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ORIGINAL RESEARCH PAPER

Multi-Objective Optimization of Tio2-Water Nanofluid Flow in Tubes Fitted with Multiple Twisted Tape Inserts in Different Arrangement

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Abstract

In this paper, experimentally derived correlations of heat transfer and pressure drop are used in a Pareto based Multi-Objective Optimization (MOO) approach to find the best possible combinations of heat transfer and pressure drop of TiO_2-water nanofluid flow in tubes fitted with multiple twisted tape inserts in different arrangement. In this study there are four independent design variables: the number and arrangement of twisted tape inserts (*N*), TiO_2 volume fraction (φ), Reynolds number (*Re*) and Prandtl number (*Pr*). Seven twisted tape arrangement in three different categories are investigated. The objectives are maximizing the non-dimensional heat transfer coefficient (*Nu*) and minimizing the non-dimensional pressure drop (*f Re*).

It is shown that some interesting and important relationships as useful optimal design principles involved in the thermal performance of nanofluid flow in tubes fitted with multiple twisted tape inserts in different arrangement can be discovered by Pareto based multi-objective optimization approach.

1. Introduction

Several heat transfer enhancement (HTE) techniques have been used in many engineering applications such as nuclear reactor, chemical reactor, chemical process, automotive cooling, refrigeration, and heat exchanger, etc. HTE techniques are powerful tools to increase heat transfer rate and thermal performance as well as to reduce of the size of Transfer system in installing and operating costs. The techniques can be classified into 2 categories; (1) active method: by supplying external power source to the fluid or the equipment; (2) passive method: by turbulence promoter (such as special surface geometries, twisted tape, propeller, tangential inlet nozzle, snail entry, axial/radial guide vane, spiral fin) or fluid additives (such as nanofluid), without using any direct external power source. Due to its easy installation/operation and cost saving passive method has drawn great attention.

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Nomenclature

		y	pitch length of twisted tape (m)
D	Tube diameter(m)		**Greek symbol**
f	Friction factor	ρ	Density(kg m^{-3})
h	Heat transfer coefficient ($Wm^{-2}K^{-1}$)	μ	Dynamic viscosity (N s m^{-2})
k	Thermal conductivity (W m^{-1} K^{-1})	φ	Volume fraction of nanofluid
L	Length of tubes (m)		**Abbreviations**
N	Number of twisted tapes	NSGA	Non-dominated Sorting Genetic Algorithms
Nu	Nusselt Number ($= hD_h / k$)	ST	single tape as single swirl flow generator
P	Pressure (Pa)	Co-DTs	dual co-tapes as co-dual swirl flow generators
Po	Poiseuille number ($= f\,Re$)	C-DTs	dual counter tapes as counter-dual swirl flow generators
Pr	Prandtl number ($= \nu / \alpha$)	Co-TTs	triple co-tapes as co-triple swirl flow generators
Re	Reynolds number ($= \rho U D_h / \mu$)	Co-QTs	quadruple co-tapes as co-quadruple swirl flow generators
U	Velocity (m s^{-1})	CC-QTs	quadruple counter tapes as counter-quadruple swirl flow generators
W	Tape width (m)	PC-QTs	quadruple counter tapes as parallel-quadruple swirl flow generators

