

OPTIMIZATION OF PLATE-FIN HEAT EXCHANGER USING ADAPTIVE DIFFERENTIAL EVOLUTION JADE

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Abstract. In this work, a plate-fin heat exchanger is optimized through the Adaptive Differential Evolution JADE method. The plate-fin heat exchangers are widely used in industrial applications such as cryogenics, microturbines, vehicle and various chemical process. This heat exchanger topology has high thermal efficiency, high heat transfer area per unit volume and high thermal conductivity. Adaptive Differential Evolution JADE is an evolutionary algorithm with self-adjustable parameters derived from the differential evolution. This method, presented to the scientific community in 2009, has a mutation strategy based on the neighborhood and an optional external file aiming to improve the convergence of the method of differential evolution. The traditional approach of the design of this heat exchanger involves several geometric parameters and operational constraints. The geometric parameters used in the optimization were heights, thicknesses, lengths, fin density and the amount of overlap of fins and the operational restriction of amount of heat to be exchanged. The optimization aimed the minimization of the total annual cost of the plate-fin heat exchanger and their results were compared with the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The results of the 50 independent experiments demonstrate improvements up to 11.80% when compared to the GA and up to 10.93% when compared with the PSO.

Keywords: differential evolution, evolutionary algorithm, plate-fin heat exchanger

1. NOMENCLATURE

A_{tot}	heat exchanger surface area (m ²)	ΔP	pressure drop (N.m ⁻²)
A_{ff}	free flow area (m ²)	Q	heat duty (W)
C	heat capacity rate (W.K ⁻¹)	Re	Reynolds number
φ	specific heat (J.kg ⁻¹ .K ⁻¹)	s	fin spacing(m)
D_h	hydraulic diameter (m)	t	fin thickness (m)
f	Fanning friction factor	T	temperature (K)
G	mass flux velocity (kg.m ⁻² .s ⁻¹)	<i>Greek letters</i>	
h	heat transfer coefficient (W.m ⁻² .K ⁻¹)	ε	effectiveness
H	height of the fin (m)	μ	viscosity (N.m ⁻² .s ⁻¹)
j	Colburn factor	ρ	density (kg.m ⁻³)
l	lance length of the fin (m)	<i>Subscripts</i>	
L	heat exchanger length (m)	c	cold stream
m	mass flow rate (kg.s ⁻¹)	h	hot stream
n	fin frequency	i	inlet
N	number of fin layers	min	minimum
NTU	number of transfer units	max	maximum
P	pressure (N.m ⁻²)	o	outlet
Pr	Prandtl number		

2. INTRODUCTION

The transfer of heat between different medias has several applications in the real world and the equipment used to accomplish that consists in the heat exchangers. There are innumerable types of heat exchangers, but one that presents high place among others is the compact heat exchanger, which can be plate-fin or tube-fin type (Rao and Patel, 2010). Cross-flow plate-fin exchangers are used in several industrial processes, especially in gas-to-gas applications such as cryogenics, micro-turbines, automobiles, chemical process plants, naval and aeronautical applications (Xie et al., 2008; Mishra et al., 2009; Rao and Patel, 2010).

Cross-flow plate-fin heat exchangers presents some important characteristics that may be considered by any designer such as high thermal conductivity, large heat transfer surface area per unit of volume and high thermal effectiveness that determinate a reduction of space and energy requirement, weight, and cost (Xie et al., 2008; Rao and Patel, 2010).

The design of plate-fin heat exchangers consists in the determination of several geometrical parameters under certain constraints. The most used geometrical parameters for optimization of this type of heat exchanger is the length, height, thickness of the fins along with lance length of fins, fin frequency and number of fin layers, all these for the hot and cold fluids involved into the process.

