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HEAT EXCHANGER DESIGN: ABC ALGORITHM

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Abstract - The most prevalent heat exchange equipment is shell-and-tube heat exchangers. Shell and tube heat exchangers, despite technological developments in other exchanger types, hold a major place in industrial applications due to their wide range of operating conditions, resilience, versatility, and reliability. Because heat exchangers are widely used in industrial processes, lowering their costs is a priority for both designers and users. A generalized approach for shell and tube heat exchanger design has been developed and presented in this paper to predict surface area, overall heat transfer coefficient, pressure drop/pumping power for known input values of heat duty, tube layout, tube outside diameter, baffle spacing, shell diameter, and thermo-physical property of working substance for known input values of heat duty, tube outside diameter, baffle spacing, shell diameter, and thermo-physical property of working substance.

An objective function in terms of fixed and operational costs has been constructed in this work for optimization. The fixed cost is calculated based on the surface area of heat transfer. Using different materials (such as carbon steel, stainless steel, and titanium steel depending on operating conditions), the cost functions of shell and tube side surface area are determined from literature. In the overall/total cost, the objective function also accounts for the current interest rate and inflation rate. The ABC algorithm technique is used to optimize costs. Data from the literature has been used to validate the ABC approach. Following validation, the ABC approach was used to optimize the cost of a shell and tube heat exchanger and to investigate the impact of key design elements (i.e. outside diameter of tubes, baffle spacing and tube pitch).

Keywords— Heat Exchanger, Design, ABC Algorithm, Heat Exchanger Design, Optimization

1. INTRODUCTION

Shell and tube heat exchanger, the widely used heat exchangers in process industries because of their relatively simple manufacturing, is the extension of the double-pipe configuration. Different approaches (for abating the thermal stress, preventing leakage, controlling corrosion and to facilitate cleaning) have been used to optimize STHEx design. Thermal and hydraulic performance, economic considerations, space and weight considerations, operational and maintenance considerations and other important parameters are also a function of heat exchanger design. Commercially, a variety of optimization tools are available, many of them have limited generality.

Investigators had employed different optimization techniques (Selbas et al. 2006, Caputo et al. 2008, Fesanghary et al. 2009). Selbas et al. (2006) employed genetic algorithm (GA) technique to minimize the total cost of STHEx. Caputo et al. (2008) also used GA technique to arrive at optimum heat exchanger architecture. On the other hand, Fesanghary et al. (2009) highlighted the global sensitivity analysis in order to identify the critical design parameters using Harmony Search algorithm. Hajabdollahi et al. (2011) combined both GA technique and Particle Swarm (PO) method to perform thermoeconomic optimization of shell and tube condenser. Rao & Patel (2013) modified the teaching-learning based optimization (TLBO) algorithm to customize for other large thermal systems; they used modified TLBO algorithm for multi-objective optimization of STHEx and plate-fin heat exchangers (PFHEx); while, Hadidi et al. (2013) applied imperialist competitive algorithm (ICA) for cost minimization with higher accuracy and computation speed.

Traditional approaches are highly iterative and time consuming. Thus, in this work, a generalized approach for STHEx design has been developed. Herein, total cost of equipment/material and operating costs were combined to define objective function. Non-traditional ABC algorithm (ABC) technique has been employed. Studies on cost optimization of STHEx are carried out by selecting various construction materials.

2. ANALYSIS

Heat exchangers are designed for many different applications, and hence may involve many different optimization criteria.

2.1 Formulation of Problem

CT is the sum of the initial cost of the shell and tube heat exchanger i.e. fixed cost (CF) and operating cost, CP (i.e. cost of pressure drop in terms of pumping power for running the system over a period of its lifespan). The capital investment CF (in €) is computed as a function of the exchanger surface, As, adopting Hall's correlation as

$$C_F = \left(\alpha_i + \beta_i A_s^{\gamma_i}\right) \quad (1)$$

The total operating cost (i.e., related to pumping power to overcome friction losses) is considered to be paid annually over the lifespan of the system. Hence, it is likely to change due to inflation rate (f) in the prices of the electricity. The total operating cost is computed from the following equations:

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$$C_{OD} = \frac{C_o}{(i-f)}\left(1-\left[\frac{1+f}{1+i}\right]^k\right)$$

(Duffie and Beckman, 1980) (2)

$$C_o = P_P C_E hr \quad (3)$$

Where P, C_E and hr represent to pumping power on both the shell and tube sides, energy costs (€/kWhr) and hours per year, respectively. The expected life of shell and tube heat exchanger (number of years) is presented as k.

Thus total present cost of the system is the sum of fixed cost and present worth of all annual payments on electricity bills over the life span of the system. This is also called 'Life Cycle Cost', which can be presented in terms of objective as follows:

$$C_T = C_F + C_{OD} \quad (4)$$

Following design variables that have been identified for economic optimization are outside tube diameter, shell diameter, and baffle spacing. These are subjected to the boundary constraints:

$0.015 \le d_o \le 0.051$ (m) (5a)

$0.1 \le D_s \le 1.5$ (m) (5b)

$0.05 \le B \le 0.5$ (m) (5c)

2.2 Artificial Bee Colony (ABC) Algorithm

ABC as an optimization tool provides a population-based search technique in which individuals termed foods positions are updated over time by artificial bees, with the bees' goal being to locate the locations of high nectar-producing food sources and, finally, the one with the most nectar. Artificial bees fly around in a multidimensional search space in the ABC system, and some (employed and observer bees) choose food sources based on their and their nest mates' experiences, and modify their positions. Some (scouts) fly and seek food sources based on chance rather than experience. They memorize the new position and forget the previous one if the nectar amount of a new source is higher than the previous one in their memory.. Thus, ABC system combines local search methods, carried out by employed and onlooker bees, with global search methods, managed by onlookers and scouts, attempting to balance exploration and exploitation process.

