META-HEURISTIC APPROACH FOR MULTI-OBJECTIVE OPTIMIZATION OF CONDENSATION HEAT TRANSFER AND PRESSURE DROP WITH TWISTED TAPE INSERTS

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The heat transfer and pressure drop during condensation of refrigerant inside horizontal twisted tape inserted tube are complex function of mass velocity, vapor quality and twist ratio of insert. The selection of optimal combination of parameters is very necessary to fulfill all the conflicting objectives during condensation. In the present paper, a meta- heuristic approach based algorithm known as 'teaching-learning based optimization algorithm (TLBO)' is used to obtain the optimum set of parameters to maximize the heat transfer and minimize the pressure drop during R-404A vapor condensation with twisted tape inserts in horizontal tube.

Keywords: condensation, heat transfer, pressure drop, twisted tape, TLBO.

1. Introduction

An efficient condenser design has always been a great challenge for the designers and users. A highly efficient condenser ensures energy saving which is very necessary due to limited availability of conventional energy resources. In order to obtain high performance condenser many heat transfer enhancement methods have been used by researchers. Bergles [1] has classified heat transfer enhancement devices in two categories, active and passive. Active devices consume external power to augment heat transfer while passive devices consume no external power to accomplish this aim. Dalkilic [2] dealt with different passive techniques of heat transfer enhancement. Dewan [3] described coiled wire and twisted tape inserts as the most inexpensive among all passive devices of heat transfer enhancement. Heat transfer enhancement devices enhance heat transfer and at the same time pressure drop along the flow also. Behabadi [4] reported rise in heat transfer and pressure drop up to 40% and 240% by using twisted tape inserts during R-134a condensation inside horizontal tube. Salimpour [5-6] found that the twisted tape inserts increase heat transfer coefficient up to 50% and pressure drop up to 89 to 239% during R-404A condensation.

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In last few years researchers have done heat exchangers design optimization using several optimization techniques. Sepehr [7] used genetic algorithm to perform multi-objective optimization of parallel flow condenser and found that optimized design parameters produced 7.1% increased heat transfer rate and 96% pressure drop in comparison to factory-made operational factors. Rao [8] implemented particle swarm optimization algorithm for minimizing the cost of shell and tube heat exchanger. Baadache [9] made cost optimization of shell and double concentric tubes heat exchanger through genetic algorithm and establish that the new optimized heat exchanger reduced the cost by 13.16%. Hajabdollahi [10] used particle swarm and genetic algorithm for cost optimization of condenser and concluded that at first cost deceases with increasing number of tubes and latter it increase with increasing the same. Rao [11] optimized the cost and effectiveness of plate fin heat exchanger by TLBO. Kumar [12] predicted heat transfer coefficient during condensation using TLBO. Farahadi [13] predicted the optimum combination of parameters to maximize heat transfer and minimize pressure drop during R-404A condensation inside tube with twisted tape inserts using artificial neural network.

In the present paper author aims to use TLBO for obtaining the best combination of parameters, refrigerant mass velocity, vapor quality and twist ratio, to maximize heat transfer and minimize pressure drop during R-404A condensation with twisted tape inserts.

2. Teaching-learning based optimization algorithm (TLBO)

Teaching-learning based optimization is a meta-heuristic a computation method developed by Rao [14]. Fig. 1 displays the flowchart of TLBO. Its working is based on influence of teachers on learners' outcome in a class. In this optimization technique, group of learners reflect the population and subjects offered them as various design considerations. Learners' output reflects the 'fitness' value of objective function is to be optimized. The teacher is taken as the best solution among entire population.

The functioning of teaching-learning based optimization method has been divided in two phases, 'Teacher phase' and 'Learner phase'. Let two teachers A and B are teaching the same subject of equal content to equal intelligence level students in two different classes C_1 and C_2 respectively. Fig. 2 shows the marks distribution of students of classes assessed by teachers. Marks secured by students are supposed normally distributed. Normal distribution of marks is evaluated as according to Eqn. 1.

$$f(x) = \frac{1}{\sigma\sqrt{2\Pi}}\exp\left\{\frac{-(x-\mu)^2}{2\sigma^2}\right\} \quad (1)$$

Here μ, σ^2 and x are mean, variance and the value for which normal distribution is to be calculated. From Fig. 2 it can be seen that C_2 has more mean value (M_B) as compared to that of C_1. This means a good teacher can produce better mean of marks secured by learners. Learners can boost their knowledge through communication with each other that also helps them in getting improved marks. A teacher raises the mean of the class up to his/her competency. Here the teacher 'A' will try best to shift M_A close to his/ her level at first and then towards mean M_B. As M_A becomes equal to M_B, a new more knowledgeable teacher 'B' is required.

