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Heat Transfer and Pumping Power of Al_2O_3-Water Nanofluids in Commercial Galvanized Iron Pipes

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Abstract: Employing nanofluids as heat transfer agents may enhance the heat transfer but at the expense of the pumping power needed. Most of the studies investigated this issue counted for smooth pipes; however, the rough pipes have larger friction factors and consequently larger pumping power penalty. To fulfill this gap, in this paper the rough pipes made of galvanized iron have been studied, rather than the smooth pipes. Particularly, Al_2O_3-water nanofluids running in commercial galvanized iron pipes have been considered. The studied variables are the nanoparticles concentration (0.01 – 0.1%) and nanofluid velocity in terms of Reynolds number (4000 - 100000). A multi- objective optimization method (ε method) is used to formulate and solve the problem considering the galvanized iron pipes roughness in order to maximize the heat transfer enhancement along with decreasing the pressure drop via manipulating the nanofluid concentration and velocity. The optimization results are plotted in a Pareto front whereby sets of trade-offs between the minimum pumping power and the maximum convective heat transfer are given along with the corresponding nanoparticles concentration and nanofluids velocity. The results indicate that at low nanoparticle concentrations, the extra pumping power is almost negligible; from Pareto front the minimum pumping power penalty along with maximum convective heat transfer can be attained for instance at a nanofluid velocity of 0.5 m/s and nanofluid concentration of 0.005. A linear relation between the maximum pressure drop and the nanofluid velocity is noticed.
Keywords: Rough galvanized pipes, Al_2O_3-water nanofluids, Convective heat transfer, Pumping power, ε multi- objective optimization method, Energy systems.

Introduction and Methodology[1]

Nanofluids as a heat transfer agent proved unique enhanced thermophysical properties that equip it to be used in industrial processes as well as the many energy systems[1]. Nonetheless these advantages may be neutralized by the extra pressure drop accompanied using the nanofluids[2]. The extra pressure drop is attributed to the increase in the density and the viscosity of the fluid by the dispersed nanoparticles. To remain the fluid flow at the designed values, it becomes a necessity to increase the pumping power in order to compensate the pressure drop. This extra pumping power is counted as a penalty of nanofluids applications as it leads to consuming electricity to run the pumps and consequently decreases the net energy efficiency of the system. Therefore, concrete effort has been directed towards this problematic issue.

The heat transfer characteristics and pressure drop of nanofluids employing multiwall carbon nanotubes attract the attention of different research groups[3-6]. MWCT-oil inside an inclined smooth and microfin have been examined experimentally[3]. They reported the pressure drop in the microfins is higher than that in the smooth tubes. Nonetheless, this conclusion was based on low MWCT concentrations (0.05- 0.2 wt. %). In another study, MWCNT- water nanofluids used inside a helically coiled heat exchanger and experimental findings reported significant pressure drop[4]. Double wall carbon nanotubes suspended in water (COOH-DWCNT-water) inside a double tube heat exchanger has a high increase in heat transfer coefficient (on average 25%) but a considerable increase pressure drop (up to 20%). Nonetheless, at low nanoparticles concentrations (0.01vol. %) the adverse effects of pressure drop neutralize the benefits of enhanced heat transfer coefficient[5]. They all demonstrated considerable pressure drop in the carbon nanotubes nanofluids.

Likewise, the nanofluids with copper oxide have been investigated by many researchers[7,8]. Nanofluid of oil- CuO nanofluids in a horizontal smooth and microfin tubes leads to 230% enhancement in heat transfer due to the increased convective heat transfer, Nu number, thermal conductivity, and the pressure drop. Nevertheless, the penalty of the pressure drop was also high; the maximum increase in the pressure drop was 47% inside the microfin tubes[7]. The same nanofluid has been investigated by Saeedinia et al.[8] and concluded maximum pressure drop of 63% and maximum heat transfer enhancement of 45% under laminar flow conditions.

TiO_2-water nanofluids under different condition of turbulent flow inside a microfin tubes also demonstrated pressure drop through CFD Ansys simulation[9]. Another study on the same nanofluids highlighted the highly dependence on the Reynolds number[10].

Wu et al. (2013) reported that Al_2O_3-Water nanofluids inside a double pipe helical heat exchanger. They concluded that usage of nanofluids in heat transfer applications is not attractive for the pressure drop penalty reduces the overall efficiency enhancement[11].