Currently, evolutionary algorithms were helpful to solve optimization problems that presents several characteristics, for example: non-linearity, non-convexity, non-continuity, non-differentiability and multi-modality (Mohamed, 2015). In general, evolutionary algorithms took inspiration by natural mechanisms of evolution where the exploration and the exploitation of the search space through selection and reproduction operators (Engelbrecht, 2006). Among these techniques, one of the most effective is the Differential Evolution that consists in a stochastic population-based search technique presented by Storn & Price in 1997 (Storn and Price, 1997) that was posteriorly modified for self-adaptation of control parameters by Zhang & Sanderson in 2009 (Zhang and Sanderson, 2009) in the called Adaptive Differential Evolution with Optional External Archive (JADE) that aim enhance the convergence of the original method.

There are many previous studies about the optimization of plate-fin heat exchangers (PFHEs). Xie et al. (2008) proposed the optimization of this heat exchanger using Genetic Algorithms using an objective function of minimization of total annual cost, Mishra et al. (2009) investigated the optimization of plate-fin heat exchangers using GA for the minimization of the entropy generation units where one conclusion was the direct relation to the value of the objective function with the pressure drops for both components of the system.

Peng et al. (2008) with the use of the Particle Swarm Optimization (PSO) optimized this type of heat exchanger utilizing a cost objective function. Posteriorly, Rao and Patel (2010) investigated the same case of Mishra et al. (2009) utilizing PSO where better results, about 16% of reduction in the value of entropy generation units, was reached. After, Ghosh et al (2011) applied the GA for the maximization of heat load through the improvement of the stacking pattern.

Other authors can be cited such as Yousefi et al. (2011, 2012, 2013) where the minimization of the heat transfer area and pressure drops were taken into account using Genetic Algorithm hybrid with Particle Swarm Optimization (GAPSO) and Harmony Search Algorithm (HSA), and Imperialist Competitive Algorithm (ICA) for the minimization of entropy generation units. Lately, Zarea et al. (2014) proposed the optimization of the plate-fin heat exchanger through the Bees Algorithms (BA) for the maximization of effectiveness and minimization of entropy generation units.

A closer look at the previous works allow to verify that the most investigated objectives functions for this heat exchanger concerns about the minimization of entropy generation units and total annual cost.

The main objectives of this study are at first to optimize the influential parameters of plate-fin heat exchangers from economic point of view and, for second, to demonstrate the effectiveness of JADE and Tsallis JADE (TJADE) in the design optimization of PFHEs from economic point of view. The results obtained with both algorithms for the case study are compared with other studies that already analyzed the same case.

3. THERMAL MODELLING, OPTIMIZATION TECHNIQUES AND OBJETIVE FUNCTION

The following sections presents the mathematical aspects of the plate-fin heat exchanger, the characteristics of the optimization methods applied in this work and the objective function aimed for the minimization of total annual cost.

3.1 Thermal modelling of plate-fin heat exchangers

The Fig. (1a) presents the configuration of a plate-fin heat exchanger from the macro point-of-view while Fig (1b) presents some geometrical parameters of the strip, in a micro point-of-view, of this heat exchanger.

From the Fig.1 it can be seen the crossflow aspect that is inherent to this tipology of heat exchanger along with the multiple layers for both fluids streams that participates in the heat transfer of the system.