One important group of devices used in passive method is swirl flow devices which produce secondary recirculation on the axial flow leading to an increase of tangential and radial turbulent fluctuation. This allows a greater mixing of fluid inside a heat exchanger tube and subsequently reduces the thickness of the boundary layer [1-6]. Among the swirl generators of tube inserts, twisted tapes (TTs) have gained great attention and widely used for producing compact heat exchangers and upgrading the heat transfer rate of the existing heat exchanger due to its low cost, acceptable thermal performance and ease of manufacture installation [2]. In the past investigations, the heat transfer enhancement by twisted tape insert has been considered on both experimental and numerical works. Saha et al. [7] studied the heat transfer and pressure drop behaviors in a tube fitted with regularly-spaced twisted tape elements. Ray and Date [8] predicted the heat transfer in a square sectioned duct fitted with twisted tape in both laminar and turbulent flows. Akhavan-Behabadi et al. [9] reported the influence of the twisted tape on heat transfer and pressure drop characteristics in horizontal evaporators for the flow using R-134a. Eiamsa-ard et al. [10] investigated the heat transfer and pressure drop behaviors in a double pipe heat exchanger fitted with regularly-spaced twisted tape elements at several space ratios. Effect of the combined conical-ring and twisted tape on the heat transfer, friction factor and thermal performance factor characteristics were also studied by Promvonge and Eiamsa-ard [11]. Influence of the tube equipped with the short-length twisted tape on the mean Nusselt number, friction factor and thermal performance factor characteristics for several tape length ratios was examined by Eiamsa-ard et al. [12]. Again, Eiamsa-ard et al. [13-15] reported the effect of the dual twisted tape elements in tandem, twin twisted tape with counter/co-swirling flow and delta-winglet twisted tape on the heat transfer enhancement, friction factor and thermal performance factor. They found that all tape arrangements provide better heat transfer rate than those of the typical twisted tape while the friction factors are also increasing. Eiamsa-ard and Promvonge [16] also studied the effect of helical tape with/without core-rod and regularly-spaced helical tape swirl generators on the heat transfer and pressure drop characteristics in a heat exchanger tube. Chang et al. [17] examined the heat transfer and pressure drop characteristics in a tube fitted with single, twin and triple twisted tapes in a heat exchanger tube. Among the tested tapes, the triple twisted tapes offered the highest heat transfer rate and thermal performance factor. Recently, Eiamsa-ard and Kiatkittipong [18] performed an experimental and numerical study to investigate the effect of the number and arrangement of twisted tape inserts on the thermal and pressure drop performance of TiO_2-water nanofluid flow. They investigated seven different arrangements of twisted tapes (ST, Co-DTs, C-DTs, Co-TTs, Co-QTs, PC-QTs, and CC-QTs) and finally they presented three pair of correlation for Nusselt number and friction factor. The empirically correlations of Eiamsa-ard and Kiatkittipong are used in the present study to investigate the multi-objective optimization of nanofluid flow in tubes fitted with multiple twisted tapes in different arrangement.

Table 1
Details of twisted tape inserts.

Twisted tape	Number of tape	Tape Width (W)	Tape pitch length (y)	Twist ratio (y/W)	Tape Thickness (δ)	Swirl type
ST	1	19 mm	57 mm	3.0	0.8 mm	S-S
Co-DTs	2	8 mm	225 mm	3.0	Same as ST	Co D-Ss
C-DTs	2	Same as Co-DTs	Same As Co-DTs	Same as Co-DTs	Same as ST	Counter D-Ss
Co-TTs	3	Same as Co-DTs	Same as Co-DTs	Same as Co-DTs	Same as ST	Co T-Ss
Co-QTs	4	Same as Co-DTs	Same as Co-DTs	Same as Co-DTs	Same as ST	Co Q-Ss
PC-QTs	4	Same as Co-DTs	Same as Co-DTs	Same as Co-DTs	Same as ST	Counter Q-Ss in P-A
CC-QTs	4	Same as Co-DTs	Same as Co-DTs	Same as Co-DTs	Same as ST	Counter Q-Ss in C-A

Nanofluid which is the suspensions of nanometer-sized particles or nanoparticles such as TiO_2, Al_2O_3 and CuO are currently attractive for using in heat transfer system as alternative mediums due to their greater thermal conductivities as compared to that of base fluids. The influences of nanofluid on heat transfer enhancement were studied by several researchers [19-23]. In general, nanofluid with higher particle loading gave higher heat transfer rate and friction loss. With proper particle loading, most nanofluid yielded appreciable heat transfer enhancement with insignificant friction loss. In addition, nanofluid was utilized together with other heat transfer enhancement devices, especially twisted tapes [24-29]. Apparently, the compound techniques possessed better performance than individual techniques, particularly at high Reynolds number [18].

