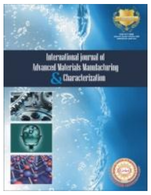

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Design Optimization of Perforated Plate Heat Exchangers using Genetic Algorithm

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ABSTRACT

Perforated plate heat exchangers (PPHEs) come under the category of compact heat exchanger; offering high effectiveness, large surface area per unit volume (as high as 6000 m^2/m^3) and better flow characteristics. PPHEs are constructed of alternately arranged perforated plates and spacers. Heat exchanging fluids flow through the holes of the plates and exchange heat by conduction through the plate material. Spacers help minimizing axial conduction and reheadering of fluids intermittently. Design of a compact heat exchanger is targeted for high effectiveness, low volume and minimum pressure drop. Performance of a PPHE depends on many design variables such as plate thickness, spacer thickness, pore diameter, porosity etc. For a given heat duty, these parameters can be optimized for maximizing effectiveness, minimizing volume and minimizing or limiting pressure drop.In this paper an attempt has been made for optimization of the design variables of a PPHE so that effectiveness of the heat exchanger per unit volume is maximized under the constraints of fluid pressure drop and length of the heat exchanger. Unlike the conventional approach, importance is given to the length of the heat exchanger which is limited to the available space inside the vacuum chamber of the diffusion bounding machine or the space available in a specific application. Using the given length of the heat exchanger and allowable pressure drop, the problem has been defined in unconstrained form and solved by Genetic algorithm.

Introduction

Heat exchanger is a device which is used to exchange heat between two or more flowing fluids that are at different temperatures and separated by a solid wall. Design of a heat exchanger is usually targeted for high effectiveness while observing limitations to the frictional pressure drop and to the size or volume of the heat exchanger. Design of cryogenic heat exchangers are complicated by axial conduction heat loss, fluid and material property variation with temperature and heat in-leak from surroundings [1-2].

Because of high cost of refrigeration at low temperature, cryogenic heat exchangers should be designed for high effectiveness (>90%). They should be compact so that i) space requirement is reduced and ii) heat in-leak through the outer surface area of the heat exchanger is minimized.Compact heat exchanger that can be used in cryogenic process plants are compact shell and tube, louvered fin, matrix type (using perforated plates or wire screens) diffusion bonded plate heat exchangers, and other types using micro machined surfaces. Because of their high surface area density, better fluid flow characteristics, low axial heat conduction and manufacturing advantages over many other types of compact heat exchangers, perforated plate heat exchangers (PPHEs) (which are also known as matrix heat exchangers) have become attractive for cryogenic applications. Construction wise a PPHE comprises a stack of alternate layers of high thermal conductivity perforated plates and low thermal conductivity insulating spacers as illustrated in Fig. 1. While heat exchange from one fluid to the other takes place through the plates, the spacers minimize heat loss due to axial conduction and reducing the effect of flow mal-distribution through continuous reheadering. Further details about the working principle of the perforated plate heat exchangers are available in ref. [1-2].

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The design variables of a heat exchanger are optimized with one or more of the following objectives: i) maximization of effectiveness ii) minimization of the volume and/or iii) minimization of pressure drop. However, the expressions for the objective function, design vector elements and constraints depend on the geometry and configuration of particular heat exchanger which is to be optimized. G Venkatarathnam and his co-workers [3-4] optimized PPHEs by minimizing the volume of the heat exchanger for a given effectiveness while fully utilizing the allowable pressure drop. Optimization was based on a closed from analytical expression. Lagrangian multiplier technique was used to convert constrained optimization problem to an unconstrained one and found the optimum values of Ntu_{f1}, Ntu_{f2} and Ntu_{po} for a given effective NTU and pressure drop by solving the formed Lagrangian equations. Using optimum values of Ntu_{f1}, Ntu_{f2} and Ntu_{po} they calculated the number of plates and optimum dimensions of the plate i.e channel height, width, plate thickness, spacer thickness, pore diameter and porosity.

