ISSN : 2248-9622 Vol. 9,Issue 5 (Series -V) May 2019, pp 01-07

RESEARCH ARTICLE OPEN ACCESS

Optimal Design of Parallel-Plate, Cross-Flow Heat Exchanger Minimizing the Entropy Generation

Hasan A. Alzanki[1], and Mubarak F. Al-Dhafiri[2]
[1, 2] The Public Authority for Applied Education and Training High Institute of Energy-Kuwait
Corresponding Author: Hasan A. Alzanki

ABSTRACT:
This paper presents a constrained optimization of a single pass, parallel-plate, cross-flow heat exchanger in terms of some geometrical features as design variables and subjected to fixed total volume and volume fraction occupied by solid walls. The objective of the optimization process is to minimize the exergy destruction in the heat exchanger by using the non dimensional entropy generation number definition as an objective function. The Cold and Hot unmixed air are the working fluids at this system, with known inlet conditions and properties. Geometrical, Heat Transfer, and Pressure Drop analysis are conducted to verify the exit conditions of the working fluids. Thermodynamic analysis is done to define the objective function in terms of the exit conditions for both streams. Graphical study of the design variables was conducted to analyze and understand the effect of the design variables on the objective function. A numerical solution for the problem defining the optimal design variables is accomplished. Graphical analysis and numerical solution are done. It is discovered that using the equality constraints in reducing the degree of freedom of the problem reduces the number of optimized design variables and also the complexity of the problem. The redundancy of some design variables are investigated and confirmed supplying a good understanding of the geometrical aspects of the system optimization.

I. INTRODUCTION AND PROBLEM FORMULATION:

A single pass, parallel-plate,cross-flow heat exchanger has the geometrical parameters shown in figure (1). Two streams pass through the heat exchanger in cross flow arrangement with the following hypotheses:

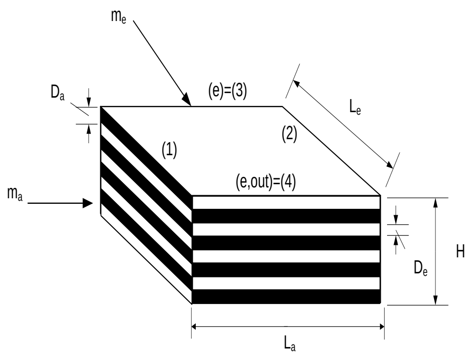

Figure (1): A single pass, parallel-plate, cross-flow heat exchanger

- Both fluids are unmixed.
- All physical properties and fluid capacity rates are constants.
- The exchanger shell or shroud is adiabatic.
- mass flow rates at the entrance of the heat exchanger on each side are constant and change in of flow distribution is neglected.
- Axial heat conduction is negligible.
- The thermal conductance on both sides are constant and inclusive of wall thermal resistance and fouling.(wall temperatures are the same on both sides)
- All geometrical parameters are not specified in priori.(the geometric features of the heat exchanger are not fixed by the " Surface Type " that may be available in a hand book and on the market)

The geometrical parameters of the heat exchanger are constrained by fixed volume of the heat exchanger as well as fixed exchanger mass expressed by the volume fraction occupied by solid walls. Geometric lengths are non-dimensionalised by using the cubic root of the volume as a length scale. Volume fraction occupied by solid walls and height of the heat exchanger increment are selected to ensure an even number of channels equally dividedfor the cold and hot streams.
Some constant parametersregarding heat exchanger material, fluids physical properties and streams thermal properties are introduced in table (1):

Parameter	Sym.	Value	
Heat exchanger Volume	B	0.5	m^3
Volume fraction occupied by solid walls	ϕ	0.1	
Plates or walls thickness	t_w	0.4	mm
Specific heats for both fluids	cp_a, cp_e	1	$kJ/kg.K$
Thermal conductivity of the cold fluid	k_a	0.02	$W/m.K$
Thermal conductivity of the hot fluid	k_e	0.03	$W/m.K$
Thermal conductivity of the wall	k_w	205	$W/m.K$
Cold stream mass flow rate	$\dot{m}_a$	0.84	kg/s
Cold stream mass flow rate	$\dot{m}_e$	0.16	kg/s
Prandtl number for both fluids	$\Pr_a, \Pr_e$	0.7	
Ideal gas constant for both fluids	R_a, R_e	0.287	$kJ/kg.K$
Viscosity of the cold fluid	μ_a	1.55×10^{-5}	$W/m.s$
Viscosity of the hot fluid	μ_e	2.12×10^{-5}	$W/m.s$

