Optimization of E-Shell Heat Exchanger using Multi-objective Evolutionary Algorithm NSGA-II

Final year project submitted in the partial fulfillment of the requirements of the degree of

BACHELOR OF TECHNOLOGY
IN
MECHANICAL ENGINEERING

By

Abhisekh Kumar Maurya
Anubhav Agarwal
Owais Ali Khan
Robert Singh

Supervisor:
Mr. Brahma Nand Agrawal

SCHOOL OF MECHANICAL ENGINEERING GALGOTIAS UNIVERSITY
GREATER NOIDA
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CERTIFICATE

This is to certify that the Research work titled **Optimization of E-Shell Heat Exchanger using Multi-Objective Evolutionary algorithm NSGA-II** that is being submitted by **ABHISEKH KUMAR MAURYA, ANUBHAV AGARWAL, OWAIS ALI KHAN and ROBERT SINGH** is in partial fulfillment of the requirements for the award of **Bachelor of Technology**, is a record of bonafide work done under my guidance. The contents of this research work, in full or in parts, have neither been taken from any other source nor have been submitted to any other Institute or University for award of any degree or diploma.

Supervisor

Mr. Brahma Nand Agrawal
Assistant Professor
School of Mechancial Engineering
Galgotias University

Internal Examiner **External Examiner**

Approval Sheet

This Research based project report entitled **Optimization of E-Shell Heat Exchanger using Multi-Objective Evolutionary algorithm NSGA-II by Abhisekh Kumar Maurya, Anubhav Agarwal, Owais Ali Khan and Robert Singh** is approved for the degree of Bachelor of Technology in Mechanical Engineering.

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(Name and Signature)

(Department of Mechanical engineering)

ABSTRACT

This study presents the use of Genetic Algorithm for thermo-economic optimization of a stainless-steel E-Shell heat exchanger. A modified NSGA-II algorithm given by Prof K. Deb has been used to optimize heat exchanger. The objective functions under consideration are the operating cost, capital cost and entropy generation number. The design parameters used are number of tubes, baffle spacing and tube outer diameter. Kern method was used for the modelling of the heat exchanger with some modifications wherever required. Relation between the hand-off of optimizing one objective to another was established. A relationship between the entropy generation number with the total cost is shown. A pareto-optimal front could be obtained for all the cases taken. The study shows that the costs obtained were lower than the values studied in the literature.

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CC	Capital cost
DOC	Discounted operating cost
EGN	Entropy generation number
EA	Evolutionary algorithm
GA	Genetic algorithm
IGD	Inversed generalized distance
LMTD	Logarithmic mean temperature difference
MOEA	Multi-objective Evolutionary algorithm
NSGA-II	Non-Dominating Sorting Genetic Algorithm II
PSO	Particle swarm optimization
STHE	Shell and Tube Heat exchanger

Nomenclature

a_1	Numerical constant (\$)	L	Tube length(m)
a_2	Numerical constant$(\$/m^2)$	LMTD	Logarithmic mean temperature difference(K)
a_3	Numerical constant	m_s	Shell side mass flow rate(kg/s)
A	Heat exchanger surface area(m^2)	m_t	Tube side mass flow rate(kg/s)
B	Baffle spacing(m)	n	Number of tube passes
C	Numerical constant	n_y	Number of years
C_e	Energy cost$(\$/kWh)$	N_s	Entropy generation number
C_i	Capital investment$(k\$)$	P	Pumping power(W)
C_o	Annual operating cost(\$)	R_{fs}	Shell side fouling resistance
C_{op}	Discounted Operating Cost	R_{ft}	Tube side fouling resistance
C_p	Specific heat(J/KgK)	S_t	Tube pitch(m)
C_{tot}	Total annual cost(\$)	T_{ci}	Cold fluid inlet temperature(K)
d_e	Equivalent shell diameter(m)	T_{co}	Cold fluid outlet temperature(K)
d_i	Tube inner diameter(m)	T_{hi}	Hot fluid inlet temperature(K)
d_o	Tube outer diameter(m)	T_{ho}	Hot fluid outlet temperature(K)
D_s	Shell inside diameter(m)	U	Overall heat transfer coefficient(W/m^2K)
F	Temperature difference correction factor	ΔP	Pressure drop(Pa)
H	Annual operating time (hrs)	$\Delta\,\dot{S}$	Entropy generation rate
h_s	Shell side convective coefficient (W/m^2K)	μ	Dynamic viscosity$(Pa-s)$
h_t	Tube side convective coefficient (W/m^2K)	ρ	Density (kg/m^3)
i	Annual discount rate(%)	η	Pump efficiency
k	Thermal conductivity (W/mK)		

1

Introduction

1.1 Project background

Shell and tube heat exchangers are the most frequently used for heating or cooling both liquids and gasses. STHEs have a huge scope of application which ranges from power generation, refrigeration, petrochemical processes, chemical industries to marine applications. They owe their significance in the industry to the design flexibility which allows a wide variety of pressures, temperatures, tubes, shell size etc. The industry always strives to achieve the minimum costs both capital and operational while not sacrificing on the performance. To achieve this goal, researchers have been working since the early 1980's.

Furthermore, NSGA-II is an evolutionary many-objective optimization algorithm which was given by Prof K. Deb, Michigan State University. This algorithm is one of the most cited papers in the field of optimization which is thanks to the fact that all source codes have been made public for other researchers. It falls under the category of genetic optimization therefore uses operators like crossover, mutation etc. These terms are taken from the theory of evolution and this algorithm strives to mimic aforementioned biological phenomena to achieve the global optimum for the problem at hand.

This project uses theory from NSGA-II algorithm to optimize the costs of STHEs.

1.2 Research purpose and meaning

Return on investment is one of the most important factors any industry considers before taking an investment decision. Reaching the lowest investment value (CAPEX or Capital cost) is a desired result. This shall not be achieved at the cost of quality, so many industries look for Value engineering or Optimization of design. This is also called removal of Gold plating in design. The challenge is to cut costs with the several constraints of space limitations, operating characteristics or some other site constraints defined by the industry. Therefore, for the project to be relevant in real life scenarios, a TEMA E type shell has been considered in this study because it is one of the most frequently used STHE design.

To optimize a standard STHE model a modified NSGA-II has been used.

In addition, looking from an environmental perspective, it is becoming evident each day now that energy requirements in the industry are ever growing and most of this energy comes from nonrenewable sources. A reduction in the operating cost in the STHE would decrease the electric requirements. This would become evident in the next chapter of the study.

1.3 Objective of study

The main objective of the project is to optimize the operating and dimensional cost of a STHE without compromising on the efficiency. This project would attempt to establish an algorithm which would be able to solve various optimization problems of STHE without many adjustments needed in the programming process.

The objective for undertaking this project also involves building concepts of design process of STHE, genetic optimization and programming skills involved to execute complex algorithms in C. Using software like Mendeley, Linux like environment implementation on windows, code editors etc. Also learning the process of publishing a research paper in a reputed journal or conference and the skills required to accomplish that.

2

Literature review

2.1 Introduction

STHEs are an integral part of industries. Research into optimization of STHE's has been continuing for the past 4 decades and still is relevant today as it was in its nascent phase. This is because the energy inflation is at a 5-year high and does not show any trend of decreasing. Also, the consumption of electricity increases at a staggering rate of 30-45%. A lion's share of the total energy requirements is met by non-renewable sources. Limited resources don't only apply to energy sources but also to the materials required for building said STHEs. Also new engineering solutions are needed to keep up with the demands of better performance in the limited installation space.

