calculating and estimating the heat transfer coefficients, h of crude oil using various correlations will able us to see the variations of its value and we can compare to the reference value that is being used in the industry to see which one of the correlations is suitable to be used for the crude oil system.

By having the knowledge of heat transfer coefficient of crude oil, the design of any heat exchangers will be simplified. It also help in developing better flow process control that will then help to reduce and conserve energy.

NOMENCLATURE

ρ_1	final density (kg/m^3)
ρ_0	initial density (kg/m^3)
β	volumetric temperature expansion coefficient ($m^3/m^3\,^{o}C$)
t_1	final temperature (^{o}C)
μ	viscosity of liquid at t degree Celsius n poise
μ_0	viscosity of the fluid at 0° Celsius in poise
a, b, c, d (Cp)	coefficients from Perry's Chemical Engineers' Handbook
a, b (k)	empirical constant

ACKNOWLEDGEMENT

First and foremost, I would like to express my praises to ALLAH for His blessing.

I would like to extend deepest appreciation and gratitude is to my supervisor, AP Dr. M. Ramasamy for all his teachings, guidance, supervision and supports from the beginning until to the final report that enable me to develop an understanding of the subject. It has been a hardship for you, sorry and thank you so much.

I would also like to thank other colleagues for their help, discussions and information sharing. Without them, I would not able to go this far until the end.

Finally, I would like to thank my father and mother for all the love, sacrifice, understanding and efforts for supporting and encouraging me to pursue this degree and also for keeping me motivated throughout the year.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Crude oil or commonly known as petroleum, a liquid found within the Earth is consist of hydrocarbons, organic compounds and small amount of metal. Hydrocarbons are the primary component of crude oil with the composition that can vary from 50% to 97%, depending on the type of crude oil and how it is extracted. Organic compound like nitrogen, oxygen and sulfur make-up between 6% to 10% of crude oil while metals such as copper, nickel, vanadium and iron account for less than 1% of the total composition.

Malaysian oilfield has the lightest and the sweetest of the main types of crude oil with the physical properties as shown below, [10];

Table 1: Crude Oil Properties

CRUDE OIL	
Density at 15°C (g/cm^3)	0.8036
Viscosity at 40°C (cSt)	3.831
API Gravity	44.5

Heat transfer may occur by any one or more of the three basic mechanism of heat transfer: conduction, convection and radiation [1].

Convection heat transfer takes place whenever a fluid is in contact with a solid surface that is at a different temperature than the fluid. If the fluid is moving past the solid surface because of an external driving force, like pump or blower, then it is called forced convection. If a fluid motion is due to density differences caused by temperature variation in the fluid, then it is called natural or free convection.

k is the thermal conductivity of the fluid (W/m.K)

D is characteristic length parameter such as diameter for flow through a pipe (m)

V is characteristic velocity (m/s)

p is the density of the fluids (kg/m^3)

u is the viscosity of the fluid (N-s/m^2)

Cp is heat capacity of the fluid (kJ/kg.K)

1.2 Problem Statement

In an oil refinery plant, the transfer of heat between two fluids is generally done in heat exchangers via convective heat transfer. For example, heat exchangers are used for crude oil/water interchange. The knowledge on heat transfer coefficient of crude oil will help in designing and calculations for heat exchanger design. It also help in developing better flow process control that will then help to reduce and conserve energy.

1.3 Objectives

- To estimate & calculate the properties of crude oil (density, heat capacity, viscosity and thermal conductivity) in function of temperature.
- To estimate & calculate heat transfer coefficients of crude oil using various correlations collected and compares the result between the different correlations used and data from experiment.

1.4 Scope of Study

The scope for this project has been scrutinized to estimate the heat transfer coefficient of crude oil via forced convection in turbulent flows inside a pipe. The physical properties of crude oil that vary with temperature and will effect the calculation of heat transfer coefficients that has been identified are thermal conductivity (k), density (p), viscosity (u) and specific heat capacity (Cp).

1.5 Relevancy of Project

With the continued increased in design complexity and modernization of oil refinery plant, the knowledge of heat transfer coefficient is necessary for heat transfer design and calculation. Heat transfer coefficient is also critical for designing and developing better flow process control in resulting in reduced energy consumption and enhanced energy conservation.

1.6 Feasibility of Project

This project is fully computer based. In the time given, the project could be done. This project can be done within 4 months given that everything goes fine. The objective can be achieved if the procedures are closely followed.

CHAPTER 2
LITERATURE REVIEW

2.1 Physical Properties of Crude Oil

One of the factors that will effect the calculation of heat transfer coefficients is the physical properties of the fluid itself. The physical properties of crude oil that will vary with temperature are density, viscosity, specific heat capacity and thermal conductivity. Different temperature will give different value of these physical properties that will then effect the calculation of heat transfer coefficients through Reynolds and Prandtl numbers.

2.1.1. Density

The density changes with temperature as the molecules moves around faster. That pushes them slightly farther apart, making the density go down.

When temperature is changed, the density of a fluid can be expressed as [3],

$$\rho_1 = \rho_0 / (1 + \beta (t_1 - t_0)) \tag{5}$$

2.1.2 Viscosity

Viscosity is the property of the fluid that resists the flow of the fluids. The viscosity behavior of most crude oil is very sensitive to temperature changes. As temperature increases, the viscosity of crude oil decreases [10].

When the temperature of fluid is changed, the viscosity of the fluid can be expressed [3];

$$\mu = \mu_0 / (1 + \alpha t + \beta t) \tag{6}$$

2.1.3 Specific Heat Capacity

Heat capacity is physical properties that may be expressed in any units of energy per unit amount per unit temperature interval. Heat capacity is a function of temperature and frequently expressed in polynomial form [4],

$$C_p = a + bT + cT^2 + dT^3 \tag{7}$$

2.1.4 Thermal Conductivity

Thermal conductivity of liquids varies moderately with temperature and often can be expressed as a linear variation [1],

$$k = a + bT \tag{8}$$

2.2 Heat Transfer Coefficients Correlation

There are several correlations available for calculation of the convective heat transfer coefficient for turbulent flow inside a circular tube.