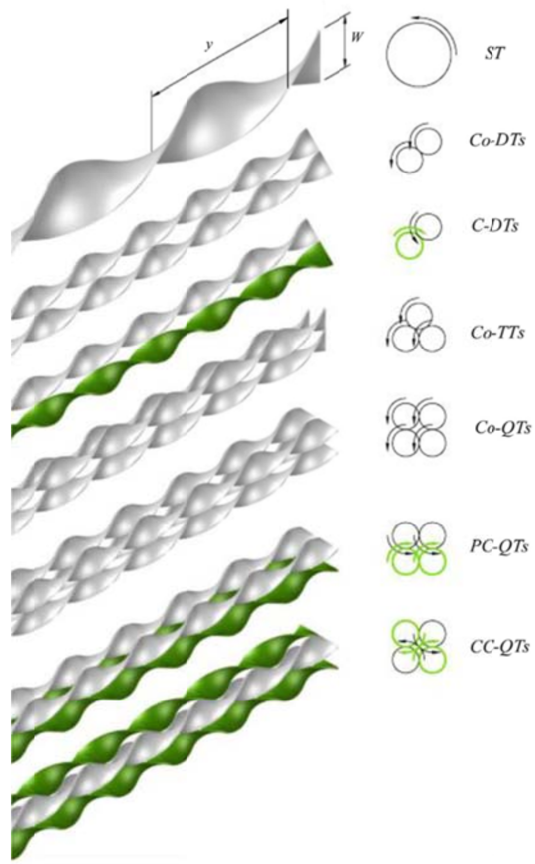


Fig. 1. Multiple twisted tapes inserts in differen arrangement which are investigated in this paper

According to the above review, it has been proven that the heat transfer enhancement by using twisted tape together with nanofluid is a promising approach. However, the influences of optimal number and also optimal arrangement of twisted tapes on thermal and pressure drop performance of nanofluids are not explored. Simultaneous using of twisted tape inserts and nanofluids will result in increasing the heat transfer and pressure drop; hence, by doing a multi-objective optimization, optimal design points should be identified. One of the most complete and the best multi-objective optimization algorithms also used in this paper is NSGA II algorithm. This algorithm proposed by Deb [30] for the first time has been applied abundantly for the multi-objective optimization of engineering issues in recent years [31-34].

In this paper, experimentally derived correlations of Nusselt number (*Nu*) and friction factor (*f*) are used in a Pareto based multi-objective optimization approach to find the best possible combinations of heat transfer and pressure drop of TiO_2-water nanofluid flow in round tubes fitted with multiple twisted tape inserts in different arrangement. It is shown that some interesting and important relationships as useful optimal design principles involved in the thermal performance of nanofluid flow in round tubes fitted with multiple twisted tape inserts in different arrangement can be discovered by Pareto based multi-objective optimization approach.

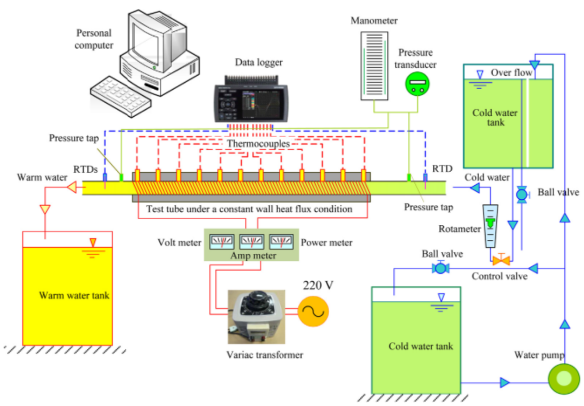


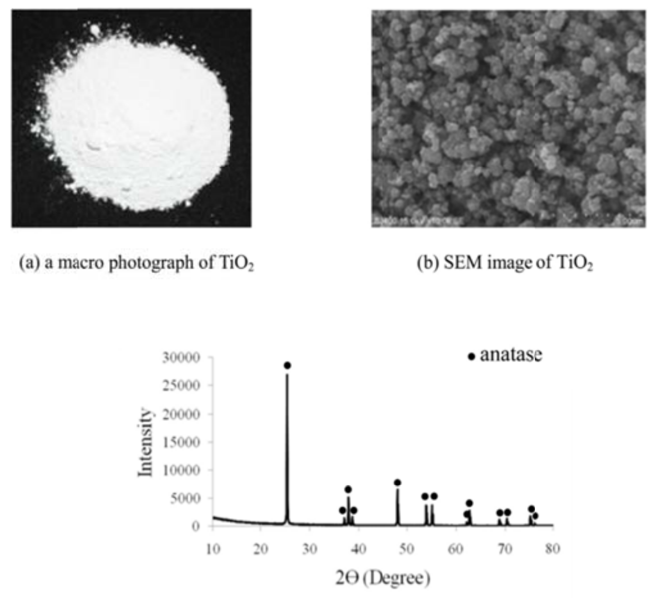
Fig. 2. Experimental set up for investigating thermal performance of tubes fitted with multiple twisted tapes inserts [18]

2. Defining the design variables

In the present study there are four independent design variables: the number and arrangement of twisted tape inserts (*N*), TiO_2 volume fraction (φ), Reynolds number (*Re*) and Prandtl number (*Pr*). In this study, seven different single, dual, triple and quadruple twisted tapes arrangement are investigated. The schematic definition and details of each one are shown in figure 1 and table 1.

