Plain Flow Vapor Condensation Optimization using Teaching-Learning Based Optimization (TLBO)

Ravindra Kumar[1] & Dilip Kumar Prajapati

Mechanical Engineering Department

Jaipur Engineering College and Research center
Jaipur, Rajasthan, India
kumarravindramahto@gmail.com

Dr. Sourabh Sinha[3]
Mechanical Engineering Department
Ramgarh Engineeing College
Ramgarh, Jharkhand, India
sourabhmilan@gmail.com

Abstract— **In this paper, R-245fa vapor condensation heat transfer and pressure drop inside a horizontal smooth tube is formulated as a multi-objective optimization problem and solved using teaching-learning based optimization (TLBO) algorithm. The TLBO is a recently proposed optimization algorithm which simulates teaching-learning method in a class. This algorithm is applied to maximize heat transfer and to minimize pressure drop simultaneously. The range of parameters taken for the current investigation are refrigerant mass flux (100-300 kg/m^2-s), quality (0.1-0.9) and saturation temperature (35-45^{0}C). The results show that the optimum heat transfer and pressure drop are achieved with mass fluxes 146.15, 159.06 and 176.10 kg/m^2-s at saturation temperatures 35, 40 and 45^{0}C respectively while optimum vapor quality is its highest value that is 0.9 and is same for all saturation temperatures.**

Keywords— Heat transfer, Pressure drop, Multi-objective optimization, Teaching-learning based optimization (TLBO), R-245fa

I. INTRODUCTION

Condensers are normally double pipe heat exchangers extensively applied in refrigeration, air conditioning, thermal power plants and some other thermal systems. In condensers, refrigerant vapor and cold fluid flow through the concentric tubes separately. The heat transfer inside condensers, take place by virtue of temperature difference between the fluids flowing inside the tubes. The refrigerant vapor coming from the compressor gets cool and condensed in the condensers. In order to enhance performance of the condensers it is essential to dissipate the heat at a suitable rate. The bigger size of condensers can increase their performance but it leads to more maintenance and more refrigerant charging. Emissions from the chlorofluorocarbons (CFC) refrigerants are one of the major roots of the ozone layer depletion and global warming. Therefore, it is essential for designers to design condensers that need less power and refrigerant charging. components, incorporating the applicable criteria that follow.

Over the years, researchers all around the world have carried out experimentation to study the vapor condensation heat transfer and fluid flow inside plain tubes. Shah [1] proposed a generalized correlation of heat transfer coefficient and compared it with several fluids. The results indicated that this correlation can predict heat transfer coefficient within acceptable range of deviation. Dobson and Chato [2] studied the effect of refrigerant mass flux, quality, saturation temperature, and tube diameter on condensation heat transfer coefficient inside horizontal plain tubes. They proposed a correlation for heat transfer coefficient which satisfactorily predicted their experimental data. Hossain et al. [3] studied the influence of mass flux and saturation temperature on R-32, R-410A and R-1234ze vapor condensation heat transfer and pressure drop. Also they compared their experimental data with some established correlations of heat transfer coefficient and pressure drop. Xing et al. [4] investigated effects of the Froude number and tube’s orientations on R-245fa heat transfer coefficient. They predicted experimental heat transfer coefficient of horizontal tubes using some widely accepted correlations and found that the Shah [1] and Dobson [2] are in good agreement with their experimental data. Dalkilic and Wongwises [5] in their review on in tubes condensation revealed that the Friedel, Chisholm, and Lockhart and Martinelli correlations are able in predicting pressure drop of conventional passages.