2.2.1 Classic Correlation – Dittus – Boelter Equation (1930) [2]

The exponent on the Prandtl number depends on the service (either heating or cooling). Different values are needed because of the variation of viscosity with temperature [5].

$$\begin{aligned} Nu &= 0.0243\, Re^{0.8}\, Pr^{0.4}, \text{ heating of fluid } (T_{wall} > T_{fluid}) \\ Nu &= 0.0265\, Re^{0.8}\, Pr^{0.3}, \text{ cooling of fluid } (T_{wall} < T_{fluid}) \end{aligned} \tag{9}$$

This equation is recommended only for rather small temperature differences between bulk fluid and pipe wall. It is valid for smooth pipe and for,

$0.6 \leq Pr \leq 160$

$Re \geq 10000$

$L/D \geq 10$

2.2.2. Sieder - Tate (1936) [2]

This equation can accommodate larger temperature differences,

$$\mathrm{Nu} = 0.023\ \mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}\,(\mu_b/\mu_w)^{0.14} \tag{10}$$

This equation is valid for smooth pipes and for,

$0.7 \le \mathrm{Pr} \le 16700$

$\mathrm{Re} \ge 10000$

$L/D \ge 10$

2.2.3 Pethukov, Gnielinski

This correlation has been based on extensive experimental data and on a better understanding of turbulent flow [6].

$$Nu_0 = \frac{\frac{\xi}{8}}{1 + 12.7\sqrt{\frac{\xi}{8}}\left(\mathrm{Pr}^{2/3}\right)}(\mathrm{Re} - 1000)\mathrm{Pr} \times [1 + (\frac{D}{L})^{2/3}]$$

$$\xi = \frac{1}{(1.82\log \mathrm{Re} - 1.64)^2} \tag{11}$$

This correlation is valid for both smooth and rough tubes with

$0.5 \le \mathrm{Pr} \le 2000$

$2300 < \mathrm{Re} < 5 \times 10^6$.

2.2.4 Colburn Equation

After simplified from Chilton-Colburn equation, the final equation is [7],

$$\mathrm{Nu} = 0.023\ \mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}$$

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

a) Research on properties of crude oil at different temperature

- Identify the properties that vary with temperature that will effect the calculation of heat transfer coefficient

↓

b) Research on suitable correlations to calculate heat transfer coefficients of crude oil

- Identify the suitable correlations that is the heat transfer coefficients correlations via forced convection in a circular tube with turbulent flow

↓

c) Equation programmed into Excel 2007

- Equation is programmed into Excel spreadsheet to calculate the heat transfer coefficients for each different correlations

↓

d) Discussion

- Comparison of data between correlations
- Objective achievement

↓

e) Conclusion

Figure 1: Flow Chart for FYP Methodology

3.2 Project Activities

For this project, the main activities that will be done are:

- Literature review – gathering information, reading journals and finding references.

- Correlations – gathering relevant correlations for this project
  - ➢ The correlations chosen must not be specially for certain fluid only

- Estimation & Calculations
  - ➢ Find the relationship for properties of crude oil (thermal conductivity, density, viscosity, and specific heat capacity) with respect to temperature through simulation of PETROSIM with temperature range from 0°C to 300°C.
  - ➢ Then, graph is plotted (ex; Temperature vs Density) to find the related equation between the physical properties and temperature.
  - ➢ Heat transfer coefficients for crude oil is calculated based on the correlations gathered (Dittus-Boelter, Sieder-Tate, Pethukov, Gnielinski & Colburn) at reference heat transfer coefficient data.

Table 2: Reference Heat Transfer Coefficient Data

Heat Exchanger	Temperature (°C)	Velocity (m/s)	Heat Transfer Coefficient ($W/m^2.K$)
E-01	58	1.79	1506
E-02	86	1.62	1567
E-03	108	1.06	1194
E-05	138.5	0.78	996
E-06	149	2.12	2241
E-07	154	1.7	1903
E-09	185.5	1.35	1769
E-10	204	2.89	3442

- Analysis of Data
  - ➢ The value of transfer coefficients calculated using the four correlations gathered is compared with the reference data.

- Graph heat transfer coefficient, h_{calc} vs. h_{ref} is plotted and one linear line is plotted to see the nearness of value of every data of heat transfer coefficient of crude oil (calculated h_{calc}) to the heat transfer coefficient of crude oil (reference, h_{ref})

3.3 Gantt Chart

No.	Detail/Week	1	2	3	4	5	6	7	MID SEMESTER BREAK	8	9	10	11	12	13	14	15
1	Project Work Continues																
	•simulation to find relationship between temperature & properties of crude oil																
	•analysis of data																
	• spreadsheet on EXCEL																
2	Submission Progress Report									■							
3	Project Work Continues																
	•program equation of correlation into EXCEL																
	•analysis on data																
4	Pre - EDX												■				
5	Submission of Draft Report													■			
7	Submission of Technical Paper														■		
8	Oral Presentation															■	
9	Submission of Project Dissertation (Hard Bound)																■

	Process
■	Suggested Milestone

Figure 2: Gantt chart for FYP II

3.4 Tools & Equipment

In this project, computers are the major tool used. Simulation is done by PETROSIM software and calculations are done using Microsoft Excel.

CHAPTER 4
RESULT & DISCUSSION

4.1 Estimation & Calculation of Properties of Crude Oil with respect to Temperature

INSTRUCTION: Insert value in blue box, spreadsheet calculate in yellow box

Calculation of Density			Calculation of Viscosity		
$y = -0.00118x^2 - 0.618x + 811.3$			$y = -8.85E\text{-}12x5 + 8.12E\text{-}09x4 - 2.90E\text{-}06x3 + 5.16E\text{-}04x2 - 4.98E\text{-}02x + 2.60$		
y = density x = temperature			y = viscosity x = temperature		
Enter Temperature	204		Enter Temperature	204	
Density	636.1211	kg/m^3	Viscosity	0.000231	Pa.s
Calculation of Thermal Conductivity			Calculation of Specific Heat Capacity		
$y = 2.19E\text{-}08x^4 - 1.16E\text{-}05x^3 + 1.30E\text{-}03x^2 - 2.91E\text{-}01x + 137$			$y = -2.02E\text{-}06x^2 + 0.00444x + 1.94$		
y = thermal conductivity x = temperature			y = specific heat capacity x = temperature		
Enter Temperature	204		Enter Temperature	204	
Thermal Conductivity	0.071185	W/m.K	Specific Heat Capacity	2.761696	kJ/Kg.K

Figure 3: Spreadsheet to calculate the properties of crude oil

Figure 3 above is the spreadsheet that calculates every physical properties of crude oil (thermal conductivity, density, viscosity & specific heat capacity) with respect to temperature. The relationship between properties of crude oil to temperature is determined through the simulation of crude oil through PETROSIM software. The value obtained from the PETROSIM simulation is attached in Appendices section.

The graph is plotted between temperature and each properties of crude oil for range of temperature between 0°C to 300°C, based on the result from PETROSIM simulation to find the equation that relates them and simplified the general correlation shown, to an equation that represents the actual result.

4.1 Density

In the PETROSIM simulation, the relationship between temperature and density is shown in the graph below.