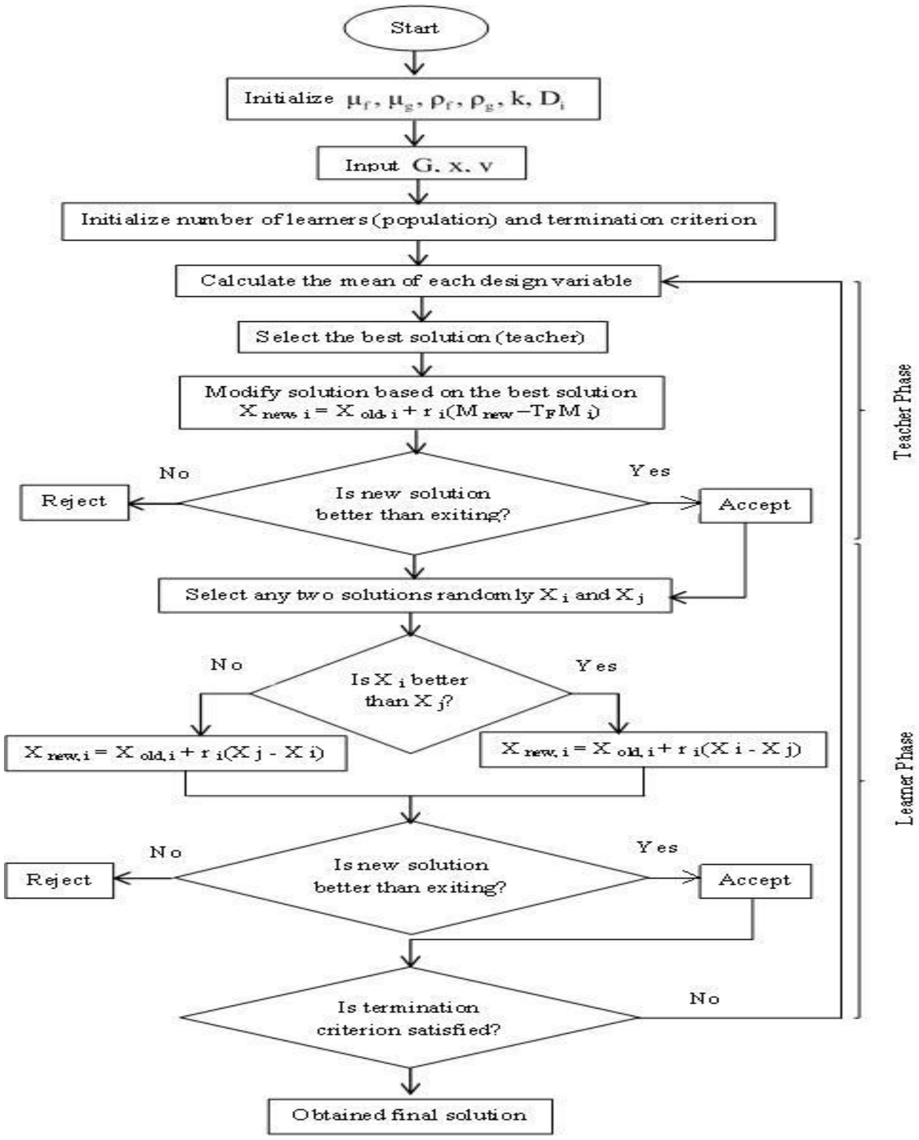

Fig. 1. Flow diagram of TLBO

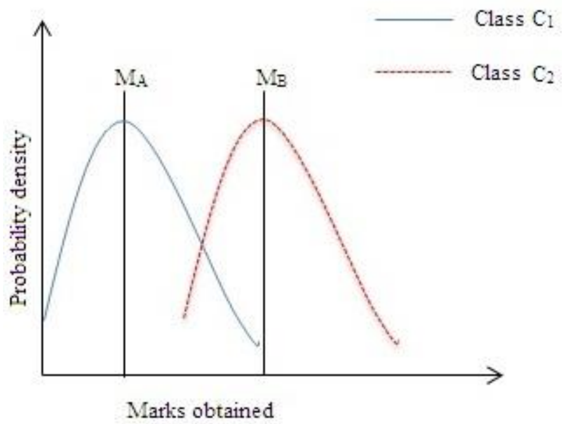

Fig. 2. Normal distribution graph

Teacher Phase

Let at i[th] iteration M_i and T_i be the mean of marks of students and teacher respectively. As T_i strives to shift mean M_i towards his/her own level, so the mean will change and is now designated as M_{new}. The difference between new mean and present mean is evaluated as given below.