Conversely, Ali (2014) used CFD ANSYS FLUENT to demonstrate that there is no pressure drop penalty with Al_2O_3 nanoparticles concentrations below 2% when turbulent flow of Al2O3- water nanofluids is used inside a coiled tube-in- tube heat exchanger[12]. Likewise, Sahin et al (2013) reported enhanced heat transfer coefficient accompanied with considerable pressure drop when turbulent Al_2O_3- water was used[13]. On the other hand, under laminar flow conditions the pressure drop of hybrid Al_2O_3-Cu/water nanofluids is experimentally investigated and the findings refer to enhanced heat transfer but with small pressure drop[14].

Kayhani et al. (2012) experimentally measured pressure drop of 40 nm Al_2O_3- water nanofluids under turbulent regime. They reported that both the water and the Al2O3 water based nanofluids are similar in sense of the pressure drop[15].

Opposing results have been reported by other studies. Alumina and copper nanofluids show no pressure drop[16]. Jamal-Abad et al. (2013) investigated Al- and Cu- water based nanofluids and demonstrated that there is not pressure drop penalty[16]. Azizi et al. (2015) experimentally tested Cu-water nanofluids pressured drop and heat transfer characteristic inside a cylindrical micro channel[17]. They reported low pressure drop with all the tested nanofluids, but increase with Reynolds number.

On the other hand, CeO_2-water nanofluids investigation showed that the heat transfer conditions can be enhanced significantly, with a negligible pressure drop, via optimizing the operating conditions[18-20].

These above studies and many others available in the literature can be classified mainly into experimental work and numerical simulation. Nevertheless, few studies paid attention to the optimization, and for our knowledge fewer studies addressed multi- objective optimization[21,22].

Similarly different types of conventional heat exchangers were investigated, also solar collectors employing nanofluids are investigated in some studies[23,24]. Most often smooth tubes are used, rather than the rough commercial pipes. Nevertheless, commercial rough pipes are used in many applications such as Flat plate solar collectors (FPSC) are used broadly especially in the residential sector for heating applications[25]. Likewise, flat plate solar collectors are used in industrial processes needing low temperature water or air[26]. The main component of FPSC is the absorber where the heat transfer fluid is circulated to absorb solar heat and then deliver it to application process[27]. Thus the internal convective heat transfer coefficient of the fluid inside the absorber tubes considerably affects the collectors' energy efficiency[28] which is dependent on the container configuration, fluid properties, and operating conditions. This absorber is manufactured from materials such as galvanized iron[29] as shown in Figure 1. Galvanized iron pipes are commercial pipes with rough surface. The roughness exists in the surface layer and other layers beyond.

There are many industrial plants and utilities have networks of commercial pipes, FSC is just an example that can be found in different places on the roof of homes. Thus it is given herein as a tangible example.

Figure 1. Absorber of a flat plate solar collector with a galvanized pipes and galvanized sheet[29]

Hence this work contributes via applying a multi- objective optimization method to enhance heat transfer characteristics and reduce the pumping penalty of Al_2O_3-water nanofluids acting as the heat transfer agent in galvanized iron tubes. The main and new contribution- as far as the author know- is investigating the commercial galvanized iron pipes, instead of the smooth pipes studied in most of the published searches. The benefits of focusing on commercial rough pipes herein is paving the way to use nanofluids in many applications that do not employ smooth pipes, and just the commercial rough pipes fit them well.

Commercial rough pipes

Commercial pipes or knowing as rough pipes are the pipes with surface imperfections existing at sub layers, in addition to the laminar sub layer, which is known as roughness height (e). This imperfection in terms of the roughness height and Reynolds number affect the hydraulic behavior of the tube through inducing turbulent flow. Thus it is a necessity to estimate the roughness (f) of the tube which can be attained from Moody's diagram and the knowing the value of relative roughness (e/D) where D is the inner diameter of the tube[30]. Moody's diagram indicates clearly that at the same Reynolds number there is a large difference between the friction factor of the rough tubes and smooth tubes. For instance, at Reynolds of 15,000 the friction factor equals 0.026 in case of smooth pipe, while it equals 0.072 in case of rough pipe with (e-D) of 0.05; this means the friction factor of rough pipe is around 2.7 times that of the smooth pipe. For each commercial material, there is a unique roughness height. Table 1 lists the average of the roughness height for common commercial materials.

Table 1. Average roughness of commercial tubes [30]

Commercial Pipe	e (mm)
Galvanized iron	0.15
Brass	0.0076
Commercial steel / wrought iron	0.046
Riveted steel	0.91- 9.1

Objective

Rather than studying nanofluids in smooth pipes which is very common in the literature, is this study commercial rough pipe employing Al_2O_3-water nanofluid is investigated. These pipes are cheaper; in addition they are already used in many systems such as flat plate solar collectors and piping networks. Consequently the results of this study may benefit these sectors with rough pipes. This study contributes via applying a multi-objective optimization method to enhance heat transfer characteristics and reduce the pumping penalty of Al_2O_3-water nanofluids. Herein the commercial galvanized iron pipe, known by its rough surfaces causing larger pressure drop, is used rather than the smooth pipes that have been intensively studied in literature.