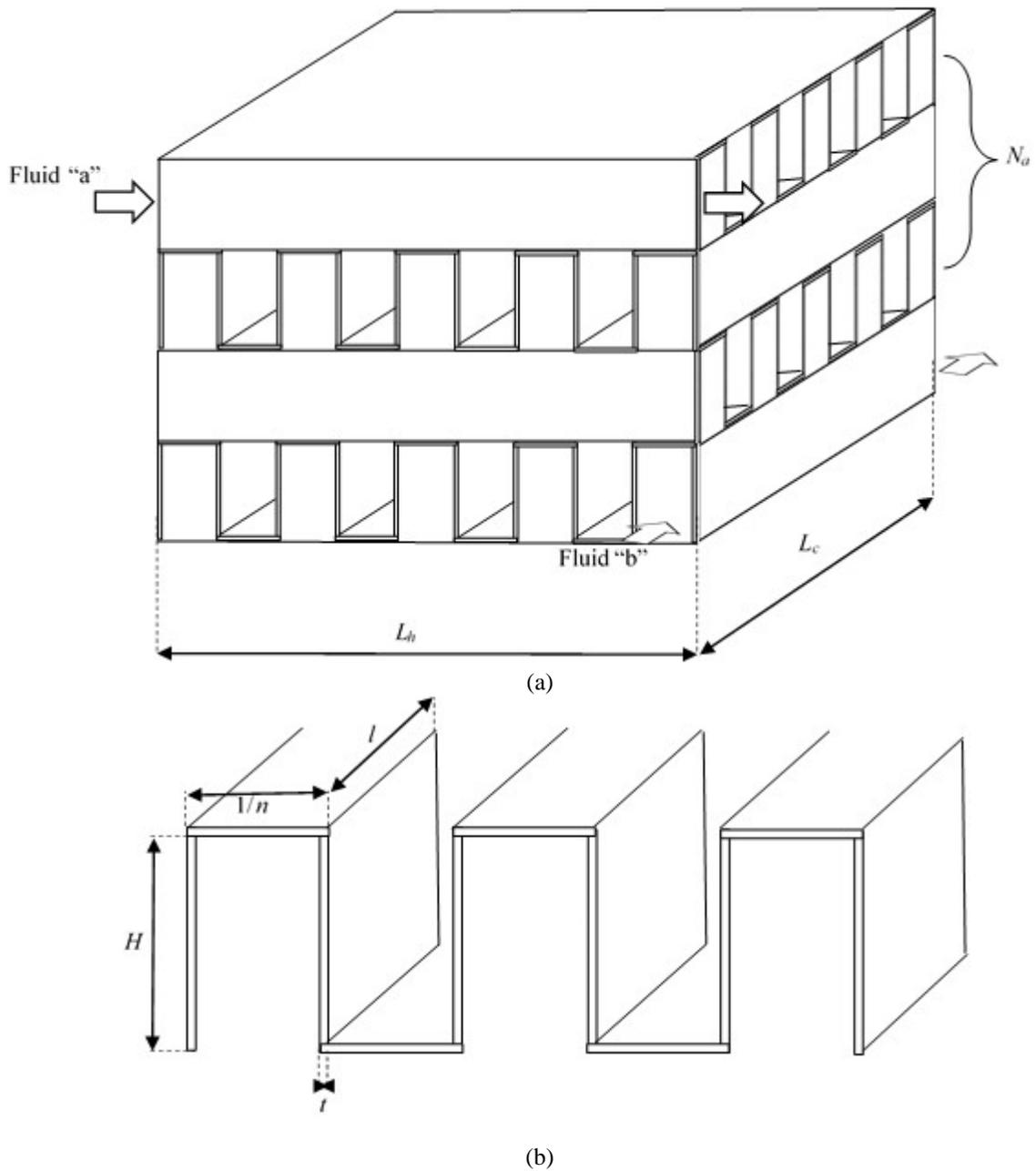


Figure 1. Configuration and strip of a plate-fin heat exchanger.

The following calculations were taken from Zarea et al. (2014) and some adaptations were made considering additional references such as Mishra et al (2009).

Considering a cross-flow plate-fin heat exchanger with both fluids unmixed, the heat transfer rate is calculated by Equation 1,

$$Q = \varepsilon C_{min}(T_{hi} - T_{ci}) \tag{1}$$

where ε is the effectiveness, C_{min} is the minimum heat capacity rate and T_{hi} and T_{ci} are the inlet temperatures of the hot and cold fluids, respectively.

The effectiveness is given by Equation 2,

$$\varepsilon = 1 - \exp(C_r^{-1} NTU^{0.22} (\exp(-C_r NTU^{0.78}) - 1)) \tag{2}$$

where $C_r = C_{min} / C_{max}$ and NTU is the number of transfer units determined from Equation 3,

$$\frac{1}{NTU} = C_{min} \left(\frac{Aff_h}{j_h \varrho_h Pr_h^{-0.667} \dot{m}_h A_h} + \frac{Aff_c}{j_c \varrho_c Pr_c^{-0.667} \dot{m}_c A_c} \right) \quad (3)$$

where Aff is the free flow area, A is the heat transfer area, j is the Colburn factor, ϱ is the specific heat and Pr is the Prandtl number for each fluid, hot and cold.