Table (1) : constant parameters of heat exchanger material, fluids physical properties and streams thermal properties

Cross-flow heat exchanger is descried by some geometrical characteristicsshown in figure (1), and defined as:

- Cold stream channel length (L_a).
- Hot stream channel length (L_e).
- Cold stream channel spacing (D_a).
- Hot stream channel spacing (D_a).
- Heat exchanger height (H).
- Number of channels for both streams (n).

II. SYSTEM ANALYSIS:

System analysis requires a full understanding of its all aspects, geometrically and thermally. Hence, the analysis will be carried out in the following steps:

1- Geometrical Analysis.
2- Heat Transfer Analysis.
3- Pressure Drop Analysis.
4- Thermodynamic analysis.

III. OPTIMIZATION PROBLEM STANDARD FORMULATION:

Given :

The heat exchanger arrangement with constant parameters and inlet conditions of Cold and Hot streams mentioned in the introduction.

Find :

The problem is to define the following design variables :

x_1 : Channel spacing ratio D_e/D_a .

x_2 : Non-dimensional cold channel length $\tilde{L}_a$.

x_3 : Non-dimensional heat exchanger length $\tilde{H}$.

Objective function :

To Minimize

$$N_S = \ln\frac{T_4}{T_3} - \frac{R_e}{cp_e}\ln\frac{P_4}{P_3} + \mu..\left(\ln\frac{T_2}{T_1} - \frac{R_a}{cp_a}\ln\frac{P_2}{P_1}\right)$$

Subjected to :

$$\Rightarrow \quad \frac{B^{1/3}\phi.x_3}{2.t_w} - Round...\left(\frac{B^{1/3}\phi.x_3}{2.t_w}\right) = 0$$

$$0.02 \le x_1 \le 4.0$$
$$0.05 \le x_2 \le 1.0$$
$$0.10 \le x_1 \le 2.0$$

IV. NUMERICAL SOLUTION PROCEDURES:

After completing the analysis part of this paperwe are able start solving the optimization problem. Solution procedures are divided to four phenomenon stages:

1- Reproducing the results of the original paper that this paper is based on.
2- Studying the effect of changing a single design variable on the objective function with fixing the other two at constant values.
3- Studying the effect of changing two design variables on the objective function with fixing the third one.
4- Solving for the optimal design that minimize the objective function.

Procedures and purposes of each stage will be discussed in following subsections. In all stages, two major Matlab Codes are used that contain all equations, receive the variables and return back the objective function value. The first code is “Ns_eval.m”which evaluate the entropy generation number for a given design variables. Formulation of the first function is dependable on the form of the design variables used in the calling function at each stage. At some cases they are in vector form and at others in matrix form. If a vector form is used,"Ns_eval.m" will evaluate the objective function as a single value and return it back to the calling function. Also some deviation of the order of the design variables in the objective function evaluation depends on the calling function aims. In the second case which is conducted for stages (3) and (4), it is of a matrix form and the design variables are entered to "Ns_eval.m" as a matrix or array and the objective function will be returned back as a matrix. One main problem faced during composing"Ns_eval.m" in matrix form that it contains a logical testing for Reynolds Number values that define the flow regime of each stream. An "if" statement in Matlab for matrices will carry out the logical testing for the entire matrix to satisfy the conditions. In our case each value in these matrices should be tested separately and then used to evaluate the other parameters in the adjacent matrices entry. To overcome this problem, a " For " loop is used to call each entry in the Reynolds Number matrix and compute the other parameters in the adjacent matrices which will construct the objective function values matrix.

The second code "con_exp_coef.m" is used to evaluate the contraction and expansion loss coefficients using interpolation. It is called by "Ns_eval.m", receives Reynolds number and the ratio of the core minimum free-flow area to frontal area (σ) and return back $(K_{ic}\ and\ K_{ie})$.