$Difference\_Mean = r_i (M_{new} - T_F M_i)$

Where r_i, and T_F are random number (0, 1) and teaching factor taken 1,

The present solution updates as given below.

$X_{new,i} = X_{old,i} + Difference\_Mean_i$

Learner Phase

In this phase learners enhance their knowledge through communication with each other. A learner gains something new from others if they are more knowledgeable. The learner modification is done as follows.

for $i = 1:P_n$

Randomly choose another learner X_j such that $i \neq j$.

if $f(X_i) < f(X_j)$

$X_{new,i} = X_{old} + r_i (X_i - X_j)$

else

$X_{new,i} = X_{old} + r_i (X_j - X_i)$

end

Accept X_{new} if it yields better function value.

3. **Geometry of tube with twisted tape inserts**

A schematic diagram of twisted tape inserted tube studied presently is displayed in Fig. 3. The test condenser used for the present investigation is a horizontal tube of length 1000 mm with inner diameter 14.1 mm and outer diameter15.9 mm. Refrigerant, R-404A, vapor flows inside this tube at different mass velocity (G) and vapor quality with a constant temperature (saturation temperature = 35^0C). The refrigerant vapor condenses inside tube by transferring heat through its wall. The refrigerant side heat transfer rate is enhanced by inserting twisted tapes of different twist ratios inside tube. Thickness of twisted tape (**δ**) is 0.7 mm. The twist ratio (y) of twisted tape is defined as the ratio of pitch length (H) to inner diameter of the tube (D_i). Parameters and their ranges taken for the present study are listed in Table 1. R-404A thermo physical properties are taken corresponding to 35^0C condensation temperature.

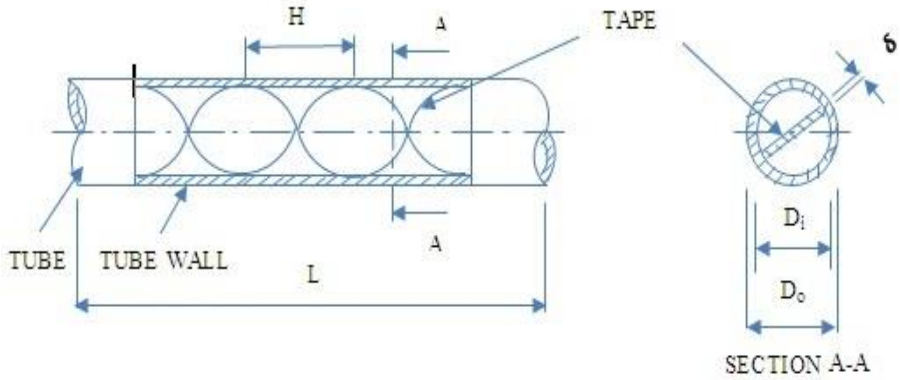

Fig. 3. Structural considerations of the twisted tape inserted tube.

Table 1

Parameters with their limits

Parameters	Limits
Refrigerant mass flux, G	71.2 – 124.6 kg/m^{2}s
Vapor quality, x	0.2 – 0.8
Twist ratio, y	4 - 14

4. Mathematical models

4.1 Heat transfer coefficient

Heat transfer coefficient (h) during R-404A condensation with twisted tape inserts inside horizontal tube is computed as according to Salimpour [5] from following correlation,

$$h = 0.0265\left(\frac{k}{d_e}\right)\left(\frac{F_t d_e G_e}{\mu_f}\right)Pr^{0.4}F_{tt} \quad (2)$$

Where,

$$d_e = \frac{\pi D_i^2}{\pi D_i + 2(D_i - \delta)} \quad (3)$$

$$G_e = G\left[x\left(\frac{\rho_f}{\rho_g}\right)^{0.5} + 1 - x\right] \quad (4)$$

$$F_t = \frac{1}{2y}\left(\sqrt{\pi^2 + 4y^2}\right) \quad (5)$$

$$F_{tt} = 1 + \frac{2}{\pi}\left(\frac{\eta}{2} - \frac{\delta}{D_i}\right) \quad (6)$$