Thus, a project undertaking the optimization of STHEs under the current circumstances is pertinent. In this chapter of the project, several suitable studies have been discussed.

2.2 Literature review

Non-dominated sorting genetic algorithm II (NSGA-II) proposed [1] attenuates all 3 difficulties of multi-objective evolutionary algorithm (EAs); non-elitism approach, computational complexity and the requirement of defining a sharing parameter. This study uses a modified NSGA II which includes inverse generalized distance (IGD) with the local search to provide the next generation of candidates with each iteration of the algorithm.

Hassan Hajabdollahi et al. [2] implemented the multi-objective exergic optimization to study and enhance the operation of STHE. The two main parameters used in the study were cost and exergy efficiency. Bell-Delaware method and ε-NTU (Number of transfer units) were used to reach the optima of pressure drop, heat transfer coefficient and design. A minimized cost and maximized efficiency were reported.

Hajabdollahi et al. [3] carried out a comparative study for thermal and economic optimization of a STHE using both GA and PSO where total cost is considered as an objective function. The procedure was selected to find the optimal total cost including investment and operation cost of the condenser. The results showed that increase in the number of tubes leads to dip in the objective function first then it leads to a significant increment. On comparison, it was concluded that particle swarm algorithm has a higher convergence rate in comparison to genetic algorithm. However, GA provides better accuracy in locating the search domain.

Sampreeti Jenaa et al. [4] implemented a multi-objective solver that used the GA available in MATLAB optimization toolbox. Length and Total cost of STHE were the two pivotal objectives of study. Total cost is a combination of the capital investment and working cost. 4 different design variations were considered for optimization. It was indicated that baffle space to be approximated to 0.5m for lower annual cost values. While for smaller length, baffle space and inner diameter to be close to 0.05 and 1.5m respectively.

J. Knowles et al. [5] proposed a simpler MOEA, called Pareto Archive Evolution Strategy (PAES). The algorithm represents the simplest possible non-trivial algorithm capable of generating diverse solutions in the Pareto optimal set. In order to find approximate dominance ranking of a solution, the algorithm uses a local search from a population of one and compare it with the archive of previously found solutions. The study shows, PAES can be viewed as a simple baseline technique for multi-objective optimization. PAES also dominates other MOEAs in terms of speed and converge of Pareto trade-off frontier.

Ghanei et al. [6] conducted a comparative study between PSO and GA for the heater deign in which the Bell Delaware method was used. The objective function was a combination of total cost and effectiveness. The authors reported that the PSO was able to achieve a better set of pareto optimal solutions.

Baadache at el [7] presented the thermal modelling for a new design of a STHE. This has been done with the help of logarithmic mean method. The author has taken the design parameters like the mass flow of both fluids, temperatures of input and output of both fluids, fixed parameters attributed by the user which are the models of the tubular plate, the height, the number of tubes passes etc. Combining these parameters, the author derived a total cost function which is described as a sum of total investment cost and operating cost. The author concluded that the operating cost of the proposed design went down by17-18% as compared to previous studies and the initial cost went up by 1.76%. Wang at el [8] presented the multi-objective optimization of shell and tube heat exchangers with helical baffles. With helical baffles included two new parameters helical angle and overlapped degree. The objective function comprises of logarithmic mean temp difference and heat pressure drop across the shell and tube heat exchanger. The paper used a multi objective genetic optimization. Compared to the original data taken by the author the optimum configurations increased by 14%. Both Baadache and Wang proposed their own design parameters to the standard model to design the heat exchanger.

Gholap et al. [9] presented a detailed thermodynamic model for a refrigerator based on an irreversible Carnot cycle, which developed with the focus on forced-air heat-exchangers. A multi-objective optimization procedure was implemented to find optimal design values for design variables. The material cost and minimization of energy consumption were the two main objectives of the study. As mentioned, the algorithm used was developed by Srinivas and Deb. The solution was divided into three regions where, Region II presented solutions where both energy and cost are better when compared to baseline designs. Optimization was stopped after 50th generation after that no other improvements were observed.

Ponce Ortega et al. [10] presented an algorithm based on genetic algorithm for the optimal design of shell and tube heat exchangers from economic point of view. The model used a Bell - Delaware method for proper calculations for heat transfer coefficients and pressure drop in the shell side. The result provided improved geometries and coefficients. In two of the three case studies, he obtained reduced value of cost as compared to the previous studies.

Guo et al. [11] proposed a study for optimization design of a shell and tube heat exchanger by entropy generation minimization and genetic algorithm. The geometrical parameters of the shell and tube heat exchanger are taken as the design variables and the genetic algorithm is applied to solve the associated optimization problem. In this study the method is proposed to put the entropy generation minimization and genetic algorithm into the shell and tube heat exchanger optimization design practice. Modified the entropy number, which taken as an objective number as it can avoid entropy generation paradox. The genetic algorithm is applied the genetic algorithm is applied to solve the multi-variable optimization problems which not only yields the globe optimum solution but also demonstrates the flexibility to select the design variables and constraint conditions.

Rajasekaran et al [12] studied a method of optimizing the early design phase of shell and tube heat exchangers via the application of modified genetic algorithm which was based on the integration of classical genetic algorithm and a systematic neighborhood structure. The modified genetic algorithm used the analytical model, the algorithm would consider the tube diameter, viscosity of the liquid, heat specific capacity, temperature, thermal conductivity and mass flow rate as the parameters and then proceeded with the cost estimation.

The pinch design method was proposed by Linhoff and Hindmarsh [13] who in their study indicated the use of pinch design method which lead to relative energy consumption, minimum number of heat transfer equipment and minimum global annual cost. Ravagnani et al [14] used the pinch analysis method together with the genetic algorithm to synthesize optimal heat exchanger networks (HEN). It was reported that the paper presented a new methodology for the optimal HEN synthesis and gave the ΔTmin optimization value; due to ΔTmin value the minimum global cost was achieved. In the second stage due to merging of pinch analysis as well as Genetic algorithm optimal HEN is achieved.

Amini et al [15] reported a solution for the optimization of shell and tube heat exchanger using two objectives. The objectives were the simultaneous optimization of heat transfer rate along with the total cost. It was reported that in his study eleven optimization variables were considered by using the ε-NTU and P-NTU method. The goal was to see how the increase of the number of variables will affect in the optimization results. All Pareto points obtained as result had lower costs and better efficiencies when compared to their alternatives [16].

Many researchers have used different techniques like particle swarm, Pareto-archived evolution strategy, genetic algorithms etc. In this article, fast and elitist multi-objective genetic algorithm NSGA-II has been used to optimize a standard STHE model. This study has been also modified via NSGA II which includes inverse generalized distance (IGD) to provide the next generation of candidates with each iteration of the algorithm.

3

Problem Analysis

3.1 Problem Description

In this project E-STHE is being optimized by using NSGA-II proposed by K. Deb. Kern method is being used for Thermal modeling of STHE. Tube inner diameter, baffle spacing and number of tube are the three design parameter considered while doing thermal modeling. Capital cost, discounted operating cost and entropy generation number are the three objective function used to optimize the STHE.