In the last few years, optimization methods are gaining popularity and are being widely applied for the design optimization of heat exchangers. Balcilar et al. [6, 7] applied genetic algorithm (GA) and artificial neural network (ANN) for the formulation of R-134a condensation heat transfer coefficient and pressure drop correlations. Also they determined the most influential factors on R-134a condensation heat transfer and pressure drop inside smooth vertical tube. Sanaye et al. [8] obtained optimum heat transfer and fluid flow inside shell and tube heat exchanger using GA. Ahmadi et al. [9] applied GA and particle swarm optimization (PSO) for heat transfer and cost optimization of heat exchanger. Patel et al. [10] presented cost, weight, fluid flow and effectiveness optimization of a plate fin heat exchanger using teaching-learning based optimization (TLBO). Rao et al. [11] applied modified teaching-learning based optimization (MTLBO) for cost and effectiveness optimization of plate fin heat exchanger.

The objective of the present paper is to obtain optimum set of parameters to maximize heat transfer and fluid flow during R-245fa condensation in horizontal plain tube using TLBO.

II. TEACHING-LEARNING BASED OPTIMIZATION (TLBO) ALGORITHM

Teaching-learning based optimization method was proposed by Rao et al. [12] in 2011. The flowchart of TLBO has been shown in figure 1. This optimization method simulates the teaching-learning process in a class. In this optimization technique, a group of learners is treated as population and subjects that they are studying as various design factors. Marks secured by learners present the 'fitness' value of the optimization problem. The teacher is taken as the finest solution in the whole population.

The TLBO works in two steps, 'teacher phase' and 'learner phase'. Let us take two teachers A and B, are educating students in two separate classes C1 and C2. It is supposed that both teachers are educating the same topic of equal content to equal quality of students. Figure 2 represents the marks distribution of students of classes C1 and C2 assessed by corresponding teachers. The marks distribution of students is supposed normally distributed. Two distinct curves in figure 2 reflect the marks distribution of students of teachers A and B. The normal distribution is evaluated by the equation given below;

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

Here, μ, σ^2 and x are mean, variance and any value for which normal distribution is to be evaluated. From figure 2 it can be seen that mean value of marks obtained by students of teacher B is more than that of students of the teacher A. This concludes that a good instructor yields better mean of marks. A teacher can raise the mean as per his/her ability. In the present case, the teacher A will try first to bring the mean up to his/her level and then up to M_B. As soon as M_A becomes equal to M_B, other teacher B is needed.

A. Teacher Phase

Let, for a particular iteration i, T_i and M_i be the teacher and mean of marks respectively. Teacher T_i will try to bring mean of class to his/her level, so now M_{new} is the new mean. The change between the new and the present mean is calculated as given below;

Difference_ Mean = $r_i (M_{new} - T_F M_i)$

Where r_i is any number between 0 and 1 while T_F is teaching factor taken as either 1 or 2. The present solution updates as given below:

$X_{new, i} = X_{old, i}$ + Difference_ Mean$_i$

B. Learner Phase

In the learner phase it is supposed that students not only learn from the teacher but also interacting with each other. A student can gain knowledge from other more learned students. And this ultimately will help in getting good marks. The learner modification is done as per given below:

For i = 1: P_n

Randomly select two students X_i and X_j such that $i \neq j$.

If $f(X_j) > f(X_i)$

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

Else

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

End

X_{new} is accepted if it provides enhanced function value.