Methodology

A modeling and optimization approach has been implemented. A model is developed to describe the problem. An optimization function has been defined based on the model equations; particularly a multi-objective optimization method is used in order to consider simultaneously more than one optimization target namely considering maximizing the convective heat transfer and minimizing the pressure drop.

A model is developed to describe the convective heat transfer flow of a nanofluid (Al_2O_3-water) inside a rough tube under a fully developed turbulent flow conditions. The model accounts for the tube configuration geometry, the operating conditions, and the nanofluids properties for they are the three factors affecting the convective heat transfer. Also the thermophysical properties of the nanofluids affecting the hydrodynamic behavior of the flow are included in order to allow calculating the pressure drop and the pumping power. These properties are calculated from particulate correlations.

The multi- objective optimization problem has been solved via implementing the ε method considering a wide range of the nanoparticles concentrations (ϕ) and fluid velocity (u) inside a rough horizontal tube made of galvanized iron.

Modeling and optimization

The density and the specific heat of the nanofluids are calculated by the mixing theory as follows[31]:

$$\rho_{nf} = \phi \ \rho_p + (1-\phi) \ \rho_{bf} \tag{1}$$

$$C_{pnf} = \phi \, C_p + (1-\phi) \, C_{bf} \tag{2}$$

The viscosity is to be predicted by Einstein's equation[32]:

$$\mu_{nf} = \mu_{bf} \ (1+2.5\phi) \tag{3}$$

Thermal conductivity of the nanofluids can be estimated using Yu and Choi formula[33]:

$$k_{nf} = [\frac{k_p + 2k_{bf} + 2(k_p - k_{bf})(1+\beta)^3 \phi}{k_p + 2k_{bf} - (k_p - k_{nf})(1+\beta)^3 \phi}] k_{bf} \tag{4}$$

β denotes the ratio between the nanolayer thickness to the original nanoparticles radius and its value can be 0.1 according to the formula developers.

The optimization problem is formulated as a multi- objective optimization due to existence of two opposed objectives functions.

$$Obj.\,fun. = Max \quad f \tag{5}$$

$$f = f_1(\phi, \mathrm{Re}, Nu, \mathrm{Pr}) - f_2(\phi, \mathrm{Re}, Nu, \mathrm{Pr}) \tag{6}$$

$$f_1 = Q_{conv.nf} = h_{nf} \ A_s \ (T_w - T_b) \tag{7}$$

$$h_{nf} = \frac{Nu_{nf} \ k_{nf}}{D} \tag{8}$$

Nusselt number can be attained from Petukhov equation[34] as:

$$Nu_{nf} = \frac{(f/8)(\mathrm{Re}\,\mathrm{Pr})}{1.07 + 12.7(\mathrm{Pr}^{2/3} - 1)(f/2)^{1/2}} \tag{9}$$

where f_1 is the convective heat transfer $Q_{conv.nf}$ of the nanofluids as a function of nanoparticles concentration, Reynolds number, and Nusselt number.

$$f_2 = \dot{W}_p = (\dot{m}_{nf} / \rho_{nf})\,\Delta P_{nf} \qquad (10)$$

where f_2 is the required pumping power $\dot{W}_p$ to circulate the nanofluids as a function of the Reynolds number, Nusselt number, Prandtl number, and nanoparticles concentration.

The pressure drop is determined by Darcy- Weisbach equation:

$$\Delta P = f\,\frac{L}{D}\,\frac{\rho_{nf}\,u^2}{2\,g_c} \qquad (11)$$

The friction coefficient f is determined by:

Smooth pipe:

$$f = (0.79 \ln \mathrm{Re} - 1.64)^{-2} \qquad (12)$$

Rough pipe:

$$f = -Log\,(\frac{\varepsilon / D}{3.7} + \frac{2.5}{\mathrm{Re}\sqrt{f}} \approx -1.8l\,Log\,(\frac{6.9}{\mathrm{Re}} + \frac{(\varepsilon / D)^{1.11}}{3.7} \qquad (13)$$

The optimization shall be conducted under restrictions and limitations that may be on some of the variables affecting the system. Thus the optimization herein is subject to:

Nanoparticles concentration:

$$0.01 \le \phi \le 0.1 \qquad (14)$$

Reynolds number:

$$4000 \le \mathrm{Re} \le 100000 \qquad (15)$$

The maximum allowed pressure drop (Pa/m) is adapted from[36];

$$\Delta P_{nf} \le 100 \qquad (16)$$

Results and Discussion

Input data

To solve the model, the physical properties of the used nanoparticles along with these of the base fluid (water) are required. Likewise, the average roughness of the galvanized roughness pipes is required to determine the friction coefficient of the pipe. These properties are listed in Table 2. Also, the geometry of the pipes is needed to estimate Reynolds number, particularly the inner diameter of the pipe is 0.15 m and 600 m length.