These two Matlab codes or functions are used in all stages depending on the form of design variables which will be stated at each stage.

V. RESULTS AND DISCUSSION:

Results based on the solution procedures of the problem will be illustrated and discussed.

5.1. Single Design Variable Effect on the Objective Function:

Figures (2), (3), and (4) show the effect of each variable alone on the objective function keeping the other two constants. As expected based on the previous stage results, the design variables (x_1) and (x_2) could be optimized to define a minimum value of the objective function even when used separately or in opposite arrangement from the original paper work.

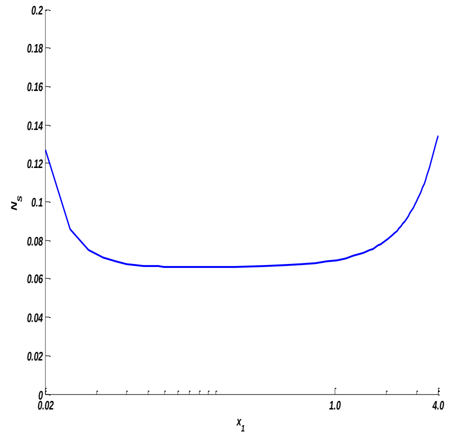

Figure (2) : The effect of the first design variable under study , x_1 (the channels spacing) , on the entropy generation number (the objective function)

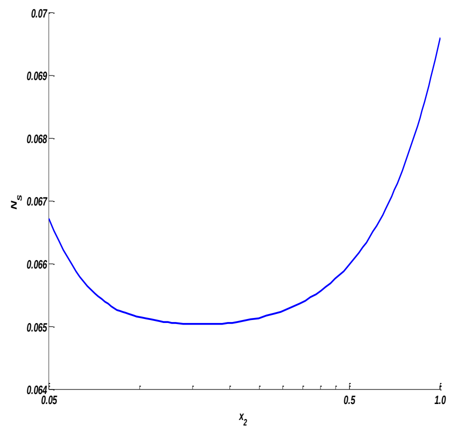

Figure (3) : The effect of the second design variable under study , x_2 (the cold stream channels length) , on the entropy generation number (the objective function)

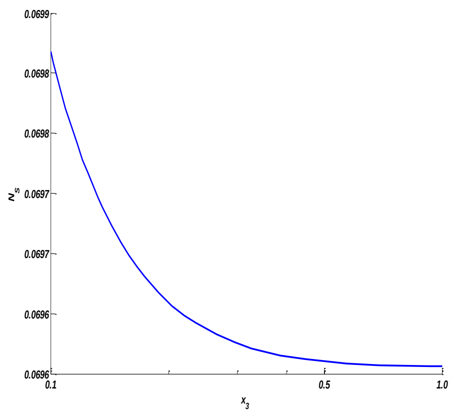

Figure (4) : The effect of the third design variable under study , x_3 (the height of the heat exchanger) , on the entropy generation number (the objective function)

The same could be shown clearly from figures (5) and (7) when they are plotted with different value of the other, with constant(x_3). Figures (4), (6), (8), (9), and (10) show the redundancy of using (x_3). as a design variable, in which the minimum value of the objective function is found to be at the higher design variable (x_3). limit.

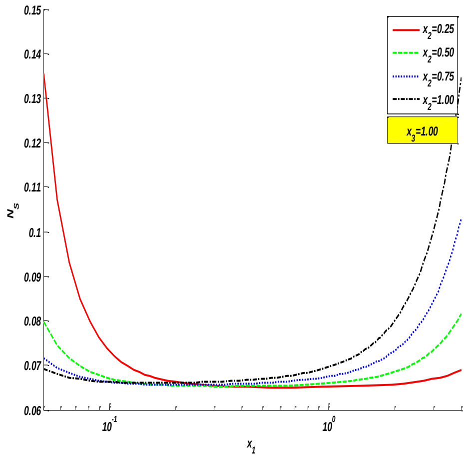

Figure (5) : The effect of the first design variable under study , x_1 (the channels spacing) , on the entropy generation number (the objective function) for different values of x_2 (the cold stream channels length)