4.2 Pressure drop

Pressure drop during R-404A condensation inside horizontal tube with twisted tape inserts is calculated as according to Salimpour [6] from following correlation,

$$\left(\frac{dp}{dz}\right)_{fric} = \left(\frac{dp}{dz}\right)_f \times \phi^2 \quad (7)$$

Where,

$$\phi^2 = 8.26\left(1 + \left(Y^2 - 1\right)\left[4.8x^{1.75}(1-x)^{2.75} + x^{1.75}\right]\right) \times \left(1 + 0.89F_t^3\right) y^{-0.18} \quad (8)$$

$$\left(\frac{dp}{dz}\right)_f = f_f\left(\frac{1.15 \times G^2}{D_i \times \rho_g}\right) \quad (9)$$

$$f_f = \frac{0.079}{Re_f} \quad (10)$$

$$Y^2 = \left(\frac{\rho_f}{\rho_g}\right)\left(\frac{\mu_g}{\mu_f}\right)^{0.25} \quad (11)$$

$$Re_f = \frac{G \times D_i}{\mu_f} \quad (12)$$

4.3 Objective function

Based on Eqn. 2 and Eqn. 7 three objective functions are formulated. Two objective functions for the optimization of heat transfer coefficient and pressure drop and third for multi-objective optimization of the same. Three objective functions formulated are given below,

$$\text{Maximize} = h \quad (13)$$

$$\text{Minimize} = \left(\frac{dp}{dz}\right)_{fric} \quad (14)$$

$$\text{Maximize,} f(z)=\left\{w_1\left(\frac{f_1(z)}{f_1*}\right)-w_2\left(\frac{f_2(z)}{f_2*}\right)\right\} \quad (15)$$

Here, f_1 (z) and f_2 (z) are maximization and minimization functions respectively, i.e. heat transfer coefficient and pressure drop. w_1 and w_2 are inertia weights taken in such a way that their sum is unity. f_1* and f_2* are optimum values of objective functions when both are optimized separately for same constraints.

5. Results and discussion

All three objective functions are optimized using teaching-learning based optimization algorithm. The TLBO algorithm is implemented for the following parameters.
Number of runs = 50; Number of population = 10
Number of iterations = 20
Teaching factor (T_F) = 1

At first TLBO algorithm is run for maximization and minimization of heat transfer coefficient and pressure drop during R-404A condensation inside horizontal tube with twisted tape inserts. Table 2 and Table 3 represent optimization results of heat transfer coefficient and pressure drop respectively. From Table 2 it becomes clear that the maximum heat transfer coefficient can be achieved at high values of mass flux and vapor quality and small value of twist ratio of twisted tape inserts. Similar results have been stated in Salimpour [5]. From Table 3 it can be inferred that the minimum pressure drop can be attained at low values of mass flux and vapor quality and high value of twist ratio of twisted tape. Similar outcomes have been described in Salimpour [6].

As could be seen from optimization results of heat transfer coefficient and pressure drop that the optimum value of parameters are contradictory to each other. So multi-objective optimization based on TLBO algorithm is done to obtain the best combination of parameters to maximize and minimize the same. Table 4 represents the multi-objective optimization results. From this table it is clear that the best values of parameters mass flux, vapor quality and twist ratio are 92.15 kg/m^2s, 0.793 and 7.56 respectively. TLBO results of multi-objective optimization are authenticated with Farahadi [13].

Table 2

Heat transfer coefficient optimization result

Parameters	TLBO result
Mass flux of refrigerant, G	123.6 kg/m^2s
Vapor quality, x	0.796
Twist ratio, y	4.132
Heat transfer coefficient, h	**1401.55** W/m^2K

Table 3

Pressure drop optimization result

Parameters	TLBO result
Mass flux of refrigerant, G	71.64 kg/m^2s
Vapor quality, x	0.205
Twist ratio, y	11.52
Heat transfer coefficient, h	**107.23** Pa/m

Table4

Multi-objective optimization results

Parameters	Artificial neural network (ANN), [13]		TLBO	
	Range	Results	Range	Results
Mass flux (kg/m^2s)	71.2-142.4	71.3-131.3	71.2-124.6	92.15
Vapor quality	0.24-0.87	0.64-0.87	0.2-0.8	0.793
Twist ratio	4-14	< 6.5	4-14	7.56

Population size and number of run taken for the current optimization problems have been decided by performing a number of trails at the start to check the uniformity of results. Fig. 4 and Fig. 5 display the convergence of objective functions using TLBO. It can be found from the figures that the objective functions converge within a few numbers of iterations.