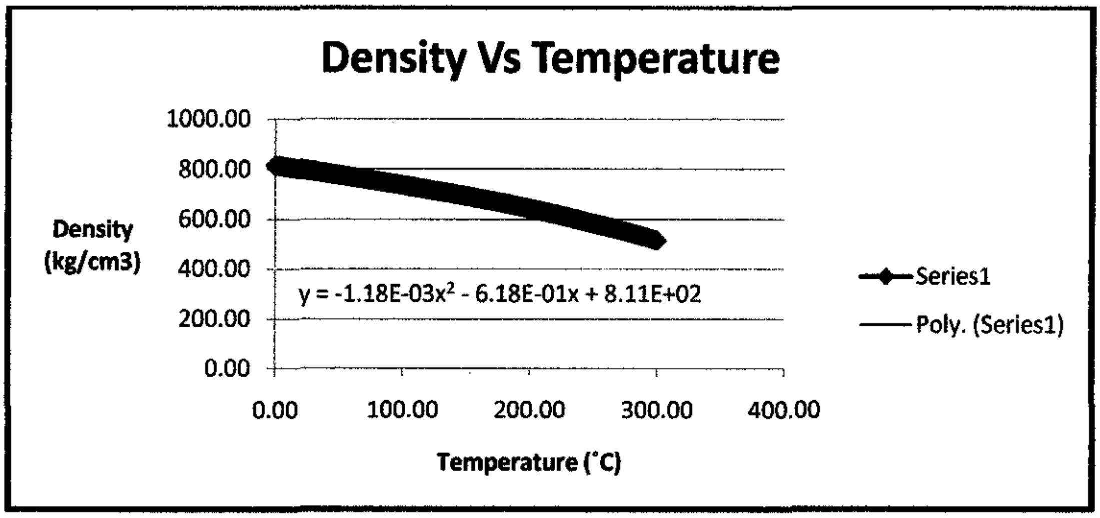


Figure 4: Graph of Density vs. Temperature from PETROSIM simulation

Based on the graph, the density of crude oil show a linear relationship to temperature that is with the increase of temperature, the density of crude oil decrease thus proving the statement above and the general correlation has been simplified to the equation below,

$$\rho = -1.18 \times 10^{-3} T^2 - 0.618T + 811 \quad (13)$$

4.2 Viscosity

In the PETROSIM simulation, the relationship between temperature and viscosity is shown in the graph below.

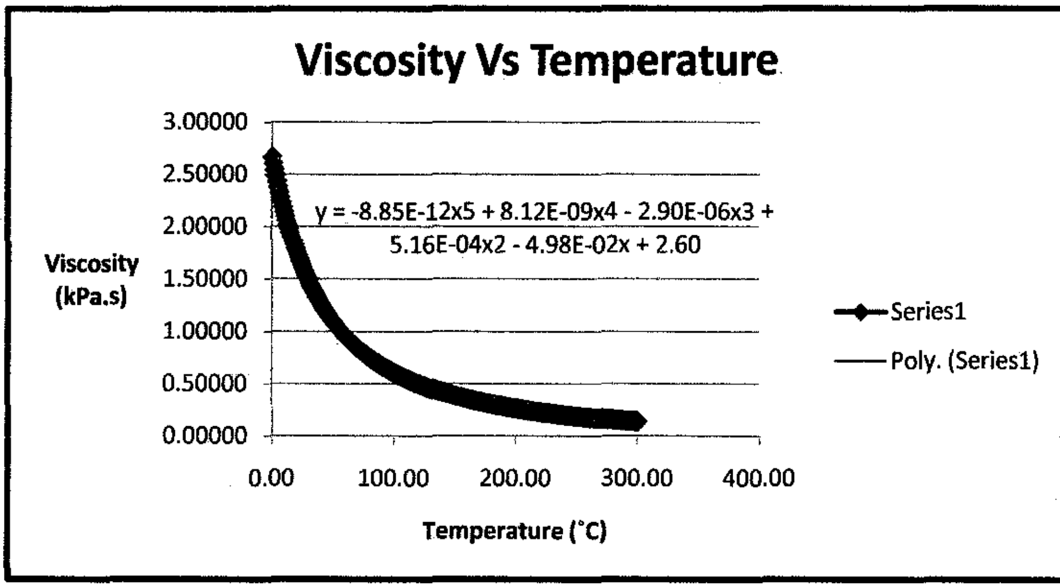


Figure 5: Graph of Viscosity Vs Temperature from PETROSIM simulation

Based on the graph, with the increase of temperature, the viscosity of crude oil will decrease of crude oil decrease and the general correlation has been simplified to the equation below,

$$\mu = -8.85 \times 10^{-12}T^5 + 8.12 \times 10^{-9}T^4 - 2.9 \times 10^{-6}T^3 + 5.16 \times 10^{-4}T^2 - 0.0498T + 2.6 \quad (14)$$

4.3 Specific Heat Capacity

In the PETROSIM simulation, the relationship between temperature and specific heat capacity is shown in the graph below.

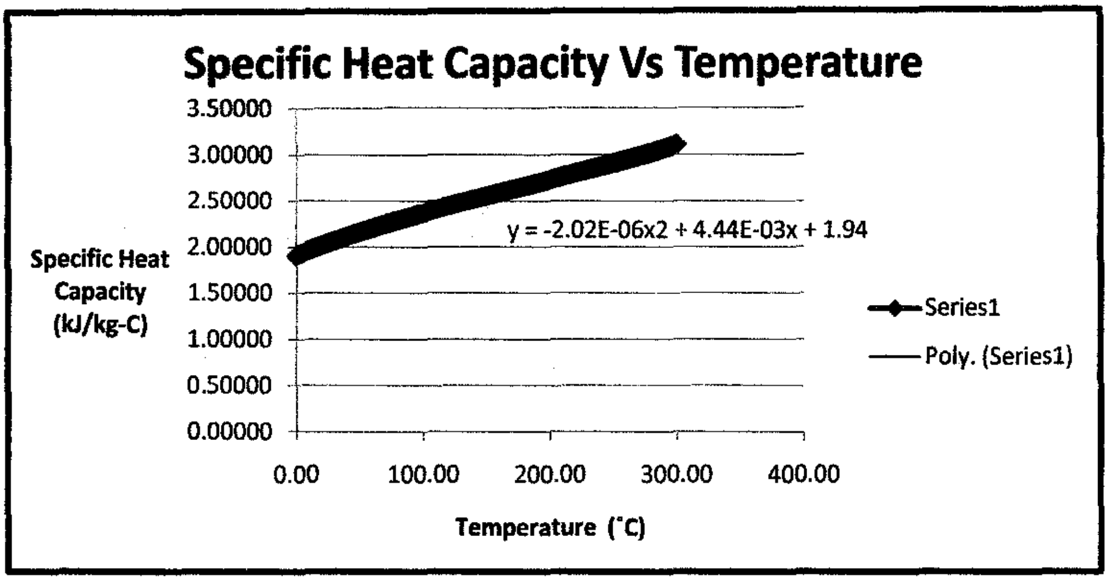


Figure 6: Graph of Specific Heat Capacity Vs Temperature from PETROSIM simulation

Based on the graph, with the increase of temperature, the specific heat capacity of crude oil will decrease and the general correlation has been simplified to the equation below,

$$Cp = -2.02 \times 10^{-6}T^2 + 0.00444T + 1.94 \quad (15)$$

4.3 Thermal Conductivity

In the PETROSIM simulation, the relationship between temperature and thermal conductivity is shown in the graph below.