The free flow areas can be obtained from Equations 4 and 5,

$$Aff_h = (H_h - t_h) (1 - n_h t_h) L_c N_h \quad (4)$$

$$Aff_c = (H_c - t_c) (1 - n_c t_c) L_h N_c \quad (5)$$

where H is the height of the fin, t is the fin thickness, n is the fin frequency, L is the heat exchanger length and N is the number of fin layers for each fluid, remembering that $N_b = N_a + 1$.

The heat exchangers areas are given by Equations 6 and 7,

$$A_h = L_h L_c N_a (1 + (2n_h (H_h - t_h))) \quad (6)$$

$$A_c = L_h L_c N_b (1 + (2n_c (H_c - t_c))) \quad (7)$$

where the total heat exchanger area $A_{tot} = A_h + A_c$.

The Colburn factor is determined by Equations 8 and 9,

$$j = 0.53 Re^{-0.5} \frac{l}{dh}^{-0.15} \frac{s}{H-t}^{-0.14}, Re \leq 1500 \quad (8)$$

$$j = 0.21 Re^{-0.4} \frac{l}{dh}^{-0.24} \frac{t}{dh}^{-0.02}, Re > 1500 \quad (9)$$

where Re is the Reynolds number, l is the lance length of the fin, dh is the hydraulic diameter and the fin spacing $s = t - l/n$ for hot and cold fluids.

The Reynolds number for each fluid of the system can be obtained from Equation 10,

$$Re = \frac{\dot{m} dh}{Aff \mu} \quad (10)$$

where \dot{m} is the mass flow rate and μ is the viscosity of each fluid, remembering that $G = \dot{m}/Aff$

The hydraulic diameter can be determined for both fluids by Equation 11,

$$dh = \frac{2(s-t)(H-t)}{s+H-t + \left(\frac{H-t^2}{l}\right)} \quad (11)$$

Also, the frictional pressure drops for the two streams are given by Equations 12 e 13,

$$\Delta P_h = \frac{2f_h \dot{m}_h^2 L_h}{\rho_h dh_h L_c^2 N_h^2 (H_h - t_h)^2 (1 - n_h t_h)^2} \quad (12)$$

$$\Delta P_c = \frac{2f_c \dot{m}_c^2 L_c}{\rho_c dh_c L_h^2 N_c^2 (H_c - t_c)^2 (1 - n_c t_c)^2} \quad (13)$$

where f is the fanning friction factor, determined by Equations 14 and 15,

$$f = 8.12 Re^{-0.74} \frac{l}{dh}^{-0.41} \frac{s}{H-t}^{-0.02}, Re \leq 1500 \quad (14)$$

$$f = 1.12 Re^{-0.36} \frac{l}{dh}^{-0.65} \frac{t}{dh}^{-0.17}, Re > 1500 \quad (15)$$

The convective heat transfer coefficient for both fluid can be determined by Equation 16,

$$h = j \varrho Pr^{\frac{2}{3}} \frac{\dot{m}}{Aff} \quad (16)$$

The outlet pressures and temperatures are given by Equations 17, 18, 19 and 20,

$$P_{ho} = P_{hi} - \Delta P_h \quad (17)$$

$$P_{co} = P_{ci} - \Delta P_c \quad (18)$$

$$T_{ho} = T_{hi} - \left(\varepsilon \frac{C_{min}}{C_{max}} (T_{hi} - T_{ci}) \right) \quad (19)$$

$$T_{co} = T_{ci} + \left(\varepsilon \frac{C_{min}}{C_{max}} (T_{hi} - T_{ci}) \right) \quad (20)$$

for both fluids.

3.2 JADE and Tsallis JADE (TJADE)

A global optimization problem can be defined as Equation 21 (Mohamed, 2015),

$$\min f(x), x = [x_1, x_2, \dots, x_D]; S.t. x_j \in [a_j, b_j], \forall j=1, 2, \dots, D \quad (21)$$

where f is the objective function, x is the variables vector and a_j and b_j are the upper and lower boundaries, respectively.