3.2 Genetic Algorithm

GAs is a traditional method for optimization. GAs use a direct analogy of the natural phenomenon of evolution like crossover and mutation. The parameter values are represented as strings in the algorithm. The GAs work with strings instead of the parameters themselves. A randomly generated population within the sample space is taken, this is then evaluated according to the underlying objective function and constraints. Fitness function is used to assign values to individual stings in population in absence of constraints. Crossover and mutation operators are applied to pairs of individuals from the parent generation. Both operators usually ensure that the values can escape from the local minima. The samples with the best fitness value have a higher probability to be included in the next generation. The selected population from the previous generation goes to the beginning of the entire process. After multiple generations, the solution starts to converge on the global minimum. [17].The multiple stopping parameters can be chosen to end the iterative process like the number of generations, time, duplicity of n and n+1 population, etc.

3.3 Non-dominated Sorting Genetic Algorithm-II

In Non-dominated sorting a solution X(a) dominates another solution X(b) if any of the following condition are true:

i. rank of X(a) < rank of X(b)
ii. if rank of X(a)= rank of X(b) then, distance of X(a) > distance of X(b).

Tournament selection is a method of selecting an individual from a population of individual in genetic algorithms. Two individuals compete in a tournament with randomly selected individual. The process imitates the survival of the fittest. Uniform crossover and random uniform mutation are operated to obtain the offspring population. Crowding distance of a solution provides an estimate of a density of a solution surrounding the solution. The crowding distance proposed by Deb and Goel [18] is used, where the crowding of an individual is the perimeter of the rectangle with its nearest neighbor at diagonally opposite corner. Thus, if individual X(a) and individual X(b) have same rank, one that has a larger crowding distance is better.

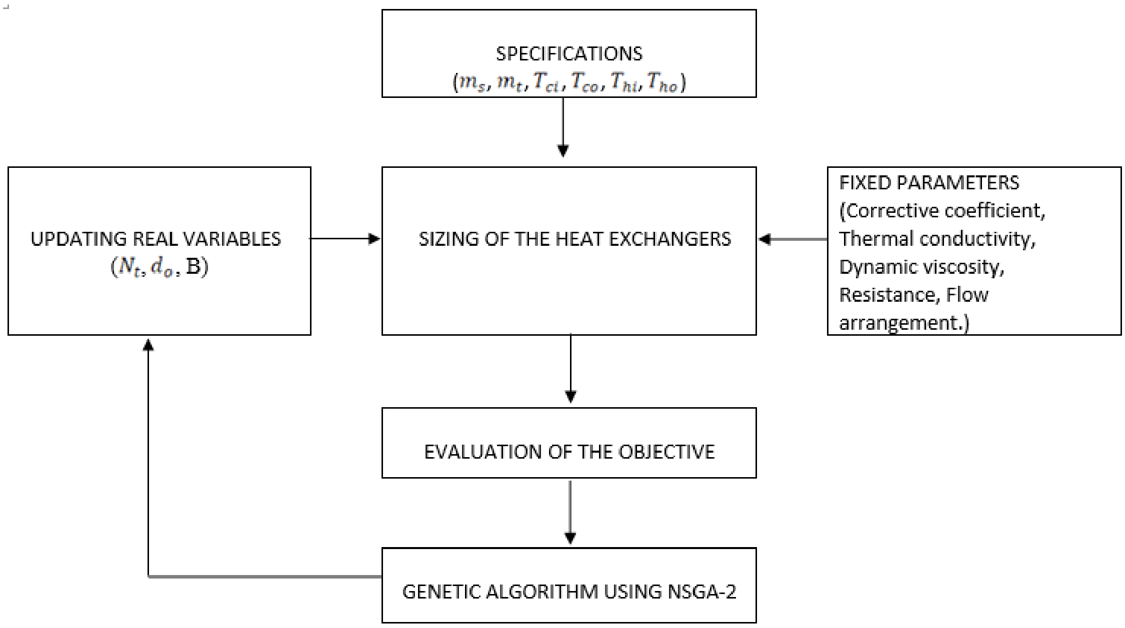


Fig 3.1: Flowchart of Algorithm

3.4 Inverse Generalized Distance (IGD) Ratio

The IGD ratio was defined to compare the IGD value of current generation to past q generations. The user-defined δ was used to decide when to execute the local search. In this study, the number of generations is determined by observing 0.001 or less change in the δ ratio as shown below Which is also given in the modified NSGA [17].

$$\frac{IGD_{max} - IGD_{min}}{q} \leq \delta$$

3.5 Mathematical Modeling:

3.5.1 Proposed Approach

In the given problem statement, the two functions pumping power and the heat transfer area are required to overcome the pressure drop. It is desired to compute the optimization of annual cost by using LMTD and a set of design variable values [19].A theoretical process for the design of STHE is given below.

- Selection of fluid on shell and tube side.
- Determine stream temperature.

- Determine the shell and tube side pressure drop.
- Determine velocity limits for shell and tube side.
- Selection of fouling coefficients and heat transfer models for shell and tube side.

Thermal modeling of the heat exchanger

The mathematical model given below has been implemented in this study for the STHE Design. The total heat transfer is given by Eq. (1). The Heat transfer coefficient is defined as a quantitative characteristic of convective heat transfer between a fluid medium and the surface or wall flowed over by the fluid. Heat transfer coefficient for tube side is given by Eq (2).

$$Q = \left(m_t c_{pt}\right) * (T_{co} - T_{ci}) \tag{1}$$

$$h_t = \ (k_t/d_i)\ 0.024{Re_t}^{0.8}\ {Pr_t}^{0.4} \tag{2}$$

Where d_i, k_t and Pr_t are tube inner diameter, tube side thermal conductivity, and Prandtl Number. Re_t is tube side Reynolds's number is given by Eq (3)

$$Re_t = m_t d_i/\mu_t A_t \tag{3}$$

Where $\mathrm{A_t}$ is tube surface area

$$A_t = \frac{0.25\pi d_i^2 N_t}{n} \tag{4}$$

N_t and n are number of tube and tube passes

The shell side heat transfer coefficient (h_s) is given by Eq (6)

$$h_s = \frac{0.36 * k_s}{d_e} * {Re_s}^{0.55} * Pr_s^{0.33} * \left(\frac{\mu_s}{\mu_{wts}}\right)^{0.14} \tag{5}$$

Where $k_s$and Pr_s are shell side thermal conductivity and Prandtl number respectively

Equivalent shell diameter, d_e (m) and Reynold's number for shell side are given by Eq (6) and Eq (7),

$$d_e = 4 * \frac{0.43S_t^2 - (\Pi * 0.25 * d_o^2)}{0.5(\Pi * d_o)} \tag{6}$$

$$Re_s = \frac{m_s d_e}{\mu_s A_s} \tag{7}$$

Shell outer diameter d_o is given by Eq (8).

$$D_s = 0.637 * s_t * \sqrt{\pi N_t (CL/CTP)} \tag{8}$$

Where, CL and CTP are tube pitch, tube layout constant and tube count calculation constant respectively, for 45° and 90° tube arrangement the value of CL is 1, and for 30° and 60°, CL = 0.87. The values of CTP are 0.93, 0.90, and 0.85 for one, two, and three tubes pass respectively.

Overall heat transfer coefficient is given by the Eq(9) [20],

$$U = \frac{1}{\left(\frac{1}{h_s}\right) + R_{fs} + \left(\frac{d_o}{d_i}\right)\left(R_{ft} + \left(\frac{1}{h_t}\right)\right) + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2k_t}} \tag{9}$$

Heat exchanger surface area

The total heat transfer surface area for a STHE is given by,

$$A = \frac{Q}{U * F * LMTD} \tag{10}$$

Where, LMTD is a logarithmic mean temperature difference between the hot and cold fluids at each end of a heat exchanger.

