Numerical Analysis of the Heat Transfer in Heat Exchangers

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Abstract

This paper presents a numerical method of solution, capable of accounting for temperature dependent variation of fluid properties and heat transfer. Field data were collected for three different industrial heat exchangers and basic governing equations were applied. The parameters analyzed include: the outlet temperatures, the heat transfer coefficients and the heat exchanger effectiveness. For the heat exchangers 1, 2 and 3, the deviations in outlet temperatures for the tube were 0.53%, 0.11% and 5.10% while the shell side gave 0.76%, 0.47% and 0.74%. Comparison of the calculated and actual overall heat transfer coefficients gave deviations of 8.7%, 7.77% and 11% for exchangers 1, 2 and 3 respectively. The heat exchangers effectiveness were 73.6%, 88.9% and 76.4% respectively, which showed high efficiency in thermal energy transfer.

Keywords: Heat exchanger, heat transfer, numerical analysis, shell-and-tube.

1.0 Introduction

Most industrial processes involve heat transfer and more often, it is required that these heat transfer processes be controlled. Heat transfer is the term used for thermal energy from a hot to a colder body. Heat transfer always occurs from a hot body to a cold one, as result of the second law of thermodynamics. Where there is a temperature difference between objects in proximity, heat transfer between them can never be stopped but can only occur through three ways which are conduction, convection and radiation or any combination of that. Though study has also shown that phase change is accompanied with thermal energy transfer[1].

Theoretically on a microscopic scale, thermal energy is related to the kinetic energy of the molecules. The greater a material's temperature, the greater the thermal agitations of its constituent molecules. Then the regions containing greater molecular kinetic energy will pass this energy to regions with less kinetic energy. Thus, when an object or fluid is at a different temperature than its surroundings or another body, heat transfer will occur in such a manner that the body and the surroundings or surrounding body reach thermal equilibrum[1].

Different heat transfer applications require different types of hardware and different configurations of heat transfer equipment. The attempt to match the heat transfer hardware to the heat transfer requirements within the specified constraints has resulted in numerous type of innovative heat exchanger designs[2]. The simplest of it is called the double-pipe heat exchanger. One fluid in a double-pipe heat exchanger flows through the smaller pipe while the other fluid flows through the annular space between the two pipes. Two types of flow arrangement are possible in a double-pipe heat exchanger: in parallel flow, both the hot and cold fluids enter the heat exchanger at the same end and move in the same direction. In counter flow, on the other hand, the hot and cold fluids enter the heat exchanger at opposite ends and flow in opposite directions.

Many engineering systems may be simplified by subdividing them into components or elements.These elements can be readily analyzed from first principles, and by assembling these together, the analysis of a complete system can be reconstructed. We refer to such systems as discrete systems. In many situations, a reasonably adequate model can be obtained using a finite number of well-defined components called elements. This technique gives a numerical solution. This technique is applied for the formulation of certain heat, fluid flow and chemical reaction phenomena[3]. In the analysis of a discrete system, the actual system response is described directly by the solution of a set of equations in a finite number of unknowns. The importance of the finite element method in conjunction with the digital computer find a place in the numerical idealization and solution of continuous systems in asystematic manner.

This in effect has made possible the practical extension and application of classical procedures to very complex engineering systems like the shell and tube heat exchanger. Some previous works have been done to analyze heat exchangers. Gaddis proposed a cell model to predict dimensionless temperature distribution in shell and tube heat exchangers with baffles.He generated £-NTU curves for shell and tube heat exchangers of various types[4]. Ozisik adopted the model and introduced the procedures followed in finite element analysis to obtain the temperature distribution. The model was extended for the analysis of heat exchanger networks[5].