The seven twisted tapes which are shown in figure 1 can be classified in three different categories. In category 1, all tapes are aligned to be twisted in the same direction. In this case, single, dual, triple and quadruple twisted tapes are assigned as ST, Co-DTs, Co-TTs and Co-QTs, respectively. In category 2, the tapes have counter-swirl flow. This arrangement is designed for dual and quadruple twisted tapes. In the case of dual twisted tapes, two tapes are aligned to be twisted in opposite directions and assigned as C-DTs. In the case of quadruple twisted tapes, two tapes are aligned to be twisted in the same direction which is opposite to that of other two tapes.

In addition, the quadruple counter tapes consisting of two pairs of tapes are in two different arrangements, to produce (1) parallel counter-swirl flow and (2) cross counter-swirl flow. For parallel counter-swirl flow, the tapes in each pair produced swirl flow in the same direction; in this case the quadruple counter tapes are assigned as PC-QTs. For cross counter-swirl flow, the tapes in each pair produced swirl flow in the opposite directions. The quadruple counter tapes are assigned as CC-QTs which are classified in category 3. According to the mentioned notes, the MOO process in the present study is performed for three different categories.



(a) a macro photograph of TiO_2
(b) SEM image of TiO_2
(c) XRD pattern of TiO_2

Fig. 3. Details of TiO_2 nanoparticles: a) macro photograph, b) SEM image, c) XRD pattern.

Design variables and their range of variations are shown in table 2.

According to Re values of table 2, it is obvious that the flow regime is turbulent. Moreover the variation range of *Pr* is related to TiO_2-water nanofluid as working fluid.

3. Defining the objective functions

In heat exchangers tubes, heat transfer coefficient and pressure drop should be maximized and minimized respectively. Recently, Eiamsa-ard and Kiatkittipong [18] performed an experimental and numerical study to investigate the effect of the number and arrangement of twisted tape inserts on the thermal and pressure drop performance of TiO_2-water nanofluid flow.

The schematic arrangement of experimental apparatus of them is shown in figure 2.

Table 2
Design variables and their range of variations.

Design Variables	Category 1: ST, Co-DTs, Co-TTs, Co-QTs		Category 2: ST, C-DTs, PC-QTs		Category 3: CC-QTs	
	From	To	From	To	From	To
N	1	4	1, 2 and 4		4	
φ (%)	0	0.21	0	0.21	0	0.21
Re	5400	15200	5400	15200	5400	15200
Pr	3	6	3	6	3	6

Moreover, figure 3 shows some detailed information about TiO_2 nanoparticles and the other experimental conditions. They investigated seven different arrangements of twisted tapes (ST, Co-DTs, C-DTs, Co-TTs, Co-QTs, PC-QTs and CC-QTs) which were classified in three different categories.

Finally they presented three pair of correlation for Nusselt number (*Nu*) and friction factor (*f*). The empirically correlations of Eiamsa-ard and Kiatkittipong are used in the present study to investigate the multi-objective optimization of nanofluid flow in tubes fitted with multiple twisted tapes in different arrangement. The empirical correlation of Eiamsa-ard and Kiatkittipong [18] for $Nu = \frac{hD}{k}$ and $f = \frac{\Delta p}{(\frac{l}{D})(\frac{1}{2}\rho \upsilon 2)}$ for category 1 included ST, Co-DTs, Co-TTs and Co-QTs tapes are as follows:

$$Nu = 0.103(1+N)^{0.768}(1+\varphi)^{0.438} Re^{0.618} Pr^{0.4} \quad (1)$$

$$f = 0.437(1+N)^{1.25}(1+\varphi)^{0.268} Re^{-0.233} \quad (2)$$

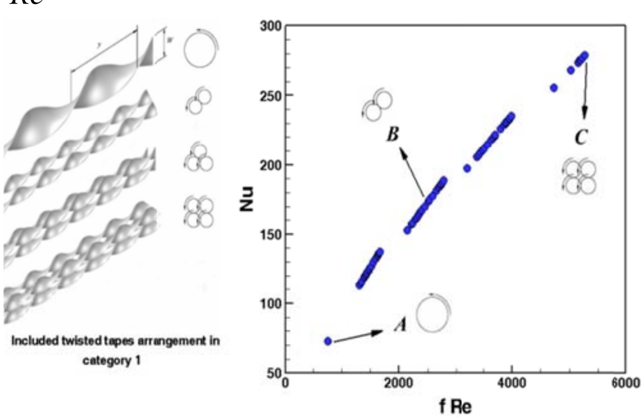


Fig. 4. Multi-objective Pareto results for Nu and f Re related to twisted tapes of category 1

Nu and *f* for category 2 included ST, C-DTs and PC-QTs tapes are as follows:

$$Nu = 0.104(1+N)^{0.789}(1+\varphi)^{0.439} Re^{0.618} Pr^{0.4} \quad (3)$$

$$f = 0.468(1+N)^{1.217}(1+\varphi)^{0.266} Re^{-0.234} \quad (4)$$

Finally *Nu* and *f* for category 3 included CC-QTs tapes are as follows:

$$Nu = 0.096(1+N)^{0.834}(1+\varphi)^{0.468} Re^{0.618} Pr^{0.4} \quad (5)$$

$$f = 0.416(1+N)^{1.221}(1+\varphi)^{0.262} Re^{-0.234} \quad (6)$$

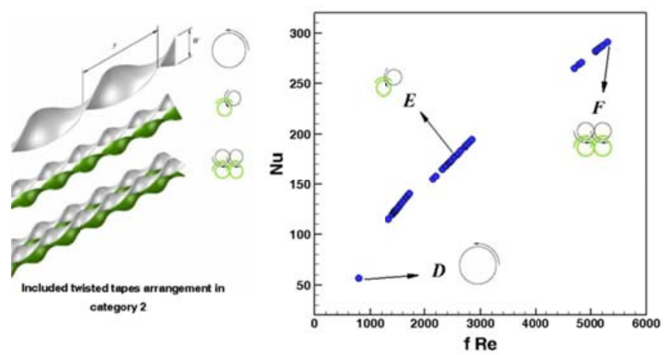


Fig. 5. Multi-objective Pareto results for Nu and f Re related to twisted tapes of category 2

It should be noted that the behavior of f with respect to changing *Re* is not similar to that of Δp, for example increasing Re leading to decrease in f but leading to increase in Δp. Hence to solve this problem, instead of *f*, another parameter namely $f\,Re = \frac{\Delta P / L}{\mu U / D^2}$ (Poiseuille number), which has the same behavior with Δp with respect to changing Re, should be investigated in optimization process [35, 36].

Multiplying a Re on both sides of equations 2, 4 and 6 yield the *f* Re number as follows:

Category 1:

$$f\ Re = 0.437(1+N)^{1.25}(1+\varphi)^{0.268}\ Re^{0.733} \quad (7)$$

Category 2:

$$f\ Re = 0.468(1+N)^{1.217}(1+\varphi)^{0.266}\ Re^{0.766} \quad (8)$$

Category 3:

$$f\ Re = 0.416(1+N)^{1.221}(1+\varphi)^{0.262}\ Re^{0.766} \quad (9)$$

Therefore the objective functions in the present paper is maximizing *Nu* (non-dimensional heat transfer coefficient) and minimizing *f Re* (non-dimensional pressure drop) which are presented in equations 1,3,5,7, 8 and 9 respectively for three different arrangements of twisted tapes.

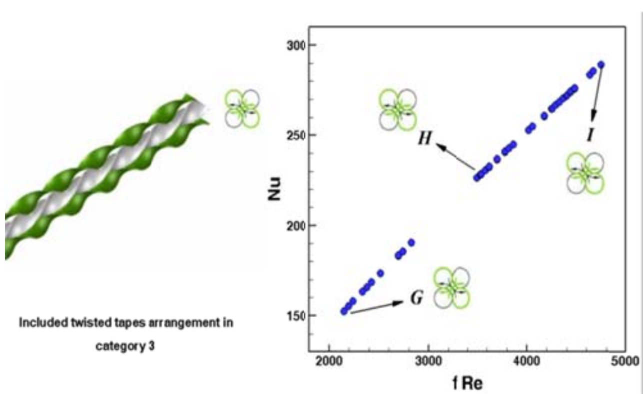


Fig. 6. Multi-objective Pareto results for Nu and f Re related to twisted tapes of category 3