The JADE basics implementation consists in the same that Differential Evolution (DE), that is generate a random population, NP vectors x , $\forall i=1, 2, \dots, NP$, within the boundaries. These individuals are evolved by operators of mutation and crossover to generate trial vector. Then, a comparison between the parent and its trial vector is made to select the vector which should survive to the next generation (Storn and Price, 1997; Mohamed, 2015). After, four major steps can describe the process of evolution of the algorithm: initialization, mutation, crossover and selection.

The initialization starts with an randomly generation of initial individuals within the boundaries as in Equation 22,

$$x_{ij}^0 = a_j + rand_j(b_j - a_j) \quad (22)$$

where $rand_j$ denotes a uniform distribution between $[0, 1]$ generating new values for each decision parameter or variable.

The major difference between JADE and DE is that the mutation occurs at each generation, G , for each target vector, x_i^G , where a mutant vector, v_i^G , is generated considering multiple optimal solutions according to Equation 23 (Wang and Zhao, 2013),

$$v_i^G = x_i^G + F_i(x_{best}^G - x_i^G) + F_i(x_{r1}^G - x_{r2}^G), r1 \neq r2 \neq i \quad (23)$$

with x_{best}^G selected between the p best members of the population where $p \in [0, 1]$ while x_i^G and x_{rj}^G is randomly chosen from the population and x_{r2}^G is randomly chosen between the union of the population and the external archive. The external archive is a selection of the rest of the individual members that were not the best member in the previous population which size is not superior to the size of the actual population. At each generation the scale factor F and the crossover CR are determined by Cauchy and Gaussian distributions with variation equal to 0.1 according to Equations 24 and 25,

$$F_i = rand_{Cauchy}(\mu_F, 0.1) \quad (24)$$

$$CR_i = rand_{Gaussian}(\mu_{CR}, 0.1) \quad (25)$$

where μ_F and μ_{CR} are the mean values of the factor scale and crossover. Both parameters are initialized with value equal to 0.5 and actualized at the end of each generation according to Equations 26 and 27,

$$\mu_F^{G+1} = (1-c)\mu_F + mean_L(S_F)c \quad (26)$$

$$\mu_{CR}^{G+1} = (1-c)\mu_{CR} + mean_A(S_{CR})c \quad (27)$$

where $c \in [0, 1]$, S_F and S_{CR} are the hall of factor that achieve success in the generation, $mean_L$ is the Lehmer mean and $mean_A$ is the arithmetic mean.

The JADE variant, denominated as Tsallis JADE, performs a self-adaptation of the scale factor and crossover in the original algorithm using the Tsallis Distribution (Tsallis, 1988) instead of the Cauchy Distribution and Gaussian Distribution, respectively. The definition of the Tsallis Distribution is given by Equations 29, 30 and 31.

$$P_q = A_q \left[1 + (q-1)B_q (x - \mu_q)^2 \right]^{1/1-q} \quad (29)$$

$$A_q = \frac{c \left[\frac{l}{q-1} \right]}{c \left[\frac{3-q}{2q-2} \right]} \sqrt{\frac{q-1}{\pi}} B_q \quad (30)$$

$$B_q = [(3-q)\sigma^2]^{-1} \quad (31)$$

where q is the first distribution control parameter linked to the type of distribution that assumes values from 1 to 3. Values of q close to 1 performs a Gaussian distribution, values of q close to 2 performs a Lorentzian distribution and values of q close to 3 perform a Lévy distribution. The normalization constant is A_q and B_q are the second distribution control parameter linked to the height and width of the distribution. The mean of the distribution is μ_q and the variance of the distribution is σ_q^2 .

For each member of the population a random value of q was generated for the determination of the distribution. This procedure is loop until the stopping criteria. The initialization values, initial means and variances of the factor scale and crossover continues as the same as JADE, both equal to 0.5 in initialization and initial mean value and variance of 0.1.