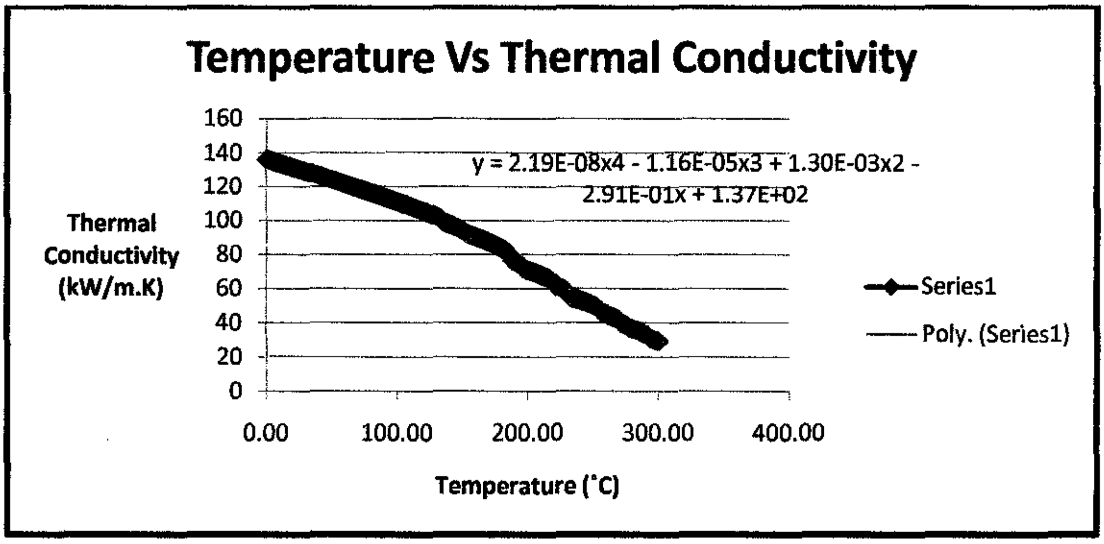
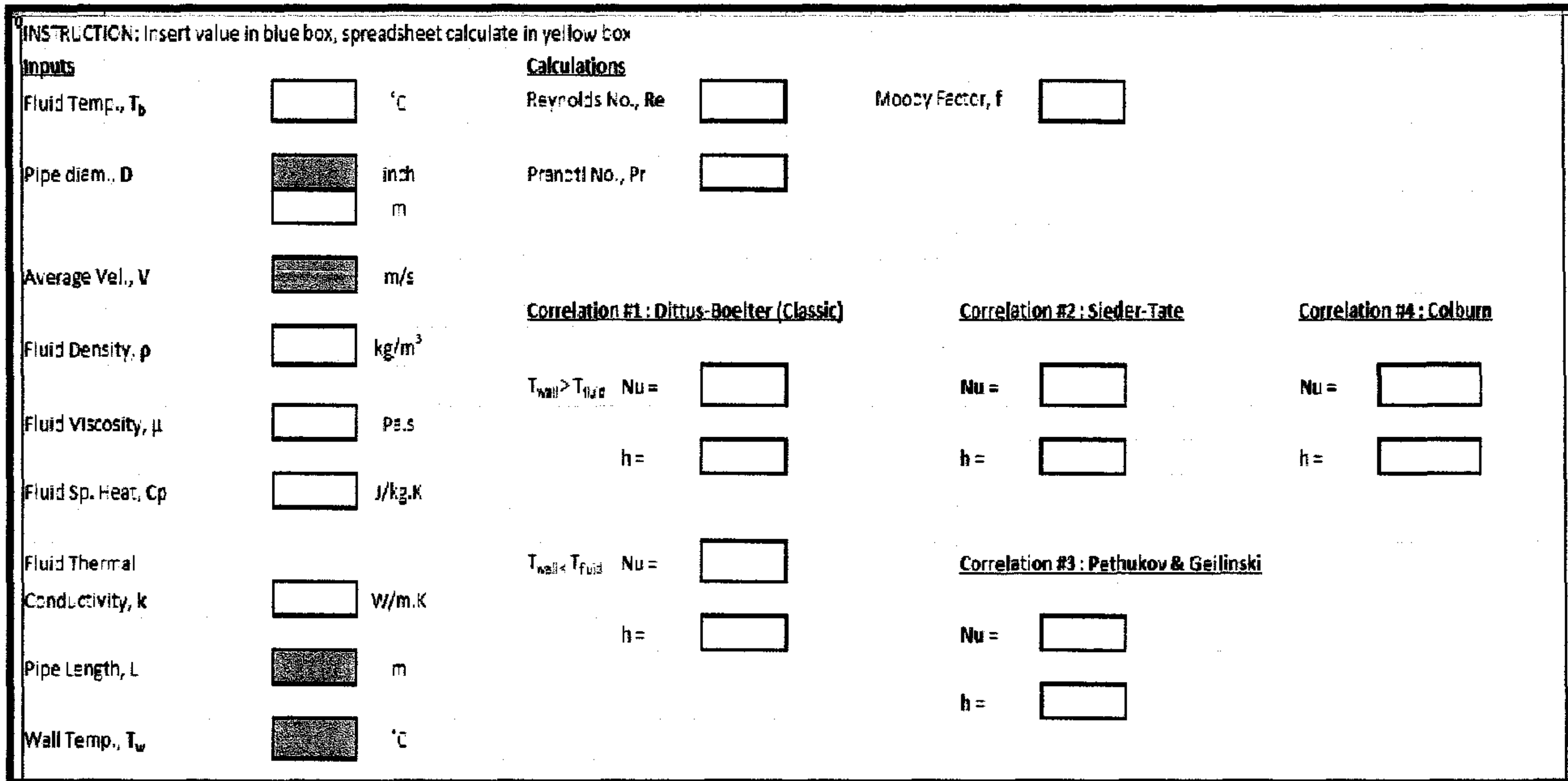


Figure 7: Graph of Thermal Conductivity Vs Temperature from PETROSIM simulation

Based on the graph, thermal conductivity of crude oil show a linear relationship to temperature that is with the increase of temperature, the thermal conductivity of crude oil decrease and the general correlation has been simplified to the equation below,

$$k = 2.19 \times 10^{-8}T^4 - 1.16 \times 10^{-5}T^3 + 0.013T^2 - 0.291T + 137 \quad (16)$$

4.2 Estimation & Calculation of Heat Transfer Coefficient


INSTRUCTION: Insert value in blue box, spreadsheet calculate in yellow box

Inputs

Fluid Temp., T_b		°C
Pipe diam., D		inch
		m
Average Vel., V		m/s
Fluid Density, ρ		kg/m^3
Fluid Viscosity, μ		Pa.s
Fluid Sp. Heat, Cp		J/kg.K
Fluid Thermal Conductivity, k		W/m.K
Pipe Length, L		m
Wall Temp., T_w		°C

Calculations

Reynolds No., Re

Moody Factor, f

Prandtl No., Pr

Correlation #1 : Dittus-Boelter (Classic)

$T_{wall} > T_{fluid}$ Nu =

h =

$T_{wall} < T_{fluid}$ Nu =

h =

Correlation #2 : Sieder-Tate

Nu =

h =

Correlation #3 : Pethukov & Geilinski

Nu =

h =

Correlation #4 : Colburn

Nu =

h =

Figure 8: Spreadsheet to calculate heat transfer coefficients for each correlation

The value of heat transfer coefficient of crude oil based on different correlations is calculated by Microsoft Excel in a spreadsheet shown above.