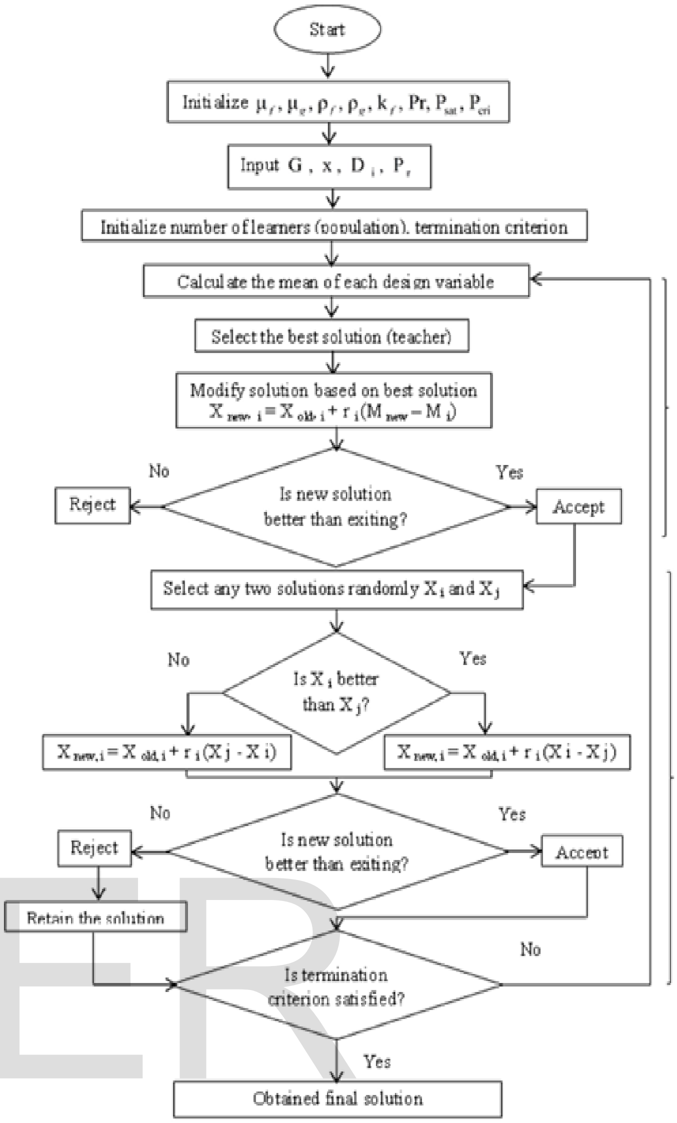

Fig.1. Flow chart of TLBO

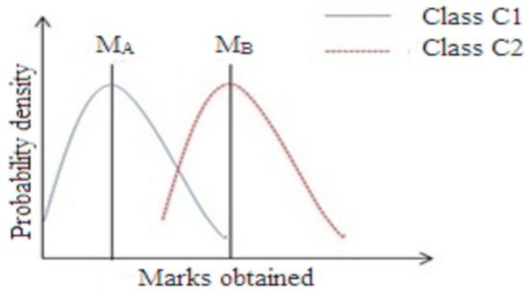

Fig.2. Marks distribution of students

III. Geometry of Tube

A schematic diagram of tube used in present investigation has been shown in figure 3. The test section used for the current study is a smooth horizontal tube of length 1000 mm and inner diameter 9 mm. Refrigerant, R-245fa vapor is flown inside this tube at different mass flux, vapor quality and saturation temperature. R-245fa vapor condenses in the tube by transferring heat through its wall. Design variables and their limit considered for the present investigation are as mentioned in section 5.

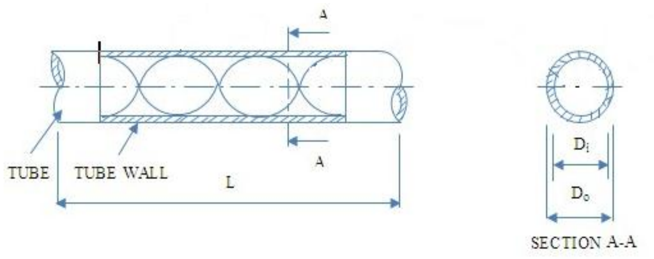

Fig. 3. Structural considerations of the tube

IV. MATHEMATICAL MODELS

A. *Heat Transfer Coefficinet(h)*

R-245fa vapor condensation heat transfer coefficient of smooth horizontal tube is computed by Shah's [1] correlation which is as given below:

$$h = 0.023 \times Re^{0.8} \times Pr^{0.4} \left(\frac{\mu_f}{14\mu_g}\right)^n \times \left[(1-x)^{0.8} + \frac{3.8 \times x^{0.76} \times (1-x)^{0.04}}{\left(\frac{P_{sat}}{P_{cri}}\right)^{0.38}} \right] \times \left(\frac{k}{D_i}\right) \quad (2)$$