The equation for calculating the LMTD is stated below,

$$LMTD = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{ln\left(\frac{(T_{hi} - T_{co})}{(T_{ho} - T_{ci})}\right)} \tag{11}$$

Correction Factor F depends upon temperature effectiveness P, heat capacity rate ratio R and flow arrangement in design process, a correction factor is applied to the LMTD to determine the true temperature difference.[19]

$$F = \phi(P, R, flow\ arrangemnt)$$

Heat capacity rate ratio R is given by (12),

$$R = \frac{(T_{hi} - T_{ho})}{(T_{co} - T_{ci})} \tag{12}$$

And temperature effectiveness P is given by Eq (13),

$$P = \frac{(T_{co} - T_{ci})}{(T_{ho} - T_{hi})} \tag{13}$$

The value of correction factor F is calculated by using the graph in Appendix E.

Pressure drop

Tube length L is given by Eq (14)

$$L = \frac{A}{\pi d_o N_t} \tag{14}$$

The tube side pressure drop is calculated by is given by Eq (15),

$$\Delta P_t = \frac{\rho_t v_t^2}{2} * (\left(\frac{L}{d_i}\right) f_t + p) n \tag{15}$$

Where f_t is the Darcy friction coefficient given by Eq (16) [17]

$$f_{t=} (1.82 \log_{10} \mathrm{Re}_3 - 1.64)^2 \tag{16}$$

Shell side pressure drop for STHE is given by Eq (17)

$$\Delta P_s = f_s \left(\frac{\rho_s v_s^2}{2}\right) \left(\frac{L}{B}\right) \left(\frac{D_s}{D_e}\right) \tag{17}$$

Where the friction coefficient f_s is given by Eq (18),

$$f_s = 2 b_o {Re_s}^{-0.15} \tag{18}$$

3.5.2 Objective Function

The total cost is the sum of material cost and discounted operating cost, which is given by Eq. (19). The material cost $C_i$for the STHE is given by Eq. (20) and the discounted operating cost is given by Eq. (21). While, the pumping power is given by Eq. (22). The values for the numerical constraints and the standard values required for calculating the costs are given in Table 1.

$$C_{tot=} C_i + C_{op} \tag{19}$$

$$C_i = a_1 + a_2 A^{a_3} \tag{20}$$

$$C_{op=} \sum_{x=1}^{n_y} \frac{C_o}{(1+i)^x} = P C_e H \tag{21}$$

$$P = \frac{1}{\eta} \left(\frac{m_t}{\rho_t} \Delta P_t + \frac{m_s}{\rho_s} \Delta P_s\right) \tag{22}$$

3.5.3 Entropy generation number (EGN)

The entropy generation rate is a parameter used to reduce the thermodynamic irreversibility that reduces the performance of the STHE. The total rate of entropy generation in STHE is given by Eq. (23). The Hessel greaves EGN shown by Eq. (24), which is a modification of the Bejan's EGN. It is used due to Bejan's EGN produces a entropy generation paradox[11].

$$\Delta\dot{S} = \Delta\dot{S}_{\Delta t} + \Delta\dot{S}_{\Delta s} \tag{23}$$

$$N_s = \frac{\Delta\dot{S}T_{c,i}}{Q} \tag{24}$$

Table 1. Standard values for stainless steel E-Shell heat exchangers.

Parameters	Values
Constant a_1 (\$)	8000
Constant a_2 ($\$/m^2$)	259.2
Constant a_3	0.93
Energy cost C_e ($\$/kWh$)	0.12
Operating time H (hrs./yr)	8000
Discount rate per annum i(%)	10
Number of years of operation n_1	5
Pump Efficiency η	0.7

3.6 Technology Used

During the course of project following software have been used:

- C Programming Language - The whole NSGA-II algorithm has been originally incorporated by C language. Thus it is necessary to learn this language to execute the objective function through the algorithm
- Cygwin- Cygwin is a POSIX-compatible environment that runs on Microsoft Windows. It is very useful in compiling and executing Unix-like applications on Windows with minimal source code modifications.
- Various other software used to facilitate the programming and editing of the project like DEVC++, Mendeley

4

Results and Discussion

4.1 Results and Discussion

The standard values for a stainless-steel E-Shell heat exchanger have been defined in the table 2. Limits for number of tubes have been given from 50-300 and the outer diameter of the tubes 0.015-0.051m for all the iterations.

Table 2. Standard data of STHE

Parameters	Tube side	Shell side
Inlet temperature T_i (K)	76.7	199
Outlet temperature T_o (K)	37.8	-
Mass flow rate m (kg/s)	18.80	5.52
Density $\rho(kg/m^3)$	995	850
Specific Heat C_p (J/KgK)	2.05	2.47
Kinematic viscosity $\mu(Pa-s)$	0.00358	0.0004
Fouling Resistance R_f	0.0061	0.0061
Prandtl number Pr	0.05645	0.0076

Table 3. Constant parameters for NSGA-II

Parameter	Value
Population	40
Max. no. of generations	500
Crossover probability	0.9
Mutation probability	0.25
Crossover operator index	15
Mutation operator index	20

The input parameters for the NSGA-II algorithm have been compiled in the table 3.

All combinations of the 3 objectives were executed against each other except the Entropy generation number vs the discounted operational cost because both are obtained from the same parameter of tube and shell pressure drop. The 4 cases are explained below,

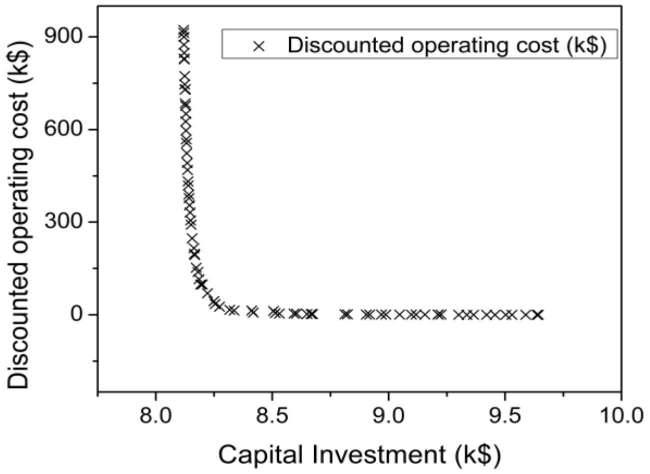


Figure 4.1 Variation Discounted Operating Cost vs Capital Investment

Case 1. The graph is plotted between discounted operating cost and capital cost shown in Fig 4.1. It can be observed that a Pareto optimal front is being formed. The graph showed a decrease in the operating cost with increasing capital investment. One of the optimal solution, C_{op} = 3124.855\$ and C_i =9096.19\$, obtained from the set of non-dominated population after the algorithm was terminated, When compared to the total cost given by Harikirupakar et al. [21], it was found that the total cost obtained in this case study was significantly lower.