4. Multi-objective optimization of TiO2-water nanofluid flow in tubes fitted with multiple twisted tapes in different arrangement

In order to investigate the optimal thermal performance of round tubes which are fitted with multiple twisted tape inserts in different arrangements, the experimentally derived correlations which were presented in section 3 are now employed in a multi-objective optimization procedure using NSGA II algorithms [30]. In all runs a population size of 60 has been chosen with crossover probability (P_c) and mutation probability (P_m) as 0.7 and 0.07 respectively.

The two conflicting objectives in this study are *Nu* (non-dimensional heat transfer coefficient) and *f Re* (non-dimensional pressure drop) that should be optimized simultaneously with respect to the design variables *N*, *φ*, *Re* and *Pr* (Table 1). The multi-objective optimization problem can be formulated in the following form:

Category 1:

$$\begin{aligned} &\text{Maximize} && Nu = f_1(N,\varphi,Re,Pr) \\ &\text{Minimize} && f\ Re = f_2(N,\varphi,Re) \\ &\text{Subject to:} && 1 \le N \le 4 \\ &&& 0 \le \varphi \le 0.0021 \\ &&& 5400 \le Re \le 15200 \\ &&& 3 \le Pr \le 6 \end{aligned} \quad (10)$$

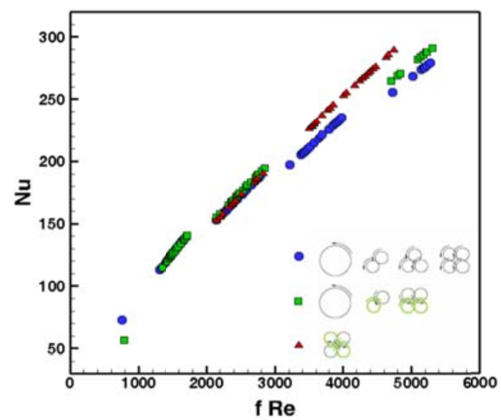


Fig. 7. Overlap graph of Pareto results of category 1, 2 and 3

Category 2:

$$\begin{cases} \text{Maximize} & Nu = f_3(N,\varphi,Re,Pr) \\ \text{Minimize} & f\ Re = f_4(N,\varphi,Re) \\ \text{Subject to:} & N = 1,\ 2\ and\ 4 \\ & 0 \le \varphi \le 0.0021 \\ & 5400 \le Re \le 15200 \\ & 3 \le Pr \le 6 \end{cases} \quad (11)$$

Figures 4-6 show the Pareto front of the mentioned objective functions for three different categories of twisted tapes.

Category 3:

$$\begin{cases} Maximize \quad Nu = f_1(N,\varphi,Re,Pr) \\ Minimize \quad f\,Re = f_2(N,\varphi,Re) \\ \\ Subject\ to: \quad N = 4 \\ 0 \le \varphi \le 0.0021 \\ 5400 \le Re \le 15200 \\ 3 \le Pr \le 6 \end{cases} \tag{12}$$

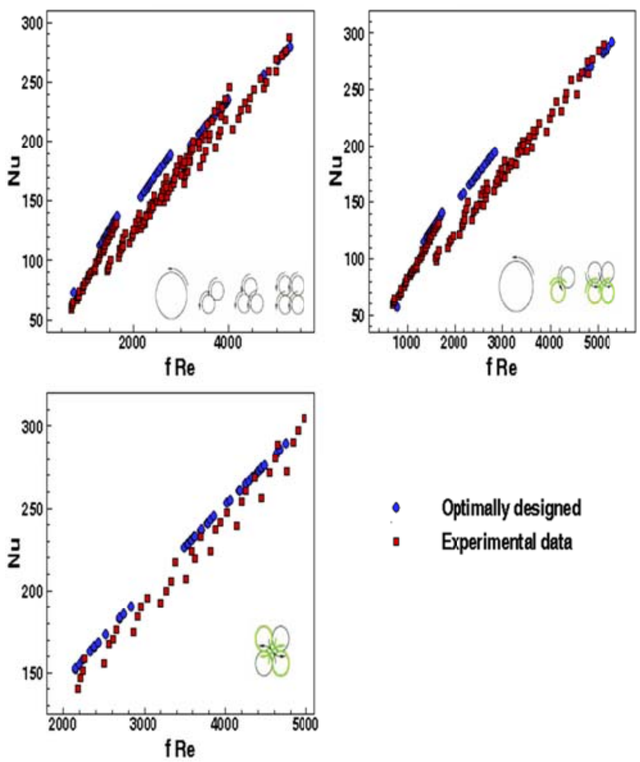


Fig. 8. Overlap graph of the obtained optimal Pareto front with the related experimental data [18] for category 1, 2 and 3