Where,

$$Re = \left(\frac{G \times D_i}{\mu_f}\right) \quad (3)$$

$$n = 0.0058 + 0.557 \times \frac{P_{sat}}{P_{cri}} \quad (4)$$

B. *Pressure drop (ΔP)*

R-245fa vapor condensation frictional pressure drop of plain horizontal tube is calculated based on Kumar et al. [13] and is as under below:

$$\left(\frac{dp}{dz}\right)_f = \varphi^2_{LO} \times 2 \times f_{LO} \times \frac{G^2}{D_i \times \rho_f} \quad (5)$$

Where,

$$f_{LO} = 0.034 \times \left(\frac{G \times D_i}{\mu_f}\right)^{-0.25}$$

$$\varphi^2_{LO} = Z + 3.595 \times F \times H \quad (6)$$

$$Z = (1-x)^2 + x^2 \times \left(\frac{\rho_f}{\rho_g}\right) \times \left(\frac{\mu_g}{\mu_f}\right)^{0.2} \quad (7)$$

$$F = x^{0.9525} \times (1-x)^{0.414} \quad (8)$$

$$H = \left(\frac{\rho_f}{\rho_g}\right)^{1.132} \times \left(\frac{\mu_g}{\mu_f}\right)^{0.44} \times \left(1 - \frac{\mu_g}{\mu_f}\right)^{3.542} \quad (9)$$

The thermo-physical properties of refrigerant taken for the current investigation are shown in table 1.

TABLE I. THERMAL AND PHYSICAL PROPERTIES OF REFRIGERANT R- 245fa

Properties	Unit	Tsat = 35^0C	Tsat = 40^0C	Tsat = 45^0C
Thermal Conductivity (k)	mW/m-K	86.936	85.416	83.904
Liquid density (ρ_f)	kg/m^3	1311.2	1297	1282.5
Vapor density (ρ_g)	kg/m^3	11.993	14.078	16.442
Liquid viscosity (μ_f)	μPa-s	357.64	336.05	316.98
Vapor viscosity (μ_g)	μPa-s	10.59	10.758	10.929
Prandtl number (Pr)		5.5997	5.4098	5.2338
Reduced pressure (P_r)		0.058	0.0689	0.081

V. PROBLEM FORMULATION FOR OPTIMIZATION

Condenser's thermal performance can be increased by increasing heat transfer rate and decreasing pressure drop in it. The literature study revealed that refrigerant vapor condensation heat transfer and the pressure drop are dependent upon mass flux (G), quality (x) and saturation temperature (Tsat) of the refrigerant flowing inside the condenser. In the current paper, heat transfer coefficient (h) and pressure drop (ΔP) are taken as objective functions for single and multi-objective optimization using TLBO. The single and multi-objective optimizations of objective functions are done for the same range of parameters. The purpose of multi-objective optimization is to obtain the set of parameters that will simultaneously give maximum heat transfer and minimum pressure drop. The optimization problems are as given below:

Determine: G, x, T_{sat}

Evaluate: $h = f\{G, x, D_i\}$ and $\Delta P = f\{G, x, D_i\}$

Maximize: $f_1 = h$ and $f_2 = -\Delta P$

Subject to: $100 \le G \le 300$ kg/m^2-s
$0.1 \le x \le 0.9$
$35^0C \le T_{sat} \le 45^0C$

The multi-objective optimization function framed for TLBO algorithm is given below:

Maximize: $f_1 - f_2$ (10)

VI. RESULT AND DISCUSSION

A. *Effect of mass flux, vapor quality and saturation temperature on heat transfer coefficient and pressure drop*

Figures 4-7 show the variation of pressure drop and heat transfer coefficient with mass flux, vapor quality and saturation temperature. It can be inferred from figures 4-5 that at any mass flux, heat transfer coefficient and pressure drop increase with decreasing saturation temperature. It can be witnessed from figures 6-7 that the heat transfer coefficient and pressure drop increases by increasing mass flux and vapor quality of refrigerant at any saturation temperatures. Thus it is clear that the maximum heat transfer coefficient can be obtained at the highest mass flux and vapor quality with the lowest saturation temperature, while the minimum pressure drop at the lowest mass flux and vapor quality with highest saturation temperature.