In the correlations of the heat transfer coefficients, there are few properties that need to be specified which is, the length of tubes (L) and diameter of tube (D). The typical length of tube being used is 20 feet (6.1m) [8] with diameter of 3/4" [9].

The calculation is done by setting the constant temperature and velocity for both reference data and calculated data. The values obtained from these correlations are then being compared to the reference data and the result is shown in the table below;

Table 3: Values of Heat Transfer Coefficient (h_{ref} and h_{calc})

Temperature (°C)	Velocity (m/s)	Reference Heat Transfer Coefficient, h_{ref}(W/m^2.K)	Calculated Heat Transfer Coefficient, h_{calc}(W/m^2.K)			
			Correlation 1 (Dittus-Boelter)	Correlation 2 (Sieder-Tate)	Correlation 3 (Pethukov, Gnielinski)	Correlation 4 (Colburn)
58	1.79	1506	1698.601	1356.509	6402.686	1327.225
86	1.62	1567	1725.015	1372.152	5993.127	1368.083
108	1.06	1194	1283.272	1035.419	4239.345	1025.386
138.5	0.78	996	1036.632	832.006	3267.409	834.406
149	2.12	2241	2322.192	1873.307	7343.314	1873.478
154	1.7	1903	1951.268	1576.080	6109.059	1575.955
185.5	1.35	1769	1632.853	1322.834	4891.746	1327.745
204	2.89	3442	2968.540	2417.560	8857.137	2420.726

The value of the reference heat transfer coefficient of crude oil is plotted against the value of calculated heat transfer coefficient of crude oil for each correlation. A linear line is also plotted to see the deviation between the reference heat transfer coefficient and the calculated heat transfer coefficient.

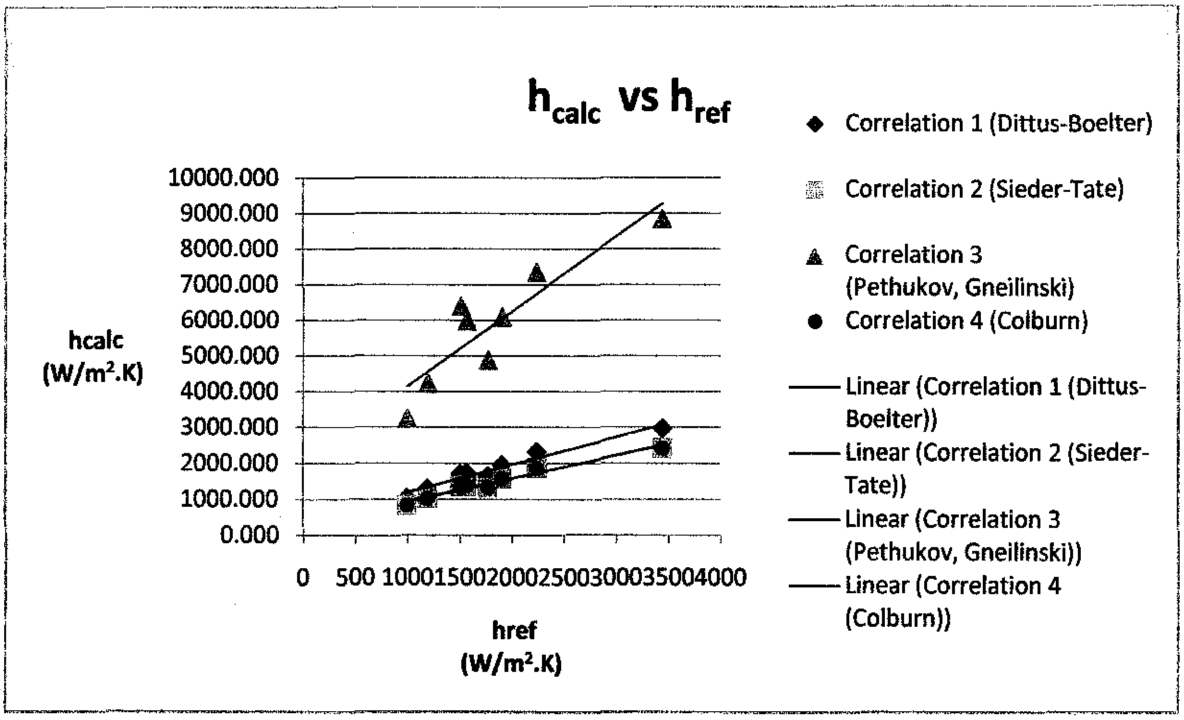


Figure 9: Graph h_{calc} Vs h_{ref}

For Correlation 1 (Dittus-Boelter), each value of calculated heat transfer coefficient does not deviate too much from the reference heat transfer coefficient. Each data falls on the linear line, showing that the calculated heat transfer coefficient gives almost the same value as the reference heat transfer coefficient value. The same goes for Correlation 2 (Sieder-Tate) and Correlation 4 (Colburn). However, for Correlation 3 (Pethukov, Gnielinski), the value deviates too much, almost all data did not falls on the linear line, proving the calculated heat transfer coefficient gives totally different value from reference heat transfer coefficient.

The table below shows the deviation between the reference heat transfer coefficients and the value from the calculated correlations.

Table 4: Deviation Percentage between h_{ref} and h_{cal}

Deviation (%)				
	Correlation 1 (Dittus-Boelter)	Correlation 2 (Sieder-Tate)	Correlation 3 (Pethukov, Gnielinski)	Correlation 4 (Colburn)
	12.789	9.926	325.145	11.871
	10.084	12.434	282.459	12.694
	7.477	13.281	255.054	14.122
	4.080	16.465	228.053	16.224
	3.623	16.408	227.680	16.400
	2.536	17.179	221.023	17.186
	7.696	25.221	176.526	24.944
	13.755	29.763	157.325	29.671
MAD =	7.755	17.585	234.158	17.889

Based on the table above, the calculated heat transfer coefficient for Correlation 1 (Dittus-Boelter) deviated from the reference data by a mean of 7.755%. This overall mean average deviation of 7.755% represents an excellent match between the calculated and reference heat transfer coefficient of crude oil and is well within an acceptable limit of reference error of 10%.

However, for Correlation 2 (Sieder-Tate), Correlation 3 (Pethukov, Gnielinski) and Correlation 4 (Colburn), the calculated heat transfer coefficient deviated from the reference data by a mean of 17.585%, 234.158%, and 17.889% each which is not within the acceptable limit of reference error of 10%.

This proved that Correlation 1 (Dittus-Boelter) is suitable to be used for heat transfer coefficient calculation for TAPIS crude oil system.

CHAPTER 5
CONCLUSION

The project is to calculate the heat transfer coefficient of crude oil of various correlations but in order to calculate this; few factors must be taken into consideration. Between the factors that will affect the calculation of heat transfer coefficients are the type and velocity of the flow, temperature difference, geometry of the system and also the physical properties of crude oil. As the physical properties of crude oil are changing with temperature, it is required to find its relationship before proceeding in calculating heat transfer coefficients for crude oil.