It is clear that the points have no dominancy over one another, meaning that no two points can be found where one of their objective functions is the same and the other one is different. In other words, as we move from one point to another, definitely, one objective function gets better and the other one gets worse. In each category, three optimal points, designated by *A*, *B* and *C* (category 1), *D*, *E*, and *F* (category 2) and *G*, *H* and *I* (category 3) can be observed, whose corresponding design variables have been presented in table 3.

The points illustrated in figures 4-6 have unique features. Points *A, D, G* exhibit the least *f Re* (pressure drop) and similarly points *A, D, G* exhibit the highest *Nu* (heat transfer) in each category. It is obvious from figures 4-6 that increasing the number of twisted tape insert leading to increase in *Nu* but increasing in *f Re* which is due to more increasing in mixing of fluid in tubes.

In general, it would be ideal to find a point at which both objective functions are adequately satisfied. To find such a point, mapping method is used [33]. For this purpose, we assume the values of both objective functions to be between 0 and 1, and calculate the norm of these functions; the point with the highest norm value constitutes the ideal design point. Points *B, E* and *H* are the points that have been obtained from this approach, and it can be said that they adequately satisfy both objective functions of *Nu* and *f Re*.

It would be interesting to overlay the three different Pareto fronts and compare them in one curve. Figure 7 shows the overlap graph of three different Pareto fronts related to three categories of twisted tapes. As shown there is not much difference between them, however it seems that the Pareto front of category 3 is able to reach higher *Nu* number moreover this Pareto front has closer range of *Nu*- *f Re* with respect to the two other Pareto fronts. It would be interesting and useful to compare the experimental data of Eiamsa-ard and Promvonge [18] with the extracted Pareto front of present study. Figure 8 shows the overlap of the Pareto front of three categories and the related experimental data. This figure indicates that in each category, the Pareto front has recognized accurately the best boundary of the experimental data with respect to the lowest *f Re* and highest *Nu*. This point verifies the validity of the optimization process performed in the present study.

The changes of the design variables associated with the Pareto front can be effective and useful in achieving the suitable thermal design conditions. Figure 9 illustrates the changes of *Nu* and *f Re*, versus the input design variables from point *A* to point *I* for three different categories.

It is obvious from this figure that *Pr* is constant in all categories and is equal to 6. Similarly, as it is obvious in this figure, in each *N*, *Re* varies almost linearly.