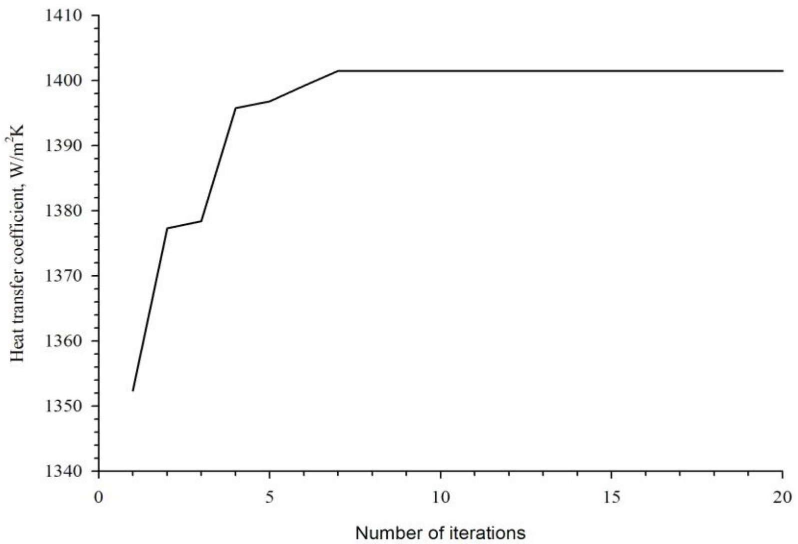

Fig. 4. Convergence of TLBO for heat transfer coefficient

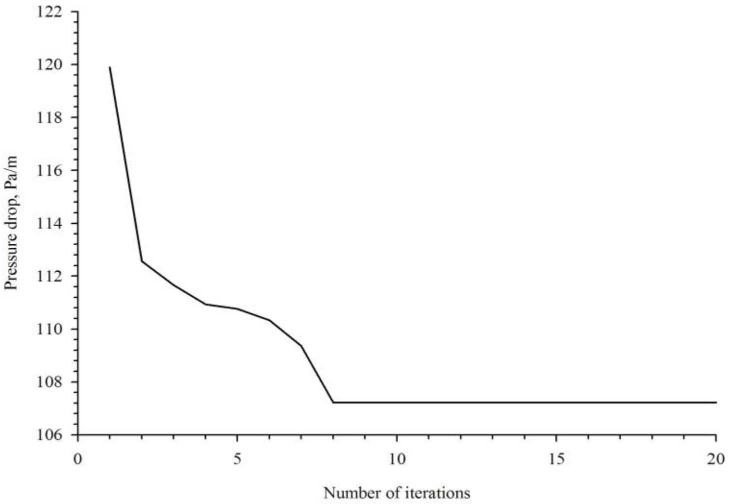

Fig. 5. Convergence of TLBO for pressure drop

5. Conclusions

In the present paper teaching-learning-based optimization algorithm is used for optimization of R-404A condensation in presence of twisted tape inserts inside horizontal tube. The key outcomes are summarized below:

Multi-objective mathematical model is taken for heat transfer coefficient and pressure drop during R-404A vapor condensation with twisted tape inserts inside horizontal tube and initially the objectives are independently optimized. A common set of parameters are also obtained for satisfying both these objectives simultaneously.

The maximum heat transfer coefficient is obtained for low twist ratio of twisted tape inserts at high mass flux and vapor quality, whereas the minimum pressure drop is reported for high twist ratio and low mass flux and vapor quality.

Based on TLBO multi-objective optimization results, the best combination of parameters are mass flux = 92.15 kg/m^{2}s, vapor quality = 0.793, twist ratio = 7.56 corresponding to minimum pressure drop and maximum heat transfer coefficient.

List of symbols

D	**Tube diameter (mm)**
F_t	Tangential velocity
F_{tt}	Fin effect
G	Mass flux, kg/m^2-s
k	Thermal conductivity, W/m^2-K
L	Length of tube, mm
Pr	Prandtl number

Greek symbols

ρ	Density, kg/m3
μ	Viscosity, Pa s,
ϕ	Two phase multiplier
η	Fin efficiency
$\boldsymbol{\delta}$	Thickness, mm
σ^2	Variance

P_n Number of population
Re Reynolds number
T_F Teaching factor
x Vapor quality
y Twist ratio (H/D_i)

Subscript

fri Friction; f Liquid; g Vapor; i Inside, o outside

R E F E R E N C E S

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