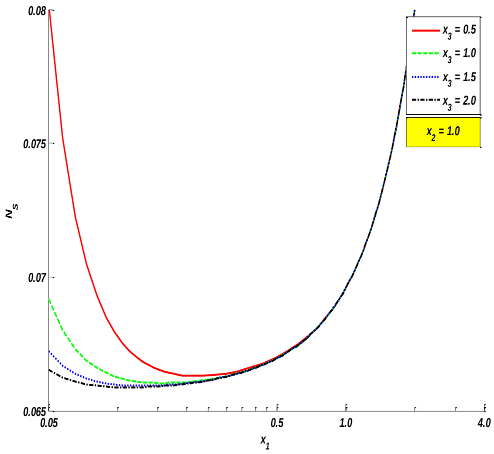

Figure (6) : The effect of the first design variable under study , x_1 (the channels spacing) , on the entropy generation number (the objective function) for different values of x_3 (the height of the heat exchanger)

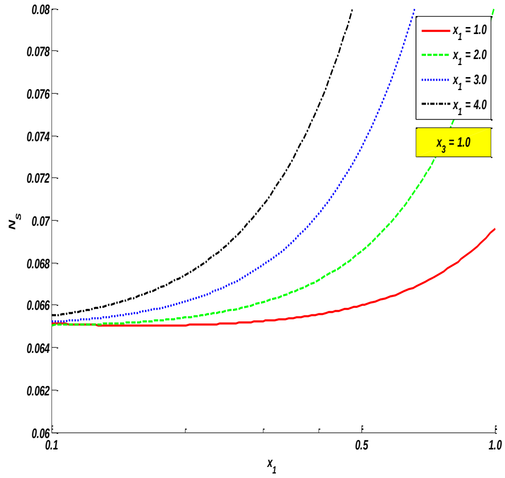

Figure (7) : The effect of the second design variable under study , x_2 (the cold stream channels length) , on the entropy generation number (the objective function) for different x_1 (the channels spacing)

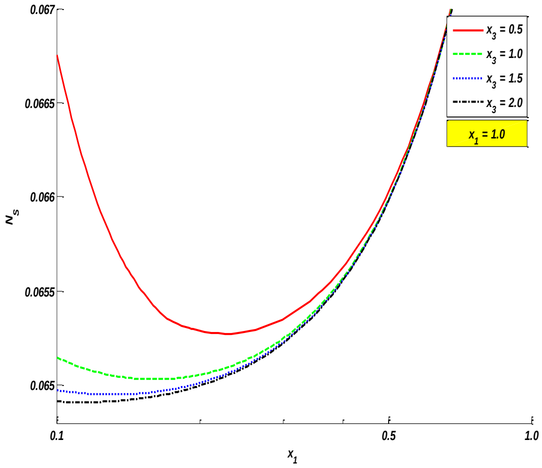

Figure (8) : The effect of the second design variable under study , x_2 (the cold stream channels length) , on the entropy generation number (the objective function) for different x_3 (the height of the heat exchanger)

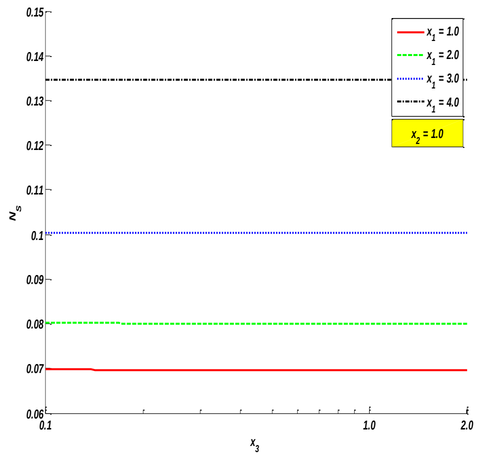

Figure (9) : The effect of the third design variable under study , x_3 (the height of the heat exchanger) , on the entropy generation number (the objective function) for different x_1 (the channels spacing)