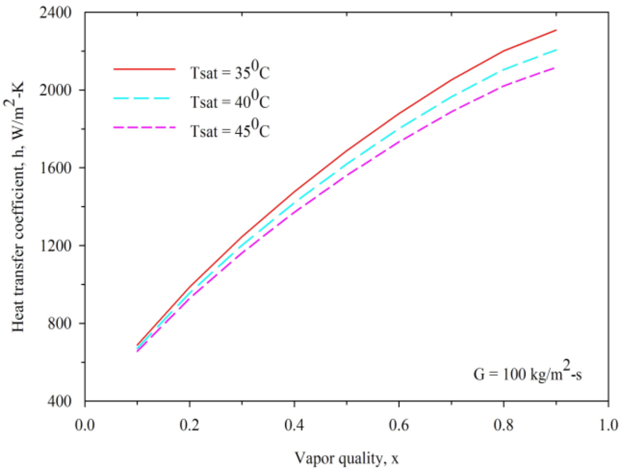

Fig.4. Effect of refrigerant vapor quality and saturation temperature on heat transfer coefficient

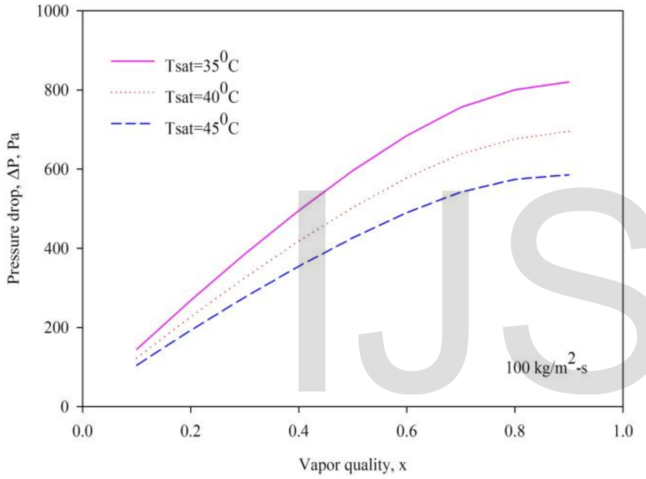

Fig.5. Effect of refrigerant vapor quality and saturation temperature on pressure drop

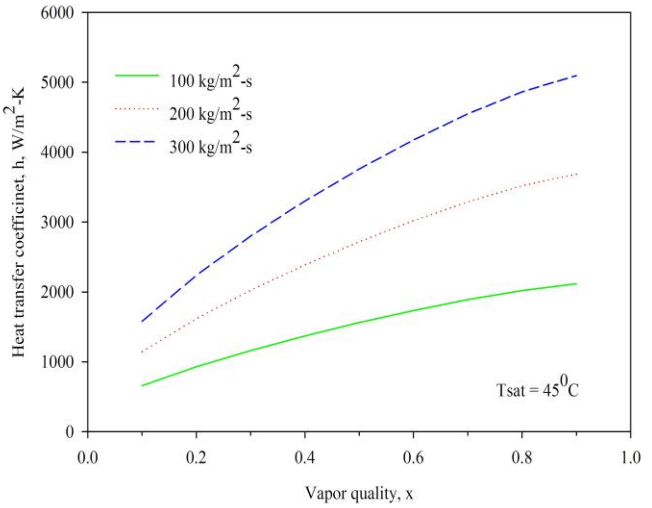

Fig.6. Effect of refrigerant vapor quality and mass flux on heat transfer coefficient