It is the first objective of this project to estimate and calculate the properties of crude oil (density, heat capacity, viscosity, and thermal conductivity) with respect to temperature. In order to see this relationship, a simulation oil crude oil is done through software PETROSIM. 400 data is gathered and each graph of these properties is plotted against temperature.

The density, thermal conductivity and viscosity of crude oil are decreasing with the increase of temperature while the specific heat capacity of crude oil is increasing. The result has been shown in Chapter 4.

Heat transfer coefficient is calculated for each correlation and the value calculated is being compared to the reference heat transfer coefficient data. It is shown that Correlation 1 (Dittus-Boelter Equation) can be used as the correlation for heat transfer coefficient calculation for crude oil system as it has the lowest mean average deviation, that is 7.755% from the reference value.

Correlation 2, 3 and 4 is not suitable as the value calculated using these correlations deviates too much from the reference data.

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APPENDICES

Table 1: Specification of crude oil

Object / *Unit*	*Property* / *Unit*	LiqVol Fractions	*MB/d (*From Data)*
Blend	*TAPIS_44_8_C_TAP*	*1.0000*	***100.00***
Blend	*MASA03*	*0.0000*	***0.00***
Blend	*MIRI_LT_06*	*0.0000*	***0.00***
Blend	*BINTULU_CRUDE*	*0.0000*	***0.00***
Blend	*ARAB_LT_06*	*0.0000*	***0.00***
Blend	*CENDOR*	*0.0000*	***0.00***
Blend	*BINTUL_COND_59_6*	*0.0000*	***0.00***
Blend	*MURBAN_39_3*	*0.0000*	***0.00***
Blend	*COSSACK_47_7*	*0.0000*	***0.00***
Blend	*BKEKWA*	*0.0000*	***0.00***
Blend	*KIKEH*	*0.0000*	***0.00***
Blend	*ANGSI05*	*0.0000*	***0.00***
Blend	*DULANG_37_6*	*0.0000*	***0.00***
	Total	***1.00***	***100.00***

Table 2: Data gathered from PETROSIM Simulation

Temperature	Mass Density	Thermal Conductivity	Viscosity (Dynamic)	Mass Heat Capacity
	kg/m3	*W/m-K*	*Pa-s*	*kJ/kg-C*
0.00	815.47	0.13647	0.00266982	1.90823
1.00	814.70	0.13623	0.00260867	1.91382
2.00	813.93	0.13599	0.00254965	1.91939
3.00	813.15	0.13575	0.00249267	1.92493
4.00	812.38	0.13551	0.00243765	1.93045
5.00	811.61	0.13527	0.00238448	1.93594
6.00	810.84	0.13503	0.00233310	1.94141
7.00	810.06	0.13479	0.00228342	1.94686
8.00	809.29	0.13454	0.00223538	1.95228
9.00	808.52	0.13430	0.00218890	1.95768
10.00	807.74	0.13406	0.00214391	1.96306
11.00	806.97	0.13382	0.00210037	1.96841
12.00	806.19	0.13358	0.00205820	1.97374
13.00	805.42	0.13333	0.00201734	1.97905
14.00	804.64	0.13309	0.00197776	1.98433
15.00	803.86	0.13285	0.00193939	1.98959
16.00	803.09	0.13261	0.00190219	1.99483
17.00	802.31	0.13236	0.00186611	2.00004
18.00	801.53	0.13212	0.00183111	2.00523

19.00	800.76	0.13188	0.00179715	2.01040
20.00	799.98	0.13164	0.00176418	2.01555
21.00	799.20	0.13139	0.00173217	2.02067
22.00	798.42	0.13115	0.00170108	2.02578
23.00	797.64	0.13090	0.00167088	2.03086
24.00	796.86	0.13066	0.00164153	2.03592
25.00	796.08	0.13042	0.00161301	2.04095
26.00	795.30	0.13017	0.00158528	2.04597
27.00	794.52	0.12993	0.00155785	2.05096
28.00	793.74	0.12968	0.00153154	2.05593
29.00	792.96	0.12944	0.00150594	2.06088
30.00	792.17	0.12919	0.00148102	2.06581
31.00	791.39	0.12895	0.00145675	2.07072
32.00	790.61	0.12870	0.00143311	2.07561
33.00	789.82	0.12845	0.00141008	2.08048
34.00	789.04	0.12821	0.00138764	2.08532
35.00	788.26	0.12796	0.00136576	2.09015
36.00	787.47	0.12772	0.00134443	2.09496
37.00	786.68	0.12747	0.00132362	2.09975
38.00	785.90	0.12723	0.00130333	2.10451
39.00	785.11	0.12698	0.00128353	2.10926
40.00	784.32	0.12673	0.00126420	2.11399
41.00	783.53	0.12648	0.00124534	2.11870
42.00	782.75	0.12624	0.00122692	2.12339
43.00	781.96	0.12599	0.00120893	2.12806
44.00	781.17	0.12574	0.00119135	2.13272
45.00	780.38	0.12549	0.00117419	2.13735
46.00	779.58	0.12524	0.00115741	2.14197
47.00	778.79	0.12500	0.00114101	2.14657
48.00	778.00	0.12475	0.00112497	2.15115
49.00	777.21	0.12450	0.00110929	2.15571
50.00	776.41	0.12425	0.00109387	2.16026
51.00	775.62	0.12400	0.00107896	2.16479
52.00	774.82	0.12374	0.00106428	2.16930
53.00	774.03	0.12349	0.00104991	2.17379
54.00	773.23	0.12324	0.00103585	2.17827
55.00	772.44	0.12299	0.00102209	2.18273
56.00	771.64	0.12274	0.00100861	2.18718
57.00	770.84	0.12248	0.00099541	2.19161
58.00	770.04	0.12223	0.00098248	2.19602
59.00	769.24	0.12198	0.00096981	2.20042
60.00	768.44	0.12172	0.00095740	2.20480
61.00	767.64	0.12147	0.00094523	2.20917
62.00	766.84	0.12121	0.00093331	2.21352