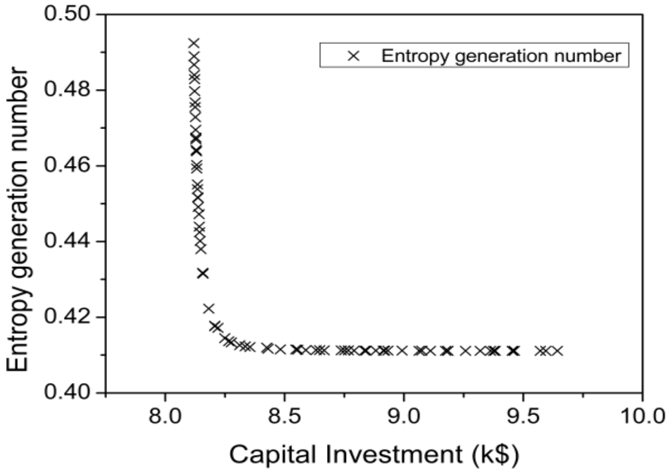


Figure 4.2. Variation EGN vs Capital Investment

Case 2. The graph was plotted between the capital cost and the EGN shown in Fig. 4.2. It has been deduced from the graph that EGN decreases with higher the capital cost which is due to increasing the volume of material required. The optimum solution obtained, by decreasing the irreversible losses of the STHE at the cost of increasing the capital investment.

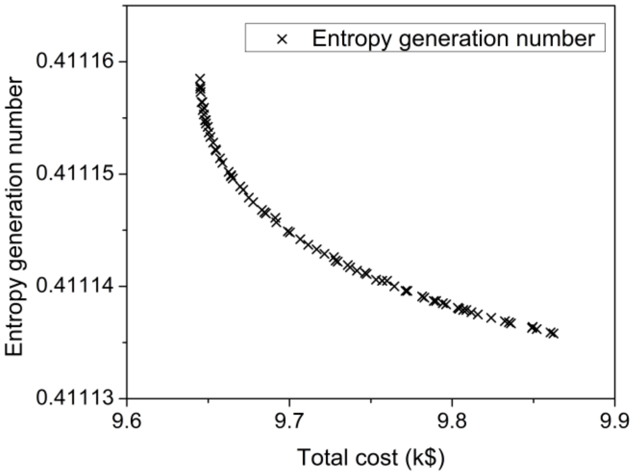
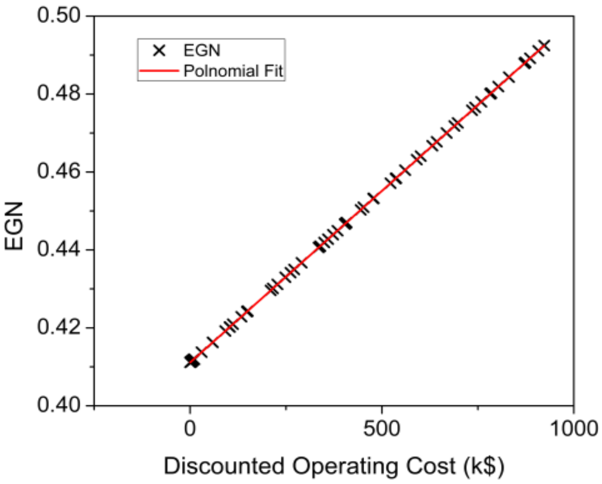
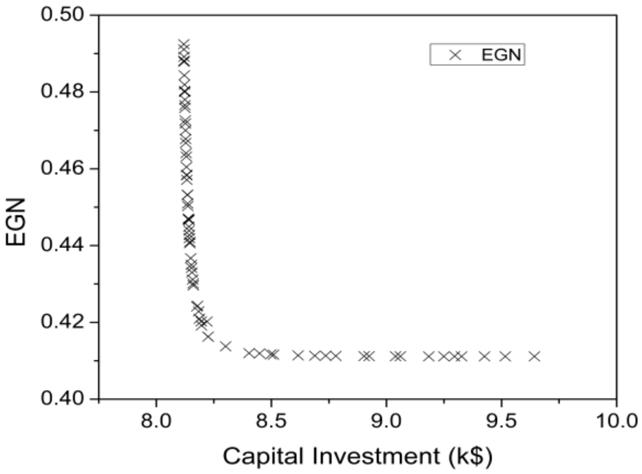


Figure 4.3 Variation EGN vs Total operating cost ($)

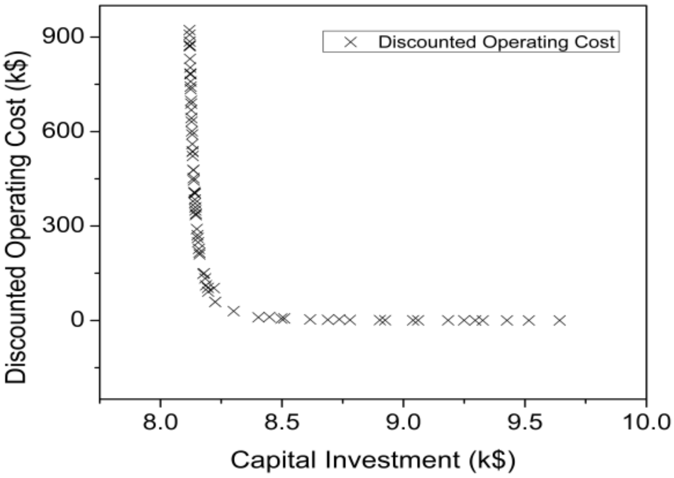
Case 3. To examine the entropy generation number and total operating cost, the graph has been plotted as in Fig. 4. The Fig. 4 shows, that the values of EGN are from 0.41-0.42, so it can be concluded that the set of population have converged to the global optimum in the same number of generation and also an inverse relation between EGN and total operating cost is being observed. The decrease in EGN is achieved on the expense of sacrificing total operating cost.



(a) EGN vs Discounted Operating Cost



(b) EGN vs Capital Cost



(c) Discounted Operating Cost vs Capital Cost

Fig 4.4 *The graphs of Case-4 involving the 3-objective optimization*

Case 4. In this case all 3 objectives have been executed simultaneously. In the fig 4.4(b) from which it can be deduced that the population has converged towards a pareto-optimal front. As stated in Elarbi et al [22] the efficiency and effectiveness of the algorithm decreases with increasing number of objectives. A similar trend can be seen in the fig 4.4(c) where some solution sets have not converged to the pareto front unlike the other cases where an optimal pareto front is obtained. Contrary to the both the other graphs the results obtained depicted in fig 4.4(a) was a linear proportionality this is because both these objectives are derived from the same parameters.

5

Conclusion

5.1 Conclusion

This study shows an entropy used optimization through a GA has been conducted to optimize the both the cost of materials and operation in the STHE. The following points can be concluded from the study:

- The optimal design has been developed for heat exchanger by reducing the overall cost of the STHE while compared with previous research results.
- With decreasing the EGN of the shell and tube heat exchanger, the capital investment of STHE increased.
- The EGN found reduced at the expense of sacrificing the total operating cost.
- By decreasing the number of objectives, the robustness of the algorithm increases.
- The combination of Total cost and EGN taken as objective functions reached the closest to the global optimum.