The developments for shell and tube heat exchangers center on better conversion of pressure drop into heat transfer by improving the conventional baffle designs. A good baffle design, while attempting to direct the flowing a plug flow manner, also has to fulfill the main function of providing adequate tube support. Helical baffle as one of novel shell side baffle geometries was developed to increased the efficiency of heat transfer. Although shell and tube heat exchanger with helical baffles appear to offer significant advantages over conventional heat exchanger with segmental baffles, very few studies of this type of heat exchanger could be found in the literature, in particular, on heat transfer enhancement and numerical simulation. Lutcha found that helical baffle geometry could force the shell side flow field to approach a plug flow condition, which increased the average temperature driving force. The flow patterns induced by the baffles also cause the shell side heat transfer to increase markedly. Kral conducted the hydro-dynamic studies of the shell side on a helically baffled heat exchanger model made of perspex using stimulus-response techniques[6]. The results showed that a helically baffled heat exchanger provided an ideal shell side geometry resulting in a uniform flow path with low degree of back mixing and nearly negligible dead volume. Performance of heat exchangers with helical baffles was discussed using the results of tests conducted on one unit with various baffle geometries[7].

The study on correction factors for shell and tube heat exchangers with segmental baffles as compared to helical baffles was carried out. Jegede attempted optimizing the design of tubes of shell and tube heat exchanger with numerical resolution of the stationary point equations of a non-linear objective function.This was applied to predicting the efficiency of segmental baffles. The results gave a leeway to parameter plotting and th resultant development was graphical analysis employed by Poddar[8]. The present work proposes a numerical solution to analyze and predict the heat exchange at any point/part of the shell and tube heat exchanger with high degree of convergence.

2.0 Methodology

To actualize the present study, the following steps were taken:

- The basic equations governing heat exchanger are presented in their most general form and applied to the various nodes / elements in the context of a one – pass, shell and tube configuration.
- A numerical method of solution capable of accounting for temperature dependant variation of fluid properties and heat transfer is also presented.
- A comparison of the results from the numerical model under ideal, constant property condition is made with the existing results obtained from the Indorama – Eleme petrochemicals operations sheet and their convergence demonstrated.
- To predict the performance of a heat exchanger, energy conservation principle is employed. Hence, the use of energy equations.

3.0 Results

The heat exchangers physical properties and performance data are presented table1.
To predict the performance of the heat exchangers, standard equations that relate the parameters are employed and the results are presented in tables2 and 3.

3.1 Heat exchanger effectiveness (ε_H)

This is the ratio of actual heat transfer to the maximum possible heat transfer[9]

$$\varepsilon_H = \frac{Q}{Q_{\max}} = \frac{T_{h_1} - T_{h_2}}{T_{h_1} - T_{c_1}} \quad (1)$$

3.2 Effective logarithmic mean temperature difference (LMTD)

This is the mean temperature difference between the two fluid streams [9]

$$\Delta \text{TM} = \text{LMTD} = \frac{(T_{h1} - T_{h2}) - (T_{c2} - T_{c1})}{In\left[\frac{(T_{h1} - T_{h2})}{(T_{c2} - T_{c1})}\right]} \tag{2}$$

3.3 Logarithmic mean temperature difference correction factor (F)

The correction factor is a function of the shell and tube fluid temperatures. This factor uses two dimensionless temperature ratios as shown below [9]

$$\text{P} = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{h2}} \tag{3}$$

where P = ratio of cold fluid temperature difference and hot fluid temperature difference.

$$\text{R} = \frac{T_{h1} - T_{h2}}{T_{c2} - T_{c1}} \tag{4}$$

Where R = ratio of hot fluid temperature difference and cold fluid temperature difference.
The correction factor, F is estimated from charts using calculated value of P and R

3.4 Overall heat transfer coefficients, U

The required overall heat transfer coefficient is given as [9]

$$U_{req} = \frac{q}{AF(\Delta TM)} \tag{5}$$

Where q = Heat transfer rate in the heat exchanger
A = Surface area
F = correction factor of logarithm mean temperature difference
ΔTM = Logarithmic mean temperature difference.

The calculated outlet temperatures of the three heat exchangers are tabulated with the actual outlet temperatures and the absolute value of deviation as shown in Table2.

From Table2, heat exchanger effectiveness from Ex. 1, Ex. 2 and Ex. 3 are 0.736, 0.889, and 0.764 respectively which means that the heat exchangers are 73.6%, 88.9%, and 76.4% efficient in its transfer of thermal energy. The effectiveness of heat exchanger is a measure of the ability of a heat exchanger to exchange heat. Another important variable to note that could measure the trend of transfer of thermal energy in a heat exchanger is the mean temperature efficiency which are obtained as 65.7%, 55.125% and 62.75% in this work. It can be deduced that the calculated reciprocal of the overall resistance to heat transfer,(ie the overall heat transfer coefficient of the heat exchangers) obtained are within 89% -93% accuracy as compared to the actual heat exchangers overall heat transfer coefficient from the data sheet of the Indorama Eleme petrochemicals.