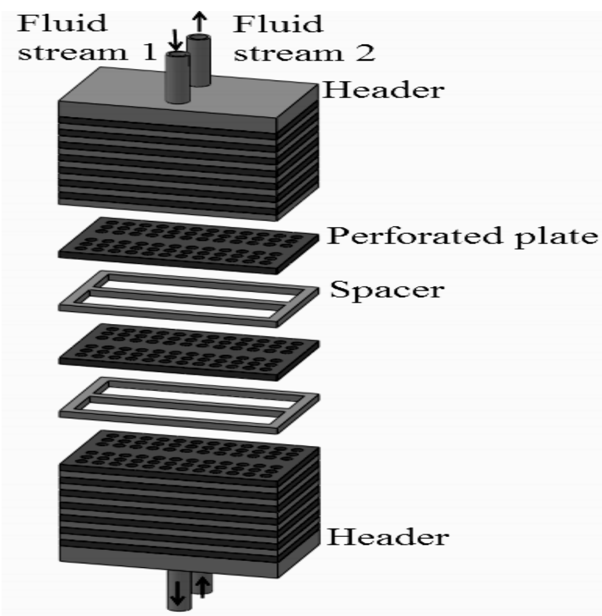


Figure 1. Perforated plate heat exchanger

GongnanXie [5] presented minimization of total weight of fin and tube heat exchangers with the help of binary coded genetic algorithm. Ibrahim Ozkol [6] carried out maximization of NTU and minimization of pressure drop of plate finned-tube heat exchanger with genetic algorithm. Jose M. Ponce-Ortega [7] implemented Genetic algorithm to minimize total annual cost of shell and tube heat exchangers. Yu Wang [8] attained maximization of heat transfer capacity and minimization of pressure drop of slotted fin by coupling genetic algorithm with numerical simulation. FatemehJoda [9] minimized total annual cost of multi-stream plate fin heat exchangers using genetic algorithm.

In this paper an attempt has been made for optimization of the design variables of a PPHE so that effectiveness of the heat exchanger per unit volume is maximized under the constraints of fluid pressure drop and length of the heat exchanger. Unlike the conventional approach, importance is given to the length of the heat exchanger which is limited to the available space inside the vacuum chamber of the diffusion bounding machine or the space available in a specific application. Using the given length of the heat exchanger and allowable pressure drop, the problem is defined in unconstrained form and solved by Genetic algorithm.

Methodology

Design optimization of a PPHE is carried out based on the following user defined input parameters:

1) Hot fluid: mass flow rate, inlet temperature and inlet pressure.
2) Cold fluid: mass flow rate, inlet temperature and inlet pressure.
3) Allowable pressure drop in LP and HP side of the heat exchanger.
4) Length of the heat exchanger.

The problem is defined and solved by using non-linear constrained optimization (Maximization) model to find out the optimum values of design parameters of PPHE. Optimization procedure will be presented on both rectangular and circular geometry.

Assumptions:

i. The allowable pressure drop on the low-pressure side is utilized fully.
ii. The thermo physical properties do not vary along the length of the heat exchanger.

Objective function

In the proposed model, effective NTU per unit volume of the heat exchanger is maximized and considered as the objective function. This objective function has been formulated based on the closed form analytical expressions developed by Venkatarathnam [1]. Considering balanced flow, objective function for a single plate-spacer unit of a heat exchanger can be expressed as

$$\text{Objective function} \quad f = \left(\frac{Ntu_{eff}}{V}\right)_{\text{Unit plate-spacer}} \qquad (1)$$

$$f = \frac{\left(\dfrac{(1-\alpha_1)(1-\alpha_2)}{\lambda'(1-\alpha_1)(1-\alpha_2)+1-\alpha_1\alpha_2+(1-\alpha_1)(1-\alpha_2)/ntu_{po}}\right)}{V_{(t_p+t_s)}} \qquad (2)$$

Figure 2.Nomenclature of plates.