2.3 Optimization procedure

Optimization of heat exchanger depends on experience and engineering judgments during various design stages. Therefore, an optimized heat exchanger design is arrived at if the objective function and constraints can be expressed mathematically. The constraints are the customer's specified explicit constraints (such as fixed frontal area, the ranges of heat transfer dimensions) and implicit constraints (such as required minimum heat transfer, allowable maximum pressure drop). Once the basic surface geometry of design chosen is selected, then minimum and maximum values for shell diameter, outer tube diameter, baffle spacing and so on. The designer desires to vary all the design and operating variables within the ranges specified such that the exchanger will meet the required heat transfer, maximum pressure drop, and other constraints with minimum total cost.

3. RESULTS AND DISCUSSION

The validation of simulation model for shell and tube heat exchanger and code for optimization and case studies for economic optimization of shell and tube heat exchanger are presented.

3.1 Validation of simulation model used for Shell and Tube Heat Exchanger

In the present work, the design data of shell and tube heat exchanger as reported in Caputo et al (2008) has been utilized for validation. Caputo et al. (2008) used the input information for outer tube diameter, baffle spacing and shell diameter to be 0.016 m, 0.5 m and 0.83 m respectively. The detailed input information for case-I are supplied in table 1

Table 1 Input Information for Case study

Case-I	Mass flow (kg/s)	T_{inlet} (°C)	T_{outlet} (°C)	ρ (kg/m^3)	cp (kJ/kg K)	μ (Pa s)	K (W/m K)	$R_{fouling}$ (m^{2}K/W)
Shell-side: Kerosene	5.52	199	93.3	850	2.47	0.00040	0.13	0.00061
Tube-side: crude oil	18.8	37.8	76.7	995	2.05	0.00358	0.13	0.00061

The results of shell and tube heat exchanger model using methanol at shell side and brackish water on tube side are compared in table 2

Table 2 Result of Shell and Tube Heat Exchanger Model

Parameter	GA	Predicted
L (m)	3.379	3.575
P_t (m)	0.02	0.020
C_l (m)	0.004	0.004
N_t	1567	1513
ΔP_t (Pa)	4298	5527
a_s (m^2)	0.083	0.083
ΔP_s (Pa)	13267	9498
U (W/m^2 K)	660	638
A_s (m^2)	262.8	272

Predicted values of overall heat transfer coefficient, surface area for heat exchanger and pressure drops on shell side and tube side are found to be agreeing fairly with data of Caputo et al. (2008).

3.2 Validation of ABC code for optimization

For case study, the original design specifications, and inputs to the optimization algorithm were shown in Table 3

Table 3 Parameters for life cycle cost analysis

Parameter	**Values**
System life	10 years
Cost of 1 unit (1 kW-hr) electricity	€ 0.12
Interest rate (i)	10 %
Work hour (annual)	7000 hrs

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Case Study

In this case, methanol is used on the shell side, while tube side has been allocated for brackish water in order to retain the architecture of original design as per the reference (Caputo et al 2008). The original design assumed the two tube side passages and one shell side passage. Various parameters for economic analysis have been listed in Table 4

Table 4 Case Study Specifications (Square Pitch Layout)

Parameter	Literature	GA	Present work
L (m)	4.880	2.153	3.6468
d_o (m)	0.025	0.02	0.0105
B_c (m)	0.127	0.12	0.0924
D_s (m)	0.539	0.63	0.3293
N_t	158	391	511
v_t (m/s)	1.44	0.87	0.43
h_t (W/m^2 K)	619	1168	2186
v_s (m/s)	0.47	0.43	0.37
h_s (W/m^2 K)	920	1034	868
U (W/m^2 K)	317	376	323
C_{iF} (€/yr)	19007	17599	19014
C_o (€)	1304	440	197.139
C_{od} (€)	8012	2704	1211.3
C_T (€)	27020	20303	20225

As can been seen in Table , the results obtained from ABC algorithm is better than results of other algorithms.

4. CONCLUSION

Thermodynamic design methodology for cost optimization of shell and tube heat exchangers was proposed in this study. A thermal design methodology for shell and tube heat exchangers has been devised. Tube length and inner diameter, number of tubes, overall heat transfer coefficient, heat transfer surface area for given heat duty, inlet and outlet flow rates and temperatures, outside tube diameter, shell diameter, baffle spacing, and thermo-physical properties of working substance are all predicted using the formula. The thermal design of a shell and tube heat exchanger has been successfully validated. Objective function has been developed in terms of total cost analysis module for shell and tube heat exchanger. Cost optimization of shell and tube heat exchanger has been carried out and model predictions have been validated with data available in the literature. Parametric study of shell and tube heat exchanger has been carried out to investigate the role of different tube and shell side materials, interest rate and inflation rate. Result shows that among above parametric variation, the selection of material is found to be much sensitive, when compared with rate of interest and inflation rate.

This work can be extended for exergy and thermo- economic analysis of STHEx. The generalized optimization approach for STHEx needs to account for effect of baffle cut on shell side heat transfer coefficient and friction factor in order to make more realistic predictions.

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