3.3 Objective function and study case

The objective function is defined as the total annual cost, that is given by Equation 32 (Xie et al.,2008),

$$C_{tot} = C_A A^n + \frac{k_{el}\tau}{\eta} (\Delta P_h V_h + \Delta P_c V_c) \quad (32)$$

where the first member of the equation represents the investment cost (C_i) and the second member of the equation represents the operational cost (C_{od}), C_A is the cost per unit of area equal to 100\$.m², η is the pumping efficiency equal to 0.6, k_{el} is the electricity price equal to 30\$.MWh⁻¹, τ is the amount of hours of operation equal to 6500h.yr⁻¹ and $V_{h,c}$ is the volumetric flow rate for hot and cold fluids equal to 1.2 m³.s⁻¹ and 0.6 m³.s⁻¹ respectively. All the previous parameters were taken from Xie et al. (2008) for comparison purposes.

The Table 1 presents the properties and input values for the temperature and pressure for both fluid streams.

Table 1. Properties and input values for the hot and cold fluids given for the case study.

Properties and input values	Hot fluid	Cold fluid
\dot{m} (kg.s ⁻¹)	0.8962	0.8296
T_i (K)	513	277
μ (kg.m ⁻³)	0.8196	0.9385
C_p (kJ.kg ⁻¹ .K ⁻¹)	1017.7	1011.8
μ (Pa.s)	0.00002410	0.00002182
Pr	0.6878	0.6954
P_i (kPa)	100	100

From Table 1 it can be observed that both fluids are very similar, with major differences being found in the values of dynamic viscosity and heat specific capacity.

The values of the optimization variables in search space for were H between 0.002 and 0.01 m, t between 0.0001 and 0.0002 m, n between 100 and 1000 fins/m, l between 0.001 and 0.01 m, N_a between 1 and 10 and both L_h and L_c between 0.1 and 1 m.

For both algorithms were performed 50 independent runs with an initial population of 10 times the number of optimization variables and 5000 evaluations of the objective function with values for the parameters c and p equal to 0.1 and 0.05 respectively.

4. RESULTS AND DISCUSSION

The results for JADE and TJADE presented minimum values (best) of 2687.85\$ and 2361.33\$, maximum values (worst) of 4545.00\$ and 4219.20\$, mean values of 3564.70\$ and 3243.30\$ and standard deviations of 407.03\$ and 400.65\$, respectively. The Fig. 2 presents the convergence of the JADE and TJADE methods applied to the study.

The TJADE method was able to outcome the original algorithm in both the best value and mean value obtained presenting a slightly larger value of amplitude, a difference of only 5.12\$ between one amplitude and the other, and standard deviation, a difference of only 6.38\$ between TJADE and JADE, with allows inferring that the range of possible distributions obtained by the Tsallis Distribution may have some advantages in the tuning of control parameters of evolution algorithms.

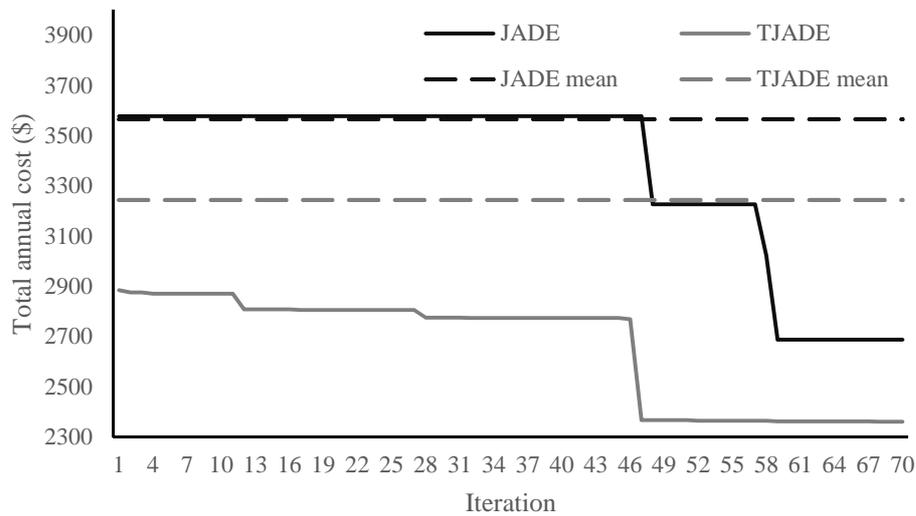


Figure 2. Convergence of JADE and TJADE methods with mean values.