Where $\alpha_i = \exp(ntu_{f,i})$; $\lambda' = \dfrac{k_s b(3w+4H+6b)}{t_s(\dot{m}c_p)}$ (3)

$$ntu_{po} = \left[\frac{1}{F\, ntu_{p1}} + \frac{1}{\lambda_p} + \frac{1}{F\, ntu_{p2}}\right]^{-1} \qquad (4)$$

Using nomenclature given in Fig. 2, volume of a set of plate and spacer $V_{(tp+ts)}$ is:

for rectangular geometry $V_{(t_p+t_s)} = (W + 2b)(2H + 2b + s)(t_p + t_s)$ (5)

for circular geometry

$$V_{(t_p+t_s)} = \pi(r_o + b)^2(t_p + t_s) \quad (6)$$

Design vector

Design vector is a set of variables which control the value of the objective function. Design variables considered for rectangular geometry are perforation diameter d, plate thickness t_p, spacer thickness t_s, porosity p, channel height to width ratio E, and for circular geometry perforation diameter d, plate thickness t_p, spacer thickness t_s, and porosity p. Individual terms in eq. (2) are expressed as function of these variables

$$ntu_{f,i} = \frac{hA}{\dot{m}c_p} \quad (7)$$

Where convective heat transfer coefficient h is estimated from the relation for Colburn (j) factor [10]. Heat transfer area for rectangular geometry

$$A=2(W\,H) \times (1-p) + \pi d t_p n_h \quad (8)$$

and for plate ntu

$$ntu_{p1} = ntu_{p2} = \frac{W t_p k_e}{H\,\dot{m}c_p} \quad (9)$$

effective thermal conductivity of perforated plate k_e in eq. (9) was estimated using the relation [11]

$$\frac{k_e}{k_p} = 1 - \frac{2p}{1 + p - \frac{0.075422p^6}{1-(1.060283\,p^{12})} - \frac{0.000076\,p^{12}}{1}}$$

$(0 < p < 0.8)$ (10)

Lateral conduction parameter in the separating wall

$$\lambda_p = \frac{k_e t_p W}{s\,\dot{m}c_p} \quad (11)$$

Table. Specifications of a problem

	Hot stream	**Cold stream**
Mass flow rate, m	1.0 g/s	1.0 g/s
Heat capacity ratio, γ	1.0	1.0
Inlet temperature	300 K	80 K
Density of fluid, ρ	4.72 kg/m^3	0.48 kg/m^3
Specific heat of helium, c_p	5.26 kJ/kg K	5.26 kJ/kg K
Thermal conductivity of helium, k	118.5 mW/m K	118.5 mW/m K
Viscosity of helium, μ	15 μpa s	15 μpa s
Width of separating wall, s	1 mm	1 mm
Width of boundary wall, b	2 mm	2 mm

The value of geometry factor F in eq. (4) is 3 for rectangular geometry and 8 for circular geometry.

Pressure drop in a heat exchanger is expressed as

$$\Delta p = 4f\frac{L}{d}\frac{G^2}{2\rho} \quad (12)$$

friction factor (f) in eq. (12) was calculated using the relation given in [10]

Equivalent equations of eq. (3), (8), (9) and (11) for circular geometry are as follows [1]

$$\lambda' = \frac{k_s \pi b(r_o+r_i)}{t_s(\dot{m}c_p)} \quad (13)$$

$$A= 2\,\pi\,r_i^2\,(1\text{-}p) + n_h \pi\,d\,t_p \quad (14)$$

$$ntu_{p1} = ntu_{p2} = \frac{\pi t_p k_e}{\dot{m}c_p} \quad (15)$$

$$\lambda_p = \frac{2k_p t_p \pi}{(\dot{m}c_p)\ln\left[\frac{r_i+b}{r_i}\right]} \quad (16)$$

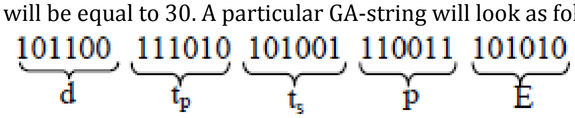
Constraints

Lower limit of the constraints are usually decided from the manufacturing capability and market availability points of view. The upper limit, however, is decided based on good engineering judgment. The lower and upper limits of design parameters are shown in Table 1. Total pressure drop in heat exchanger in LP side is assumed as 1500 pa. The heat exchanger is to be fabricated by diffusion bonding. In the present problem we take length of the heat exchanger as 100 mm; based on the diffusion bonding facility available in the Centre i.e L = 100 mm.