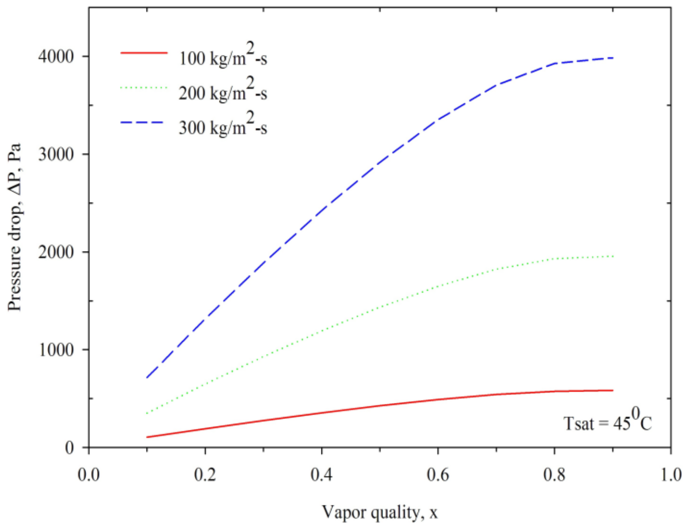

Fig.7. Effect of refrigerant vapor quality and mass flux on pressure drop

B. *TLBO Results*

In the present work, single and multi-objective optimization of the objective functions, maximization of heat transfer coefficient and minimization of pressure drop, are carried out using TLBO algorithm. Initially, a number of trails are done for the single and the multi-objective optimization to determine the optimum combination of parameters for executing the TLBO algorithm. The parameters, number of iteration and population size used to run the algorithm is found by knowing the consistency of the results. The parameters, taken to execute the TLBO for the present work has been listed in Table 2.

Table II. Parameters taken to run TLBO algorithm

Parameters	Value
Number of run	50
Number of population	10
Number of iterations	20
Tube diameter (D_i), mm	9
Length of tube (L), mm	1000
Teaching factor (T_F)	1

Table III. TLBO objective optimization results

Objective functions	Optimum results			
	Function value	x	G	Tsat
Heat transfer coefficient maximization	5834 W/m^2-K	0.895	298.57 kg/m^2-s	35^{0}C
Pressure drop minimization	114.73 Pa	0.13	102.24 kg/m^2-s	45^{0}C

At first, the maximization of heat transfer coefficient and the minimization of pressure drop are done separately using TLBO. The optimum values of objective functions obtained using TLBO for the given range of parameters have been listed in Table 3. The highest heat transfer coefficient 5834 W/m^2-K is attained with mass flux 298.57 kg/m^2-s and vapor quality 0.895 at 35^{0}C saturation temperature while the lowest pressure drop of 114.73 Pa is achieved with mass flux 102.24

kg/m^2-s and vapor quality 0.13 at 45^{0}C saturation temperature.

The TLBO technique is now applied for the multi-objective optimization of objective functions. The aim of optimization is to maximize heat transfer coefficient and minimize pressure drop simultaneously. Table 4 represents the optimum values of objective functions for the given rage of parameters. The optimum mass fluxes obtained using TLBO are 146, 159.06 and 176.10 kg/m^2-s for saturation temperatures 35^{0}C, 40^{0}C and 45^{0}C respectively. The optimum vapor quality for all saturation temperatures are almost same and are around 0.895.

Table IV. TLBO multi-objective optimization results

Parameters	Unit	Tsat = 35^{0}C	Tsat = 40^{0}C	Tsat = 45^{0}C
Pressure drop	Pa	1535.2	1531.9	1508.6
Heat transfer coefficient	W/m^2-K	3124.5	3197.8	3226.2
Vapor quality		0.895	0.892	0.893
Mass flux	kg/m^2-s	146	159.06	176.73

CONCLUSIONS

Following inferences can be drawn from the current investigation:

1. Condensation heat transfer coefficient and pressure drop of R-245fa in horizontal tube are directly proportional to its mass flux, vapor quality and saturation temperature.