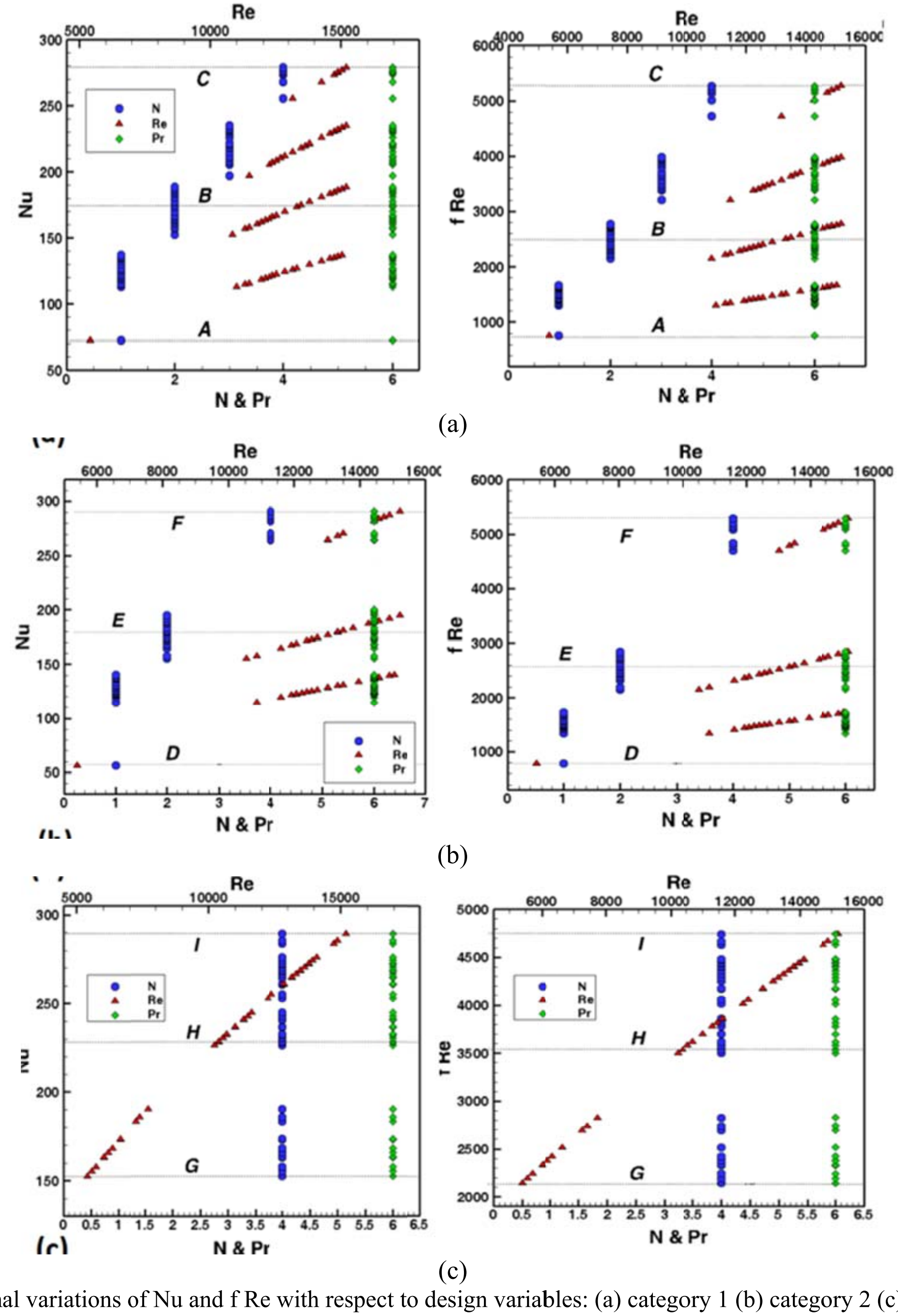


Fig. 9. Optimal variations of Nu and f Re with respect to design variables: (a) category 1 (b) category 2 (c) category 3.

Table 3
The values of objective functions and their associated design variables of the optimum points.

Point		N	φ	Re	Pr	Nu	f Re
Category 1	A	1	0.00	5400	6	72.76	757.74
	B	2	0.0013	13488	6	175.02	2539.37
	C	4	0.0021	15200	6	279.01	5270.80
Category 2	D	1	0.00	5400	6	56.49	786.35
	E	2	0.0014	13022	6	176.96	2528.79
	F	4	0.0021	15200	6	291.32	5300.52
Category 3	G	4	0.00	5400	6	135.57	2145.60
	H	4	0.0013	10222	6	226.27	3499.44
	I	4	0.0021	15200	6	289.25	4743.14

5. Conclusion

In this paper, multi-objective optimization of TiO_2-water nanofluid flow in round tubes fitted with multiple twisted tape inserts in different arrangement has been successfully implemented using the combination of experimentally derived correlations and NSGAII algorithm. The design variables were the number and arrangement of twisted tape inserts (N), TiO_2 volume fraction (φ), Reynolds number (Re) and Prandtl number (Pr). Seven twisted tape arrangement in three different categories were investigated and the ultimate goal was to simultaneously increase the non-dimensional heat transfer coefficient (Nu) and reduce the non-dimensional pressure drop ($f\ Re$). It was shown that some interesting and important relationships as useful optimal design principles were discovered by Pareto based multi-objective optimization approach, which could not be obtained except by this method.

Finally the optimal Pareto front of the present study were overlaid with the available experimental data and it was seen that the Pareto front is able to recognize the best boundary of experimental data with respect to the lowest $f\ Re$ and highest Nu, which verifies the validity of the optimization process performed in the present study.

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