Solution using genetic algorithm

A GA has been used here for optimization of the PPHE. These references [12-14] are useful for understanding the principle of GA. Optimization of PPHE is carried out with a problem with details given in Table 2. Helium is used as the working fluid. Copper is the preferable material for perforated plate and stainless steel for spacer.Thermal conductivity of plate and spacer material is taken as 400 and 12 W/m K respectively. The width of the boundary wall is taken as 2 mm and 1 mm for separating wall. Five parameters t_p, t_s, d, p and factor E in the case of rectangular geometry and t_p, t_s, d and p in the case of circular geometry are selected for optimization of PPHE.

The GA starts with a population of possible solutions (different options of PPHE geometry in the present case), which are generated at random. Let us assume that a GA-string carries information of five geometrical parameters of a PPHE (i.e. d, t_p, t_s, p and E). These five parameters are coded within the chromosome. The field size of each parameter is chosen as 6. As there are five parameters, the total length of the chromosome will be equal to 30. A particular GA-string will look as follows:



The first six bits, that is (101100) yields the decoded value (DV) as $1\times2^5+0\times2^4+1\times2^3+1\times 2^2+0\times2^1+0\times2^0$ = 44. The real value of d can be determined following the linear mapping rules as given below:

$$d = d_{min} + \frac{d_{max}-d_{min}}{2^{field\ size}-1} \times DV \qquad (17)$$

The real values of other variables can also be calculated following the similar procedure. After determining the real values of the design variables, the fitness values of all members of the population are calculated. In the present context, the fitness value is nothing but $(Ntu_{eff}/V)_{unit\ plate\text{-}spacer}$ of PPHE. The better solutions from the present population poll are selected for the next operations by Crossover and Mutation as represented in Fig. 3. To exchange properties between two parents, crossover operator is used. Mutation operation is then performed to introduce some diversity in the solution space and to avoid convergence in the local optima. Once the new population is obtained through crossover, it is subjected to mutation to bring some local changes around the current solutions. The above basic steps are repeated for a large number of generations, so that globally optimized solutions are obtained. Fig. 4 presents the flow diagram by using GA principle.

Table 3. Optimized values of rectangular and circular geometries

	rectangular	circular
NTU_{eff} / V	7.29×10^4	6.75×10^4
Effectiveness	0.93	0.92
Volume	197.5 cm^3	172.4 cm^3
Number of plates	132	133
Width of the channel, W / Outer radius, R_o	75.9 mm	21.4 mm
Height of the channel, H / Inner radius, R_i	9.8 mm	14.6 mm
Perforation diameter, d	0.52 mm	0.58 mm
Plate thickness, tp	0.42 mm	0.44 mm
Spacer thickness, ts	0.34 mm	0.31 mm
Porosity, p	0.29	0.29
Channel height to width ratio, E	0.13	---

Step-wise execution of Genetic algorithm

i. Initialization of Population size, Crossover probability, Mutation probability.
ii. The initial population is randomly generated.
iii. Select the fitness function, here the fitness function is $(NTU_{eff} / V)_{unit\ plate\text{-}spacer}$.
iv. Evaluate the fitness value of the initially generated population.
v. Select the individuals from current population having better fitness values.
vi. Perform crossover and mutation operations among the selected individuals to generate new population.
vii. Find out the fitness values of newly generated population.
viii. Repeat the steps from (v) to (vii) till convergence attained.
ix. Display optimized values.