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Appendix

Appendix A

This appendix shows the data for the Fig. 4.1

Capital Cost	Discounted Operating Cost
8119.385	922724.3
9642.948	219.3469
8823.157	1264.774
8148.777	305593.1
8162.948	215625.4
8192.387	98527.48
8666.787	2169.852
8130.847	568071.7
8412.184	13594.58
9503	274.5526
8132.695	523296.5
8248.879	44198.28
8128.329	626503.5
8125.339	728901.4
9420.767	297.2556
8335.415	13629.65
8530.316	3926.857
8135.81	469349
8504.769	12104.43
9588.872	238.5915
9364.29	327.3996
8649.214	2351.51
8123.337	772877.8
8166.926	193371.5
8126.29	684948.7
8120.564	874806.3
9117.559	542.1079
9155.691	492.8327
8184.74	115333.9
8918.071	909.3228
9301.089	372.6763
8144.835	354713.4
8139.004	418373.1
8121.785	827142.8
9224.965	449.1124
9047.175	640.7432
8121.742	848297.6

8119.814	913069.8
8968.957	785.6839
8173.433	152759.7
9642.948	219.3469
8119.385	922724.3
9335.762	346.6663
8165.379	197109.4
8512.882	5640.288
8131.102	556870
8124.058	746339.1
8221.367	69758.17
8129.376	597099.6
8119.913	900174.1
8811.865	1287.422
8673.04	2148.95
8146.593	331545.5
8156.123	247724.8
9097.138	596.8315
8121.734	829856.6
8126.648	676952.3
8128.96	650559
9212.961	435.8543
8254.126	34591.37
9456.902	291.3035
8181.201	138790.2
8121.734	829856.6
8126.629	730690.6
9211.378	438.1346
9529.821	257.7849
9637.151	223.2235
8134.374	491517
8987.519	740.9847
8417.776	7270.287
8142.537	377720.6
8903.605	957.5652
8592.924	3734.534
8138.398	431837
8273.257	26305.18
8141.581	389583.7
8150.91	291859.6
8317.639	16080.8
8604.103	3550.998

Appendix B

This appendix shows the data for the Fig. 4.2

Capital Cost	Entropy Generation Number
9642.948	0.41114
8119.385	0.49244
9075.013	0.41118
8125.515	0.47289
8128.156	0.46699
9594.438	0.41114
8181.941	0.4223
8932.757	0.4112
8143.693	0.44247
9454.325	0.41114
9320.136	0.41115
9184.28	0.41116
8120.943	0.48677
9375.919	0.41115
8751.101	0.41125
8122.151	0.48288
8665.465	0.4113
8439.694	0.41167
8248.992	0.41447
8125.022	0.47677
8207.621	0.41774
8546.719	0.41153
9183.865	0.41116
8355.002	0.41212
8335.266	0.41233
8157.179	0.43179
8220.375	0.41721
8136.645	0.45156
8429.924	0.4117
8140.896	0.44725
8842.015	0.41122
8790.948	0.41124
8882.222	0.41121
8130.445	0.46385
8134.423	0.45512
8588.99	0.41136
8276.063	0.41339
9453.925	0.41114
8131.178	0.46028
8631.319	0.41134

9642.948	0.41114
8119.385	0.49244
8206.946	0.41762
8131.562	0.4593
8647.216	0.41133
8121.769	0.48403
8123.084	0.47977
8126.912	0.46956
8265.402	0.41368
8991.913	0.41118
8311.758	0.41265
8425.215	0.41201
9362.185	0.41115
8736.527	0.41126
8146.164	0.44021
8124.532	0.47555
8129.139	0.4642
8120.31	0.48899
8134.705	0.45387
8482.01	0.41154
9258.365	0.41115
9174.551	0.41116
9382.448	0.41115
8138.139	0.44915
8142.507	0.44399
8554.206	0.41145
9462.088	0.41114
8767.009	0.41125
9571.393	0.41114
8136.25	0.45172
8149.349	0.43802
9063.998	0.41117
8158.237	0.43154
8127.789	0.46749
8835.181	0.41122
9258.365	0.41115
8913.95	0.41121
8124.532	0.47555
8918.155	0.4112
9111.025	0.41117

Appendix C

This appendix shows the data for the Fig. 4.3

Total Cost	Entropy Generation Number
9862.295	0.41114
9645.054	0.41116
9669.764	0.41115
9677.681	0.41115
9691.963	0.41115
9700.273	0.41114
9658.762	0.41115
9764.481	0.41114
9706.672	0.41114
9645.248	0.41116
9664.062	0.41115
9684.606	0.41115
9716.726	0.41114
9741.474	0.41114
9803.563	0.41114
9651.366	0.41115
9747.445	0.41114
9685.489	0.41115
9756.97	0.41114
9654.808	0.41115
9735.864	0.41114
9654.549	0.41115
9647.411	0.41116
9772.508	0.41114
9645.984	0.41116
9832.434	0.41114
9849.481	0.41114
9788.767	0.41114
9851.991	0.41114
9650.415	0.41115
9727.292	0.41114
9648.55	0.41115
9662.652	0.41115
9834.915	0.41114
9808.714	0.41114
9648.075	0.41115
9811.883	0.41114
9796.267	0.41114
9757.056	0.41114
9782.859	0.41114

9862.295	0.41114
9645.054	0.41116
9691.264	0.41115
9849.106	0.41114
9781.523	0.41114
9657.265	0.41115
9746.499	0.41114
9698.981	0.41114
9664.023	0.41115
9759.95	0.41114
9711.541	0.41114
9771.355	0.41114
9653.086	0.41115
9790.11	0.41114
9671.53	0.41115
9721.489	0.41114
9836.113	0.41114
9860.522	0.41114
9649.783	0.41115
9753.264	0.41114
9674.989	0.41115
9806.806	0.41114
9824.016	0.41114
9646.468	0.41116
9683.1	0.41115
9772.396	0.41114
9729.656	0.41114
9815.796	0.41114
9645.38	0.41116
9804.261	0.41114
9794.242	0.41114
9728.362	0.41114
9737.244	0.41114
9647.338	0.41116
9737.244	0.41114
9645.171	0.41116
9648.602	0.41115
9721.49	0.41114
9646.718	0.41116
9665.186	0.41115

Appendix D

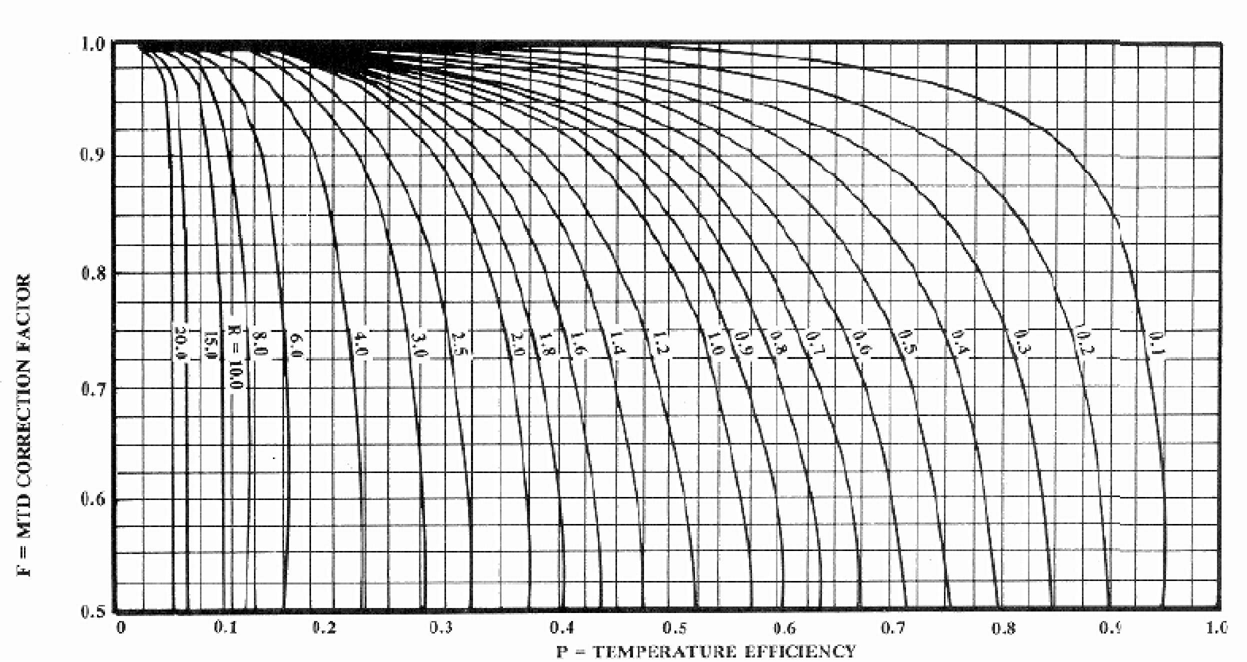
This appendix shows the data for the Fig. 4.4