63.00	766.04	0.12096	0.00092162	2.21785
64.00	765.23	0.12070	0.00091016	2.22218
65.00	764.43	0.12045	0.00089891	2.22648
66.00	763.62	0.12019	0.00088789	2.23078
67.00	762.82	0.11993	0.00087707	2.23505
68.00	762.01	0.11968	0.00086646	2.23932
69.00	761.21	0.11942	0.00085604	2.24357
70.00	760.40	0.11916	0.00084582	2.24780
71.00	759.59	0.11890	0.00083579	2.25203
72.00	758.78	0.11864	0.00082594	2.25624
73.00	757.97	0.11838	0.00081627	2.26043
74.00	757.16	0.11812	0.00080677	2.26461
75.00	756.35	0.11786	0.00079744	2.26878
76.00	755.53	0.11759	0.00078828	2.27294
77.00	754.72	0.11733	0.00077928	2.27709
78.00	753.90	0.11707	0.00077043	2.28122
79.00	753.09	0.11680	0.00076174	2.28534
80.00	752.27	0.11654	0.00075320	2.28945
81.00	751.45	0.11627	0.00074480	2.29354
82.00	750.64	0.11601	0.00073655	2.29763
83.00	749.82	0.11574	0.00072844	2.30170
84.00	749.00	0.11547	0.00072046	2.30576
85.00	748.18	0.11520	0.00071261	2.30981
86.00	747.35	0.11494	0.00070489	2.31385
87.00	746.53	0.11467	0.00069730	2.31788
88.00	745.71	0.11439	0.00068983	2.32189
89.00	744.88	0.11412	0.00068249	2.32590
90.00	744.05	0.11385	0.00067526	2.32990
91.00	743.23	0.11358	0.00066814	2.33388
92.00	742.40	0.11330	0.00066114	2.33786
93.00	741.57	0.11303	0.00065425	2.34182
94.00	740.74	0.11275	0.00064747	2.34578
95.00	739.91	0.11248	0.00064079	2.34972
96.00	739.08	0.11220	0.00063421	2.35366
97.00	738.24	0.11193	0.00062774	2.35758
98.00	737.41	0.11167	0.00062136	2.36150
99.00	736.57	0.11141	0.00061508	2.36541
100.00	735.73	0.11115	0.00060891	2.36931
101.00	734.89	0.11089	0.00060280	2.37320
102.00	734.06	0.11062	0.00059680	2.37708
103.00	733.21	0.11036	0.00059088	2.38095
104.00	732.37	0.11009	0.00058506	2.38481
105.00	731.53	0.10983	0.00057931	2.38867
106.00	730.68	0.10956	0.00057365	2.39252

107.00	729.84	0.10929	0.00056807	2.39635
108.00	728.99	0.10902	0.00056258	2.40018
109.00	728.14	0.10875	0.00055716	2.40401
110.00	727.29	0.10848	0.00055181	2.40782
111.00	726.44	0.10820	0.00054654	2.41163
112.00	725.59	0.10793	0.00054135	2.41543
113.00	724.74	0.10765	0.00053623	2.41922
114.00	723.88	0.10737	0.00053117	2.42301
115.00	723.03	0.10709	0.00052619	2.42678
116.00	722.17	0.10681	0.00052128	2.43056
117.00	721.31	0.10652	0.00051643	2.43432
118.00	720.45	0.10623	0.00051165	2.43808
119.00	719.59	0.10594	0.00050693	2.44183
120.00	718.73	0.10565	0.00050227	2.44557
121.00	717.86	0.10535	0.00049768	2.44931
122.00	717.00	0.10505	0.00049315	2.45304
123.00	716.13	0.10474	0.00048868	2.45676
124.00	715.26	0.10444	0.00048426	2.46048
125.00	714.39	0.10412	0.00047991	2.46419
126.00	713.52	0.10380	0.00047561	2.46790
127.00	712.64	0.10348	0.00047136	2.47160
128.00	711.77	0.10314	0.00046717	2.47529
129.00	710.89	0.10280	0.00046304	2.47898
130.00	710.01	0.10244	0.00045895	2.48267
131.00	709.13	0.10207	0.00045492	2.48634
132.00	708.25	0.10167	0.00045094	2.49002
133.00	707.37	0.10122	0.00044701	2.49368
134.00	706.48	0.10066	0.00044313	2.49735
135.00	705.59	0.09893	0.00043929	2.50100
136.00	704.70	0.09865	0.00043550	2.50466
137.00	703.81	0.09837	0.00043176	2.50830
138.00	702.92	0.09809	0.00042807	2.51195
139.00	702.03	0.09781	0.00042442	2.51559
140.00	701.13	0.09752	0.00042081	2.51922
141.00	700.23	0.09723	0.00041725	2.52285
142.00	699.33	0.09693	0.00041373	2.52647
143.00	698.43	0.09664	0.00041025	2.53009
144.00	697.52	0.09633	0.00040681	2.53371
145.00	696.61	0.09602	0.00040342	2.53732
146.00	695.71	0.09570	0.00040006	2.54093
147.00	694.79	0.09538	0.00039675	2.54454
148.00	693.88	0.09504	0.00039347	2.54814
149.00	692.97	0.09468	0.00039023	2.55173
150.00	692.05	0.09429	0.00038702	2.55533

151.00	691.13	0.09383	0.00038386	2.55892
152.00	690.20	0.09289	0.00038073	2.56250
153.00	689.28	0.09225	0.00037764	2.56609
154.00	688.35	0.09197	0.00037458	2.56966
155.00	687.42	0.09169	0.00037155	2.57324
156.00	686.49	0.09141	0.00036857	2.57681
157.00	685.56	0.09113	0.00036561	2.58039
158.00	684.62	0.09085	0.00036269	2.58395
159.00	683.68	0.09056	0.00035980	2.58752
160.00	682.74	0.09027	0.00035694	2.59108
161.00	681.79	0.08998	0.00035411	2.59464
162.00	680.84	0.08969	0.00035132	2.59819
163.00	679.89	0.08939	0.00034855	2.60175
164.00	678.94	0.08909	0.00034582	2.60530
165.00	677.98	0.08879	0.00034311	2.60885
166.00	677.02	0.08848	0.00034043	2.61240
167.00	676.06	0.08817	0.00033779	2.61594
168.00	675.10	0.08786	0.00033517	2.61948
169.00	674.13	0.08754	0.00033258	2.62302
170.00	673.15	0.08722	0.00033001	2.62656
171.00	672.18	0.08689	0.00032748	2.63010
172.00	671.20	0.08655	0.00032497	2.63363
173.00	670.22	0.08622	0.00032249	2.63717
174.00	669.23	0.08587	0.00032003	2.64070
175.00	668.25	0.08552	0.00031760	2.64423
176.00	667.25	0.08515	0.00031519	2.64776
177.00	666.26	0.08478	0.00031281	2.65129
178.00	665.26	0.08440	0.00031046	2.65481
179.00	664.25	0.08400	0.00030813	2.65834
180.00	663.25	0.08359	0.00030582	2.66186
181.00	662.24	0.08316	0.00030353	2.66538
182.00	661.22	0.08271	0.00030127	2.66890
183.00	660.20	0.08221	0.00029904	2.67243
184.00	659.18	0.08167	0.00029682	2.67595
185.00	658.15	0.08105	0.00029463	2.67947
186.00	657.12	0.08027	0.00029246	2.68298
187.00	656.08	0.07881	0.00029031	2.68650
188.00	655.04	0.07652	0.00028818	2.69002
189.00	653.99	0.07620	0.00028607	2.69354
190.00	652.98	0.07588	0.00028399	2.69705
191.00	651.96	0.07555	0.00028192	2.70057
192.00	650.93	0.07520	0.00027988	2.70409
193.00	649.90	0.07482	0.00027785	2.70760
194.00	648.87	0.07441	0.00027584	2.71112