2. The TLBO algorithm has been successfully applied for the single and the multi-objective optimization of R-245fa vapor condensation heat transfer coefficient and pressure drop. The optimum heat transfer coefficient and pressure drop for the multi-objective optimization are obtained with mass fluxes 146, 159.06 and 176.1 kg/m^2-s at saturation temperatures 35^{0}C, 40^{0}C and 45^{0}C respectively.

3. The optimum vapor qualities for the multi-objective optimization are almost same for all the three saturation temperatures and is close to 0.9

NOMENCLATURE

D_i	Inner diameter of tube (mm)
G	Mass flux (kg/m2-s)
h	Heat transfer coefficient (W/m2-K)
k	Thermal conductivity (W/m-K)
x	Vapor quality
f_{LO}	Liquid friction factor
f	Liquid
D_o	Outer diameter of tube (mm)
P_r	Reduced pressure
Pr	Prandtl number
Re	Reynolds number
L	Length of tube (mm)
μ	Viscosity (Pa-s)
ρ	Density (kg/m^3)

REFERENCES

[1] Shah M.M., "An improved and extended general correlation for heat transfer during condensation in plain tubes," HVAC&R RESEARCH, vol.15, no.5, 2009

[2] Dobson M. K. and Chato J.C., "Condensation in Smooth Horizontal Tubes," Journal of Heat Transfer, vol. 120/193, 1998

[3] Hossain M.A., Onaka Y., Miyara A., "Experimental study on condensation heat transfer and pressure drop in horizontal smooth tube for R-1234ze (E), R-32and R-410A," International Journal of Refrigeration, vol. 35, pp.927-938, 2012

[4] Xing F., Xu J., XieJ., Liu H., Wang Z., Ma X, "Froude number dominates condensation heat transfer of R-245fa in tubes: Effect of inclination angles," International Journal of Multiphase Flow, vol. 71, pp. 98–115, (2015)

[5] Dalkilic A.S., Wongwise S., "Intensive literature review of condensation inside smooth and enhanced tubes," International Journal of Heat and Mass Transfer, vol. 32, pp. 3409-3426, 2009

[6] Balcilar M., Dalkilic A.S., Wongwises S., ‘‘ Investigation of empirical correlation on the determination of condensation heat transfer characteristics during downward annular flow of R-134a inside a vertical smooth tube using artificial intelligence algorithm", Journal of Mechanical Science and Technology, vol.25, pp. 2683-2701, 2011

[7] Balcilar M, Aroonrat K., Dalkilic A.S., Wongwises S., "A numerical correlation development study for the determination of Nusselt number during boiling and condensation of R-134a inside smooth and corrugated tubes", International Communication in Heat and Mass Transfer, vol. 48, pp. 141-148, 2013

[8] Sepher S, Hajabdollahi H., "Multi-objective optimization of shell and tube heat exchanger", Applied Thermal Engineering, vol. 30, pp. 1937-1945, 2010

[9] Ahmadi P., Hajabdollahi H., Dincer I., "Thermo economic optimization of a shell and tube condenser using both genetic algorithm and particle swarm", International journal of refrigeration, vol. 34, pp. 1066-1076, 2011

[10] Patel V., Savsani V, "Optimization of a plate-fin heat exchanger design through an improved multi-objective teaching-learning based optimization (MOITLBO) algorithm," Chemical Engineering Research and Design, vol. 92, pp. 2371–2382, 2014

[11] Rao R.V., Patel V., "Multi-objective optimization of heat exchangers using a modified teaching–learning based optimization algorithm", Applied Mathematical Modeling, vol. 37, pp. 1147-1162, 2013

[12] Rao R.V., Savsani V.J., Vakharia D.P., "Teaching-learning based optimization: a novel method for constrained mechanical design optimization problems", Computer Aided Design, vol. 43, pp. 303-315, 2011

[13] Kumar R., Kumar P., "Multi-objective optimization of condensation heat transfer using teaching- learning based optimization algorithm", Journal of Power and Energy, vol. 0(0), pp. 1-10, 2017