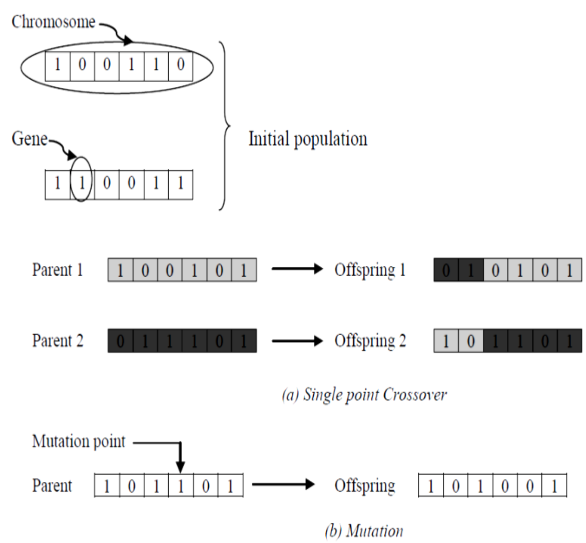


Figure 3.representation of (a) Single point Crossover and (b) Mutation

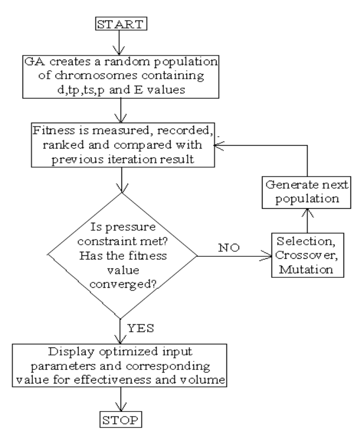


Figure 4. Flow chart of a simple coded GA

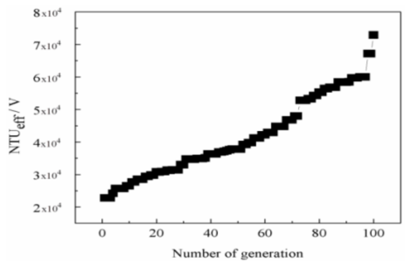


Figure 5.GA results.

Optimized GA results are shown in Fig.5. The effectiveness and volume of a PPHE of rectangular (two channel) and circular geometries for the same length are compared and given in Table3

Conclusion

This paper presents the successful application of genetic algorithm for optimal design of perforated plate heat exchanger. In a given problem effective NTU to volume ratio of plate-spacer unit is maximized. The optimization results reveal that for same length of heat exchanger effective NTU to volume ratio of rectangular geometry is more than that of circular geometry.

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Nomenclature

A = heat transfer surface area, m^2
A_f = flow area, m^2
b = width of the boundary wall, m
d = perforation diameter, m
E = channel height to width ratio (H/W)
F = geometric factor
G = mass flux, kg/m^2
H = Plate height in any channel, m
h = convective heat transfer coefficient, W/m^2 K
k_e = effective thermal conductivity of perforated plate, W/m K
K_p = thermal conductivity of plate material, W/m K
k_s = thermal conductivity of spacer material, W/m K
m = mass flow rate, kg/s
n = number of plates
n_h = number of holes in a channel
$ntu_{f,i}$ = fluid ntu per stream
$ntu_{p,i}$ = dimensionless plate conductance
$ntu_{p,o}$ =overall dimensionless plate conductance
NTU_{eff} = Effective NTU
p = plate porosity
r_i = inner channel radius of a circular PPHE, m
r_o = outer channel radius of a circular PPHE, m
s = width of the separating wall, m
t_p = plate thickness, m
t_s = spacer thickness, m
V = heat exchanger volume, m^3
W = Plate width, m

Greek Letters
α = intermediate parameter
ΔP = pressure drop in the low-pressure channel, Pa
λ = overall axial conduction parameter
λ_p= dimensionless lateral conductance of the separating wall
μ = viscosity of the fluid (Pa. s)
ρ = density of the fluid (kg/m^3)

Subscripts
1 = cold fluid
2 = hot fluid
eff = effective