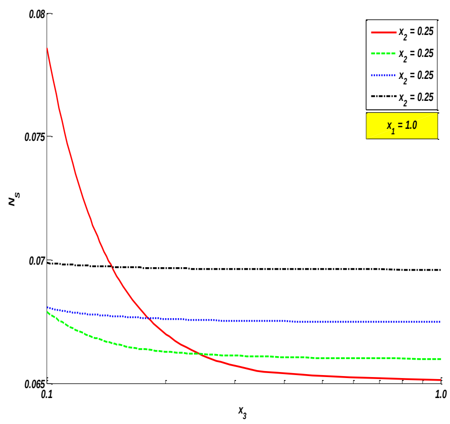

Figure (10) : The effect of the third design variable under study , x_3 (the height of the heat exchanger) , on the entropy generation number (the objective function) for different values of x_2 (the cold stream channels length)

5.2: Two Design Variables Effect on the Objective Function:

This stage is conducted to presents a better visualization of the same results discussed in the second stage. A contour and mesh plots are used for a three sets of two design variable combination shown in figures (11) to (16). The set of x_1 and x_2 combined together in a mesh matrices shown in figures (15) and (16), and they confirm the ability of optimizing both features together.

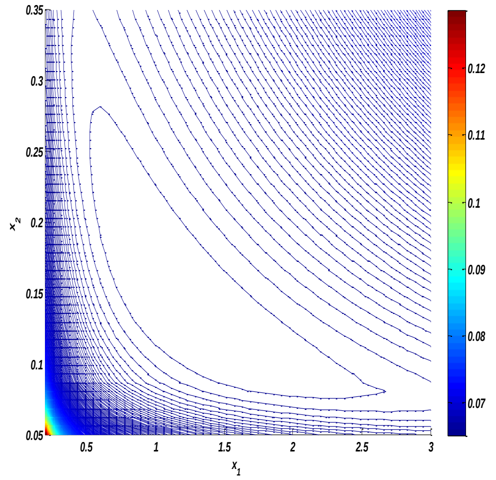

Figure (11): Function is to plot the entropy generation number (the objective function) contour for a mesh of x_1 (the channels spacing) and x_2 (the cold stream channels length).

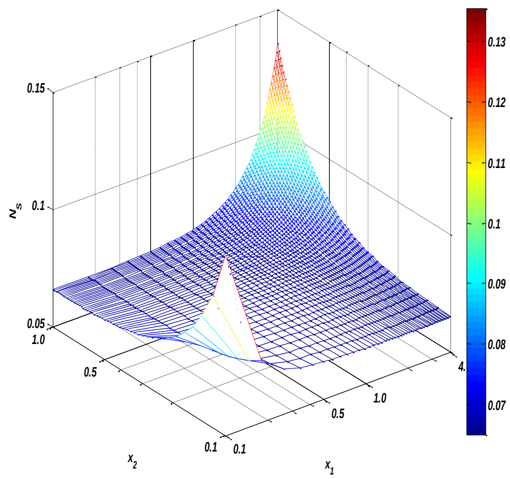

Figure (12): Function is to mesh plot the entropy generation number (the objective function) for a mesh of x_1 (the channels spacing) and x_2 (the cold stream channels length)

The redundancy of using x_3 as a design variable is confirmed by the rest figures (13 to 16), since the three design variables are independent of each other.

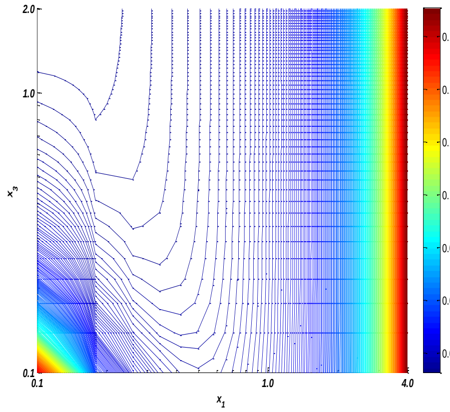

Figure (13) : Function is to plot the entropy generation number (the objective function) contour for a mesh of x_1 (the channels spacing) and x_3 (the height of the heat exchanger).