195.00	647.84	0.07392	0.00027386	2.71464
196.00	646.80	0.07320	0.00027189	2.71816
197.00	645.75	0.07168	0.00026994	2.72167
198.00	644.70	0.07142	0.00026802	2.72519
199.00	643.65	0.07116	0.00026611	2.72871
200.00	642.60	0.07090	0.00026421	2.73223
201.00	641.53	0.07063	0.00026234	2.73575
202.00	640.47	0.07037	0.00026048	2.73927
203.00	639.40	0.07009	0.00025865	2.74279
204.00	638.33	0.06982	0.00025682	2.74631
205.00	637.25	0.06954	0.00025502	2.74983
206.00	636.16	0.06925	0.00025323	2.75336
207.00	635.07	0.06896	0.00025146	2.75688
208.00	633.98	0.06866	0.00024971	2.76041
209.00	632.88	0.06836	0.00024797	2.76394
210.00	631.78	0.06805	0.00024625	2.76747
211.00	630.67	0.06774	0.00024454	2.77100
212.00	629.55	0.06741	0.00024285	2.77453
213.00	628.43	0.06708	0.00024118	2.77807
214.00	627.30	0.06673	0.00023952	2.78161
215.00	626.17	0.06636	0.00023787	2.78515
216.00	625.03	0.06598	0.00023624	2.78869
217.00	623.89	0.06557	0.00023463	2.79223
218.00	622.74	0.06513	0.00023303	2.79578
219.00	621.58	0.06462	0.00023144	2.79933
220.00	620.41	0.06397	0.00022987	2.80288
221.00	619.24	0.06221	0.00022832	2.80643
222.00	618.06	0.06145	0.00022677	2.80999
223.00	616.88	0.06115	0.00022524	2.81355
224.00	615.68	0.06084	0.00022373	2.81711
225.00	614.48	0.06051	0.00022222	2.82068
226.00	613.27	0.06016	0.00022073	2.82425
227.00	612.06	0.05979	0.00021926	2.82782
228.00	610.83	0.05939	0.00021779	2.83139
229.00	609.60	0.05893	0.00021634	2.83497
230.00	608.36	0.05833	0.00021490	2.83856
231.00	607.10	0.05704	0.00021348	2.84215
232.00	605.84	0.05652	0.00021207	2.84574
233.00	604.57	0.05475	0.00021066	2.84934
234.00	603.29	0.05453	0.00020928	2.85294
235.00	602.03	0.05431	0.00020790	2.85655
236.00	600.77	0.05409	0.00020653	2.86016
237.00	599.50	0.05386	0.00020518	2.86377
238.00	598.22	0.05363	0.00020384	2.86740

239.00	596.93	0.05340	0.00020251	2.87102
240.00	595.63	0.05316	0.00020119	2.87465
241.00	594.31	0.05291	0.00019988	2.87829
242.00	592.99	0.05267	0.00019858	2.88193
243.00	591.75	0.05241	0.00019729	2.88558
244.00	590.58	0.05216	0.00019602	2.88924
245.00	589.40	0.05189	0.00019475	2.89290
246.00	588.22	0.05162	0.00019350	2.89657
247.00	587.03	0.05134	0.00019225	2.90024
248.00	585.83	0.05105	0.00019102	2.90392
249.00	584.64	0.05075	0.00018979	2.90761
250.00	583.43	0.05043	0.00018858	2.91131
251.00	582.23	0.05008	0.00018738	2.91501
252.00	581.02	0.04971	0.00018618	2.91872
253.00	579.80	0.04927	0.00018500	2.92244
254.00	578.57	0.04837	0.00018382	2.92617
255.00	577.35	0.04792	0.00018266	2.92991
256.00	576.11	0.04712	0.00018150	2.93365
257.00	574.87	0.04609	0.00018035	2.93741
258.00	573.63	0.04584	0.00017922	2.94117
259.00	572.38	0.04557	0.00017809	2.94494
260.00	571.12	0.04528	0.00017697	2.94872
261.00	569.86	0.04495	0.00017586	2.95252
262.00	568.59	0.04426	0.00017476	2.95632
263.00	567.32	0.04401	0.00017366	2.96013
264.00	566.04	0.04375	0.00017258	2.96396
265.00	564.76	0.04348	0.00017150	2.96780
266.00	563.46	0.04319	0.00017044	2.97164
267.00	562.16	0.04288	0.00016938	2.97550
268.00	560.86	0.04254	0.00016833	2.97938
269.00	559.55	0.04215	0.00016729	2.98326
270.00	558.23	0.04167	0.00016625	2.98716
271.00	556.90	0.04074	0.00016523	2.99107
272.00	555.57	0.03970	0.00016421	2.99500
273.00	554.23	0.03944	0.00016320	2.99894
274.00	552.88	0.03916	0.00016220	3.00289
275.00	551.53	0.03884	0.00016120	3.00686
276.00	550.17	0.03844	0.00016021	3.01085
277.00	548.80	0.03721	0.00015923	3.01485
278.00	547.42	0.03701	0.00015826	3.01887
279.00	546.03	0.03681	0.00015730	3.02290
280.00	544.64	0.03661	0.00015634	3.02695
281.00	543.23	0.03639	0.00015539	3.03102
282.00	541.82	0.03615	0.00015445	3.03511

283.00	540.40	0.03591	0.00015351	3.03922
284.00	538.97	0.03563	0.00015258	3.04335
285.00	537.54	0.03531	0.00015166	3.04750
286.00	536.09	0.03462	0.00015075	3.05167
287.00	534.63	0.03421	0.00014984	3.05586
288.00	533.17	0.03398	0.00014894	3.06008
289.00	531.69	0.03373	0.00014804	3.06431
290.00	530.20	0.03345	0.00014716	3.06857
291.00	528.71	0.03313	0.00014627	3.07286
292.00	527.20	0.03273	0.00014540	3.07717
293.00	525.68	0.03203	0.00014453	3.08151
294.00	524.15	0.03086	0.00014367	3.08587
295.00	522.61	0.03067	0.00014281	3.09027
296.00	521.06	0.03046	0.00014196	3.09469
297.00	519.49	0.03016	0.00014112	3.09914
298.00	517.92	0.02970	0.00014029	3.10362
299.00	516.33	0.02953	0.00013945	3.10814
300.00	514.73	0.02935	0.00013863	3.11269
301.00	513.11	0.02915	0.00013781	3.11727
302.00	511.48	0.02891	0.00013700	3.12189
303.00	501.71			3.12509
304.00	489.39			3.12775
305.00	477.58			3.13040

Table 2: Reference data for Heat Transfer Coefficient

Heat Exchanger	Temperature (°C)	Velocity (m/s)	Heat Transfer Coefficient ($W/m^2.K$)
E-1101A/B	58	1.79	1506
E-1102A/B	86	1.62	1567
E-1103A/B	108	1.06	1194
E-1105A-D	138.5	0.78	996
E-1106	149	2.12	2241
E-1107	154	1.7	1903
E-1109	185.5	1.35	1769
E-1110	204	2.89	3442