4.0 Conclusion

The numerical analysis had shown that the calculated outlet temperatures of both shell and tube heat exchanger and overall heat transfer coefficients obtained for the three cases considered agree reasonably with the stated values in the Indorama -Eleme Petrolchemicals Performance data with a corresponding high efficient transfer of thermal energy (heat exchanger effectiveness) of 73.6%, 88.9%, and 76.4% for Ex.1, Ex.2, and Ex.3 respectively. This indicates high efficiency in thermal energy transfer.

5.0 References

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Table1: Heat exchangers physical properties and performance data

			EX1		EX2		EX3	
S/N	Parameters	Units	Shell side fluid	Tube side fluid	Shell side fluid	Tube side fluid	Shell side fluid	Tube side fluid
A	**Physical Properties**							
1	Specific Gravity		0.73	0.82	0.85	0.82	0.85	0.82
2	Viscosity	Ns/m^2	0.43	3.2	0.17	3.2	0.17	3.2
3	Heat Capacity	KJ /KgK	2.47	2.05	2.28	2.05	2.28	2.05
4	Thermal Conductivity	W /Mk	0.132	0.134	0.125	0.134	0.125	0.134
5	Thermal Conductivity at the wall temperature	W /mK	55		45		45	
B	**Performance Data**							
1	Fluid stream		KERO	CRUDE	HDO	CRUDE	LDO	CRUDE
2	Inlet Temperature	K	441	365	581	382	480	365
3	Outlet Temperature	K	388	382	406	402	395	411
4	Mass Flow Rate	Kg /s	32.23	116.14	10.9	116.14	56	116.14
5	Pressure Drop	Kpa	19.620	34.335	9.810	34.335	58.860	63.765
6	Heat Transfer coefficient (U)	$KW /(m^2K)$	0.3033		0.1737		0.3341	

Table2: Temperature distribution efficiencies, effectiveness and overall heat transfer coefficients of the heat exchangers.

Variable	Ex.1	Ex.2	Ex.3
Inlet Temp. Of hot fluid, T_{h1} (K)	441.00	581.00	480.00
Outlet Temp. Of hot fluid, T_{h2} (K)	385.05	404.07	392.07
Inlet Temp. Of cold fluid, T_{c1} (K)	365.00	382.00	365.00
Outlet Temp Of cold fluid, T_{c2} (K)	384.02	402.45	390.00
Temp. Efficiency for hot fluid, φ_{Th}	98%	98.8%	97.7%
Temp. Effeciency for cold fluid, φ_{Tc}	33.4%	11.45%	27.8%
Mean Temp. Efficiency, φ_{Tm}	65.7%	55.125%	62.75%
Heat Exchanger Effectiveness, ε_H	0.736	0.889	0.764
Effective Log. Mean Temp. Diff.,LMTD	34.23	72.52	50.04
Temp. Ratio, P	0.34	0.12	0.28
Temp. Ratio. R	2.9	8.6	3.5
Effective LMTD correction Factor, F	0.9	0.95	0.81
Heat Transfer Rate, Q	2186.9547	2897.174	3494.2932
Calc. Overall Heat Transfer Coeff, U_{calc}	0.2769	0.1602	0.2962
Actual Overall Heat Transfer Coeff, U_{req}	0.3033	0.1737	0.3341
U% Deviation	8.7%	7.77%	11%

Table3: Calculated and stated outlet temperatures and overall heat transfer coefficients comparison

Fluid properties	Ex.1		Ex.2		Ex.3	
	Tube	Shell	Tube	Shell	Tube	Shell
Calc. Outlet Temp. (K)	384.02	385.05	402.45	404.07	390.00	392.07
Stated Outlet Temp. (K)	382.00	388.00	402.00	406.00	411.00	395.00
Calc. Overall Heat Transfer Coeff, U_{calc}	0.2769		0.1602		0.2962	
Actual Overall Heat Transfer Coeff, U_{act}	0.3033		0.1737		0.3341	