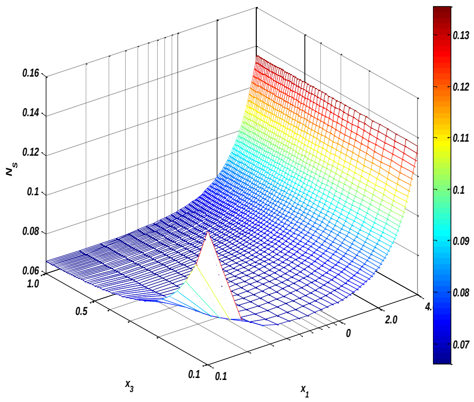

Figure (14) : Function is to mesh plot the entropy generation number (the objective function) for a mesh of x_1 the channels spacing) and x_3 (the height of the heat exchanger)

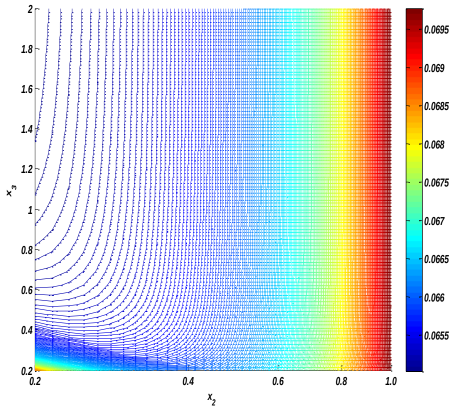

Figure (15): Function is to plot the entropy generation number contour for a mesh of x_2(the cold stream channels length) and x_3 (the height of the heat exchanger)

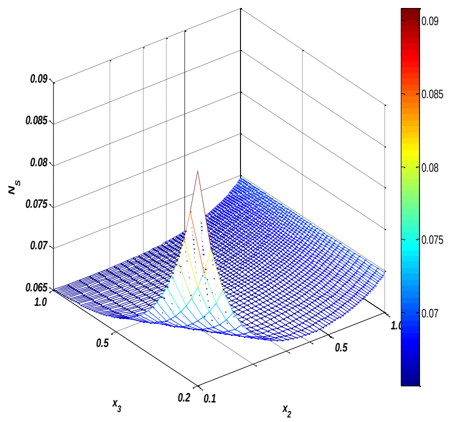

Figure (16): Function is to mesh plot the entropy generation number (the objective function) for a mesh of x_2 (the cold stream channels length) and x_3 (the height of the heat exchanger).

5.3: Optimal Design of the System:

By using the Matlab function "fmincon", the optimal solution of the system minimizing the objective function is defined. First using the three design variables together, the solution is:

$$x_{1,opt} = 1.9008$$
$$x_{2,opt} = 0.0713$$
$$x_{3,opt} = 2.0000$$
$$N_{S,\min} = 0.06491755$$

Which results the minimized value of the objective function at an optimal x_1 and $x_2$and the biggest limit value of x_3.
Keeping x_3 at constant value x_3=1.0, will result an optimal design for the system at fixed height, and the optimal is:

$$x_{1,opt} = 1.9082$$
$$x_{2,opt} = 0.1048$$
$$x_{3,\ fixed} = 1.0000$$
$$N_{S,\min} = 0.06505656$$

Which indicate that to define an optimal design for the system, the system could be optimized using x_1 and x_2 as design variables with considering the maximum value for x_3 as a given parameter of the system.

VI. CONCLUSION:

The main conclusion of this work is that, a single pass, parallel-plate, cross-flow heat exchanger geometrical features could be optimized in order to minimize the Entropy Generation Number subjected to physical and geometrical constraints.

The redundancy of some design variables could assist the designer to minimize the degree of freedom further more of the optimization problem, since it could be set as a constant value at the geometrical limitation (lower or upper limit) depending on the behavior of the objective function for such variables.

Physical understanding of the optimized system geometrics, operation, and process governing equations is a great advantage in solving the optimization problem. Furthermore, in some specific cases using the equality constraints to define physical variables could reduce the complexity of the problem hence it could decrease the degree of freedom for the optimized system.

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Hasan A. Alzanki" Optimal Design of Parallel-Plate, Cross-Flow Heat Exchanger Minimizing the Entropy Generation" International Journal of Engineering Research and Applications (IJERA), Vol. 09, No.05, 2019, pp. 01-07