From the Fig. 2 an observation about the convergence can be presented, where the TJADE obtained convergence below 50 iterations and JADE below 60 iterations. Although the TJADE method has wider range of possible distributions it can achieve the convergence with less iterations that the original method, JADE.

The Fig. 3 shows a contour plot with the variation of L_h and L_c for JADE and TJADE methods pointing the position of the best value reached for each technique. The values of the others optimization variables for JADE method were H equal to 0.009 m, t equal to 0.0001 m, n equal to 157 fins/m, l equal to 0.0094 m and N_a equal to 10. The values of the same optimization variables for TJADE method were H equal to 0.009 m, t equal to 0.0001 m, n equal to 157 fins/m, l equal to 0.0094 m and N_a equal to 10.

It can be seen that for both methods that lower values of the lengths for the hot and cold fluids produces decreasing values for the investment cost while produces increasing values for the operational cost.

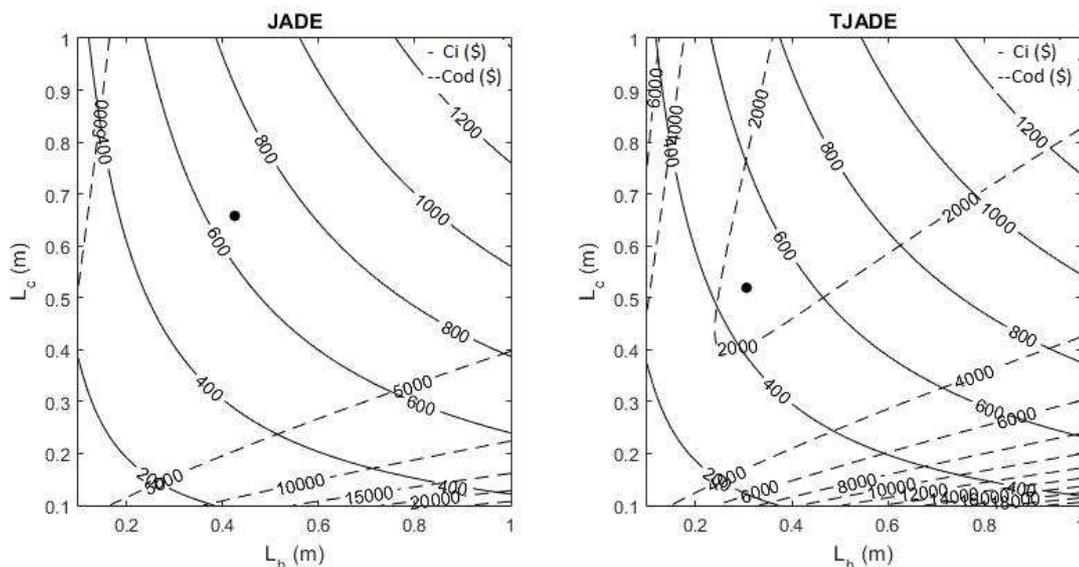


Figure 3. Contour plots of cost (C_i and C_{od}) for JADE and TJADE methods.

The Table 2 presents the results of the simulation and a comparison against the Genetic Algorithms (Xie et al., 2008) and Particle Swarm Optimization (Rao and Patel, 2010) methods results.

Table 2. Results and comparison for the optimal geometry obtained for the plate-fin heat exchanger.

Parameter	GA	PSO	JADE	TJADE
L_h (m)	0.235	0.219	0.427	0.305
L_c (m)	0.500	0.500	0.657	0.520
ΔP_h (kPa)	0.2979	0.264	2.322	1.930
ΔP_c (kPa)	1.8995	2.000	4.022	4.192
C_i (\$)	-	-	660.06	477.23
C_{od} (\$)	-	-	2027.79	1884.10
C_{tot} (\$)	3047.67	3017.90	2687.85	2361.33

From the Table 2 it can be observed that JADE had a reduction in the total annual cost of 11.80% and 10.94% in comparison with GA and PSO, respectively, while TJADE had a reduction in the total annual cost of 22.52% and 21.76% in comparison with the same methods.