Capital Cost	Discounted Operating Cost	Entropy Generation Number
9642.948	219.3469	0.41114
8119.385	922724.3	0.49244
8160.92	210095.8	0.42961
8924.298	993.166	0.4112
9060.484	625.1159	0.41117
9426.16	305.1248	0.41114
9295.747	382.9183	0.41115
8143.684	359434.9	0.44276
8126.623	668376.9	0.47001
8179.26	150138.9	0.42432
8132.213	535669.2	0.45831
8779.926	1574.503	0.41126
8120.552	873951.1	0.48814
8225.481	59115.1	0.4163
8145.301	335047.8	0.44063
8158.339	227696.3	0.43116
8220.129	103115.4	0.42021
8136.613	452143.7	0.45095
8183.971	133562.6	0.42287
8139.83	405057.3	0.44679
8120.261	885897.7	0.48919
8735.636	3571.348	0.41133
8127.994	631453.8	0.46676
8142.121	403183.4	0.44664
8121.659	831063.1	0.48436
8121.656	831063.5	0.48436
8152.138	271209.2	0.435
8153.297	261899.5	0.43418
8123.005	782230.8	0.48005
8123.515	782153.9	0.48005
8130.95	560291.9	0.46049
8509.387	6430.69	0.4116
8124.204	742865.4	0.47658
8124.204	742865.4	0.47658
8135.391	478484.5	0.45325
9039.597	657.6756	0.41118
8195.163	103679.9	0.42025
9295.747	382.9183	0.41115
8402.968	10045.03	0.412
8125.963	697635.3	0.4726

9642.948	219.3469	0.41114
8119.385	922724.3	0.49244
9183.485	479.7471	0.41116
8120.623	870937.8	0.48788
8149.666	290489.6	0.4367
8126.343	688870.2	0.47182
8122.616	803325.3	0.48192
8902.816	1103.568	0.41121
8688.706	2394.004	0.41133
8135.135	477304	0.45317
8137.115	444552.6	0.45028
9516.154	268.7812	0.41114
8132.157	537175.2	0.45844
8902.73	1104.173	0.41121
8130.387	590804.4	0.46317
8187.03	111717.9	0.42094
8139.465	407795.8	0.44704
9326.242	376.0565	0.41115
8145.728	339240.9	0.44097
8132.888	522291.8	0.45712
8154.838	248329.3	0.43298
8129.659	601079.3	0.46408
8123.97	758880.3	0.478
8196.216	91821	0.41919
8127.563	642876.4	0.46777
8616.272	3282.265	0.4114
8122.941	784614.1	0.48026
8497.29	6329.012	0.41167
8127.563	642876.4	0.46777
8160.111	215804.2	0.43011
9249.683	412.2149	0.41115
8176.202	148227.3	0.42414
8448.569	11281.96	0.4119
8224.867	58893.31	0.41626
8301.17	29921.09	0.41376
8119.737	907665.3	0.49111
8141.934	384231.9	0.44493
8124.428	734634.1	0.47585
8142.161	372529.3	0.44393
8143.978	349619.2	0.44191

Appendix E

The following fig shows the graph referred for calculation of the Correction Factor (F). The values taken are in accordance to the Tubular Exchangers Manufacturers Association standards.[19]



LMTD correction factor for a shell and tube heat exchanger.

Appendix F

This appendix includes the code utilized in the NSGA-II algorithm.

It should be noted that in this appendix, all the text in red are helpful comments for the reader to make the code more readable.

```
double dou,B,Nt;
double st,vt,di,Ret,ft,At;           /*tube side parameters*/
double Ds,de,As,vs,Res;              /*shell side parameters*/
double ht,hs,A,U;                    /*thermal modeling*/
double pt,fs,ps,f1,f2,len,fl,Co;
double s1,s2,sgen,Ns;
/*variables*/
dou= xreal[0];          /* outer dia of tube (0.01905m-0.0381m) */
B= xreal[1];            /* Baffle spacing  */
Nt=xreal[2];            /*number of tube  50-300  */

/*CONSTANTS*/
double a1=8000.00;           /*numerical constant (Rs)*/
double a2=259.2;             /*numerical constant (Rs/m2)*/
double a3=0.93;              /*numerical constant*/
double n=1;                  /*number tube passes*/
double eff=0.7;              /*pump efficiency*/
double LMTD=81.72;           /*log mean temperature*/
double Q=1499.206;           /*total heat transfer*/
double pi=3.14;
double ce=0.12;              /*energy cost*/
double CTP=0.93;
double CL=1.0;
double F=0.89;               /*temperature difference correction factor*/
double H=8000;
 /*tube side constant */
double mt=18.80;             /*tube side mass flow rate*/
double rhot=995.0;           /*tube side fluid density*/
double Tco=76.7;             /*tube side outlet temperature*/
double Tci=37.8;             /*tube side inlet temperature*/
double mut=0.00358;          /*fluid viscosity*/
double cpt=2.05;             /*specific heat*/
double kt=0.13;              /*thermal conductivity*/
double Rft=0.0061;           /*tube side fouling resistance */
/*shell side constant */
double ms=5.52;              /*shell side mass flow rate */
double Thi=199.0;            /*shell side inlet temperature*/
double Tho=89.04;            /*shell side outlet temperature*/
double rhos=850.0;           /*shell side fluid density*/
double cps=2.47;             /*shell side fluid specific heat*/
double mews=0.0004;
```

```
double mewws=0.00036;
double ks=0.13;              /*shell side thermal conductivity*/
double Rfs=0.00061;           /*shell side fouling resistace*/
double Prs=0.0076;           /*shell side prandtl number*/
/*Pressure drop constant*/
double p=4;
double bO=0.72;
/*TUBE SIDE PARAMETERS*/
st=1.25*dou;                               /*tube pitch*/
vt=(mt/(rhot*pow(dou,2) *pi/4))*n/Nt;      /*velocity of fluid on tube side*/
di=0.8*dou;                                /*tube inner diameter*/
At=0.25*pi*pow(di,2) *Nt/n;                /*tube side surface area*/
Ret=(mt*di)/(mut*At);                      /*tube side Reynold’s number*/
/*Darcy friction factor*/
 ft=0.079/pow(Ret,0.25);
/*SHELL SIDE PARAMETERS*/
/*Shell diameter*/
Ds=0.637*st*pow((pi*Nt)*(CL/CTP),0.5);
/*equivalent dia*/
de=4*((0.43*0.004064)-(0.125*pi*pow(dou,2)))/(0.5*pi*dou);
 /*shell side cross-section area*/
As=Ds*B*(1-(dou/st));
/*velocity of fluid on shell side*/
vs=ms/(rhos*As);
/*shell side Reynold's number*/
Res=ms*de/(As*mews);
/*HEAT TRANSFER COEFFICIENTS*/
/* Shell side heat transfer coefficient*/
hs=0.36*(ks/de)*pow(Res,0.55)*pow(Prs,(1/3))*pow((mews/mewws),0.14);
/*Tube side heat transfer coefficient*/
ht=(kt/di)*0.024*pow(Ret,0.8)*pow(Prt,0.4);
/*overall heat transfer coefficient*/
U=1/((1/hs)+Rfs+(dou/di)*(Rft+(1/ht))+(dou*log(dou/di))/2*kt);
/*heat exchanger surface area*/
A=Q/(U*F*LMTD);
/*tube lenght*/
len=A/(pi*dou*Nt);
/*PRESSURE DROP*/
/*tube side pressure drop*/
pt=0.5*rhot*pow(vt,2)*(p+(len*ft/(0.8*dou)))*n;/*changes*/
/*shell side pressure drop*/
fs=2*bO*pow(Res,-0.15);
ps=fs*(rhos*pow(vs,2)/2)*(len/B)*(Ds/de);
/*objective function*/
f1=(a1+a2*pow(A,a3));        /*investment cost*/
/*friction losses*/
fl=(mt*pt/rhot+ms*ps/rhos)/eff;
/*annual operating cost*/
```

```
Co=(ce*H*fl);
/*discounted operational cost */
f2=(Co*((1/1.1)+(1/1.21)+(1/1.331)+(1/1.4641)+(1/1.611)));
/*entropy generation number*/
s1=(mt*cpt*log(Tco/Tci))+(mt*(pt/rhot)*(log(Tco/Tci)/(Tco-Tci)));
s2=(ms*cps*log(Tho/Thi))+(ms*(ps/rhos)*(log(Tho/Thi)/(Tho-Thi)));
sgen=s1+s2;
Ns=sgen*Tci/Q;
double f3=f1+f2;
```