About the parameters, L_h presented an increase of 81.70% and 94.98% with JADE in comparison to the values reached with GA and PSO, respectively. The TJADE presented for the same parameter increases of 29.79% and 39.27% in comparison with the same methods. For the parameter L_c the increases of 31.40% and 4% were achieved with JADE and TJADE, respectively, in comparison to GA and PSO. The pressure drops obtained significant changes in the values for both algorithms. Moreover, still looking at the Table 2, it is possible to discriminate the contribution that both investment and operational costs has over the total annual cost, where the first contributes with 24.56% of the total value for JADE and 20.21% for TJADE.

About the convective heat transfer coefficients, the JADE method achieved values of $1.025 \text{ W.m}^{-2}.\text{K}^{-1}$ for the hot fluid and $1.095 \text{ W.m}^{-2}.\text{K}^{-1}$ for the cold fluid while TJADE reached values of $1.101 \text{ W.m}^{-2}.\text{K}^{-1}$ for the hot fluid and $1.238 \text{ W.m}^{-2}.\text{K}^{-1}$ for the cold fluid. The modification provided in the original method was able to enhance the convective heat transfer coefficient up to 7.41% and 13.05% for hot and cold fluids, respectively. It is important to notice that higher convective heat transfer coefficients provides higher effectiveness in the heat transfer of the system.

5. CONCLUSIONS

The present work investigated the application of the Adaptive Differential Evolution JADE and a modification, called Tsallis Adaptive Differential Evolution TJADE, in the optimization of a plate-fin heat exchanger from the economic point of view. In the modification provided in the original method, JADE, the Gaussian and Cauchy Distributions were substituted for the Tsallis Distribution in the tuning of the control parameter of evolution for factor scale and crossover parameters. Both algorithms reached the convergence under 60 iterations and the results showed that JADE had a reduction in the total annual cost of 11.80% and 10.94% in comparison with Genetic Algorithm and Particle Swarm Optimization, respectively, while TJADE had a reduction in the total annual cost of 22.52% and 21.76% in comparison with the same methods where the best results obtained for JADE was 2687.85\$ and for TJADE was 2361.33\$. About the optimization values, L_h presented an increase of 81.70% and 94.98% with JADE, with value equal to 0.427 m, in comparison to the values reached with GA and PSO, respectively. The TJADE presented for the same parameter value of 0.305 m, that increases this variable about 29.79% and 39.27% in comparison with the same methods. For the parameter L_c the increases of 31.40% and 4% were achieved with JADE, with value 0.657 m, and TJADE, with value equal 0.520 m, in comparison to Genetic Algorithm and Particle Swarm Optimization respectively. The pressure drops obtained significant changes in the values for both algorithms. The values of the others optimization variables for JADE method were H equal to 0.009 m, t equal to 0.0001 m, n equal to 157 fins/m, l equal to 0.0094 m and N_a equal to 10. The values of the same optimization variables for TJADE method were H equal to 0.009 m, t equal to 0.0001 m, n equal to 157 fins/m, l equal to 0.0094 m and N_a equal to 10. The results for the convective heat transfer coefficients showed that JADE method achieved values of $1.025 \text{ W.m}^{-2}.\text{K}^{-1}$ for the hot fluid and $1.095 \text{ W.m}^{-2}.\text{K}^{-1}$ for the cold fluid while TJADE reached values of $1.101 \text{ W.m}^{-2}.\text{K}^{-1}$ for the hot fluid and $1.238 \text{ W.m}^{-2}.\text{K}^{-1}$ for the cold fluid. The modification provided in the original method was able to enhance the convective heat transfer coefficient up to 7.41% and 13.05% for hot and cold fluids, respectively.

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8. RESPONSIBILITY NOTICE

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