Appendix G

This appendix includes the test code for solutions and verification of all functions used in the thermal modeling and performing dry runs of the objectives with predetermined values.
It should be noted that in this appendix, all the text in red are helpful comments for the reader to make the code more readable.

```
/*fuc 1 tube pitch*/
double  t_pitch()
{
        double st=1.25*dou;
        return (st);
}
/*fuc 2 velocity of fluid on tube side*/
double t_fvel()
{
        double vt=(mt/(rhot*0.8*pow(dou,2)*pi/4))*n/Nt;
        return (vt);
}
/*fuc 3 tube inner diameter*/
double  t_inner_dia()
{
        double di=0.8*dou;
        return (di);
}
/*func 4 tube area*/
double t_area()
{
        double At=0.25*pi*pow(t_inner_dia(),2)*Nt/n;
        return(At);
}
/*fuc 5 tube side Reynold’s number*/
double t_rey_no()
{
        double Ret=(mt*t_inner_dia())/(mut*t_area());
        return (Ret);
}
/*fuc 6 Darcy friction factor*/
double  df_factor()
{
        double ft=0.079/pow(t_rey_no(),0.25);
        return (ft);
}
/*fuc 7 shell dia */
double s_dia()
{
        double Ds=0.637*t_pitch()*pow((pi*Nt)*(CL/CTP),0.5);
```

```
        return(Ds);
}
/*fuc 8 equivalent dia*/
double  equ_dia()
{
        double de=4*((0.43*0.004064)-(0.125*pi*pow(dou,2)/4))/(0.5*pi*dou);/*correction*/
        return (de);
}
/*fuc 9 shell side cross-section area*/
double  s_area()
{
        double As=s_dia()*B*(1-dou)/(1.25*dou);
        return (As);
}
/*fuc 10 velocity of fluid on shell side*/
double  s_fvel()
{
        double vs=ms/(rhos*s_area());
        return (vs);
}
 /*fuc 11 shell side Reynolds's number*/
double  s_rey_no()
{
        double Res=ms*equ_dia()/(s_area()*mews);
        return (Res);
}
/*THERMAL MODELING*/
/*fuc 12 Shell side heat transfer coefficient*/
double  s_ht_coeff()
{
double hs=0.36*(kt/equ_dia())*pow(s_rey_no(),0.55)*pow(Prs,(1/3))*pow((mews/mewws),0.14);
return (hs);
}
/*fuc 13 Tube side heat transfer coefficien*/
double  t_ht_coeff()
{
        double Ret=t_rey_no();
        double ht;
        ht=(kt/ t_inner_dia())*0.024*pow(t_rey_no(),0.8)*pow(Prt,0.4);
}
/*fuc 14 overall heat transfer coefficient*/
double  o_ht_coeff()
{
        double U=1/((1/
        s_ht_coeff())+Rfs+(dou/t_inner_dia())*(Rft+(1/t_ht_coeff()))+((dou*log(dou/t_inner_dia()
        ))/2*kt));
        return (U);
}
```

```
        /*fuc 15 heat exchanger surface area*/
 double  hte_sarea()
 {
        double A=Q/(o_ht_coeff()*F*LMTD);
        return (A);
}
        /*fuc 16 sthe length*/
        double sthe_len()
        {
                double len=hte_sarea()/pi*dou*Nt;
        }

        /*PRESSURE DROP*/
        /*fuc 17 tube side pressure drop*/
        double  t_predrop()
        {
        double pt=0.5*rhot*pow(t_fvel(),2)*(p+(sthe_len()*df_factor()/(0.8*dou)))*n;
        return (pt);
        }
        /*fuc 18 shell side pressure drop*/
        double  s_predrop()
        {
                double fs=2*bO*s_rey_no();
                double ps=fs*(rhos*pow(s_fvel(),2)/2)*(sthe_len()/dou)*(s_dia()/equ_dia());
                return (ps);
        }
        /*entropy generation number*/
        /*fuc 19*/
        double s_gen_t()
        {
        double s1=(mt*cpt*log(Tco/Tci))+(mt*(t_predrop()/rhot)*(log(Tco/Thi)/(Tco-Tci)));
                return(s1);
        }
        /*fun 20*/
        double s_gen_2()
        {
        double s2=(ms*cps*log(Tho/Thi))+(ms*(s_predrop()/rhos)*(log(Tho/Thi)/(Tho-Thi)));
                return(s2);
        }
        /*fun 21*/
        double egn()
        {
                double Ns=((s_gen_t()+s_gen_2())*Tci)/Q;
                return (Ns);
        }


      /*objective function*/
```

```
/*fuc 22 objective function1*/
double  obj_f1()
{
            double f1=(a1+a2*pow(hte_sarea(),a3));       /*investment cost*/
            return (f1);
}
/*func 23*/
double f_losses()
{
            Double  fl=(mt*t_predrop()/rhot+ms*s_predrop()/rhos)/eff;
                        return(fl);
}
/*func 24*/
double a_cost()
{
            double Co=(ce*H*f_losses());
                        return(Co);
}
/*fuc 25 objective function2*/
double  obj_f2()
{
double f2=(a_cost()*((1/1.1)+(1/1.21)+(1/1.331)+(1/1.4641)+(1/1.611)));
return (f2);                              /*annual operating cost*/
}
```