Table 2. Physical properties of the used nanoparticles and the base fluid[30,36-40]

	Water	Al_2O_3	Galvanized iron pipe
ρ (kg/m^3)	1000	3960	---------
k (w/m K)	0.6	40	---------
μ (kg/m s)	0.0008	---------	---------
Cp (J/kg K)	4182	773	---------
Average roughness ε (mm)	---------	---------	1.52

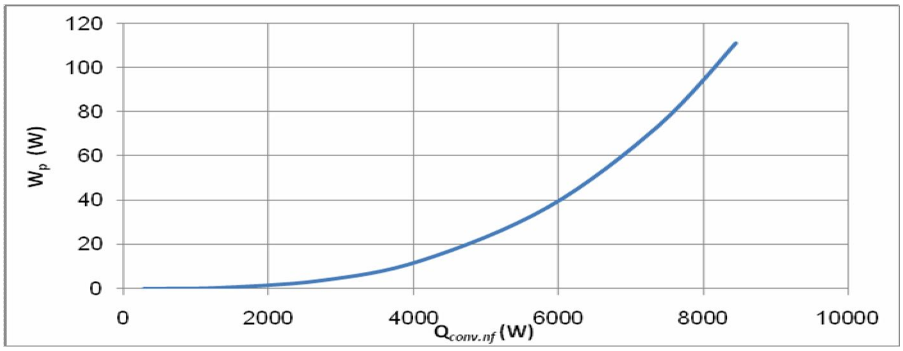
Model verification

The model is first solved for water as the working fluid and the results are compared to that in references [30, 36-40]. When the nanoparticles concentration is set equal to zero, the model results match water properties. Thus the model herein is considered valid and then used with nanofluids. Furthermore, all the used formulas describing the nanofluids have are well-known and have been picked up among the tested and widely approved formulas.

Multi- objective optimization results

The multi- objective optimization problem has been solved via implementing the ε method considering a wide range of the nanoparticles concentrations (ϕ) and fluid velocity (u) inside a rough horizontal tube made of galvanized iron. The results include many trade- offs between the maximum convective heat transfer and the minimum pumping power as represented in Figure 2.

Figure 2. Pareto front for Al_2O_3- water nanofluids in a commercial galvanized tube.



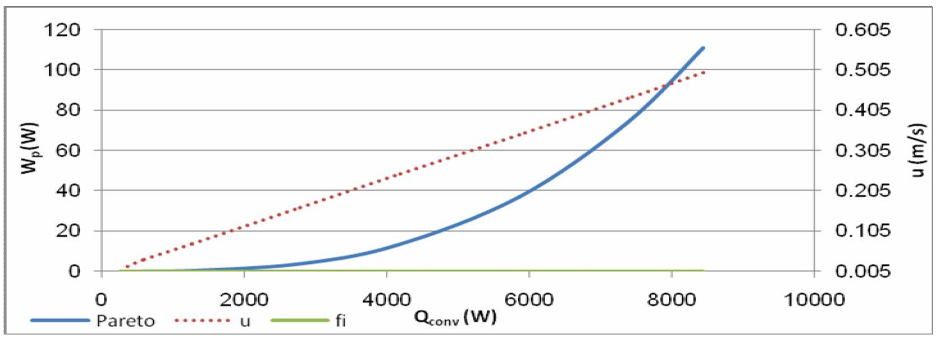
The Pareto front represents that at low convective heat transfer the extra pumping power is almost negligible, but with increasing the heat transfer above a certain limit a significant increase in the pumping power occurs.

This trend is a significant finding because it captured the conflicting findings of the experimental and theoretical work published in the literature. The same system can report negligible pressure drop and can report significant pressure drop because it depends on a number of overlapped variables that must be considered simultaneously (by multi- objective optimization) and not one by one (as in the experiments and numerical simulation).

To find an interpretation for this trend, the factors affecting the nanofluids behavior are plotted along with Pareto curve in Figure 3.

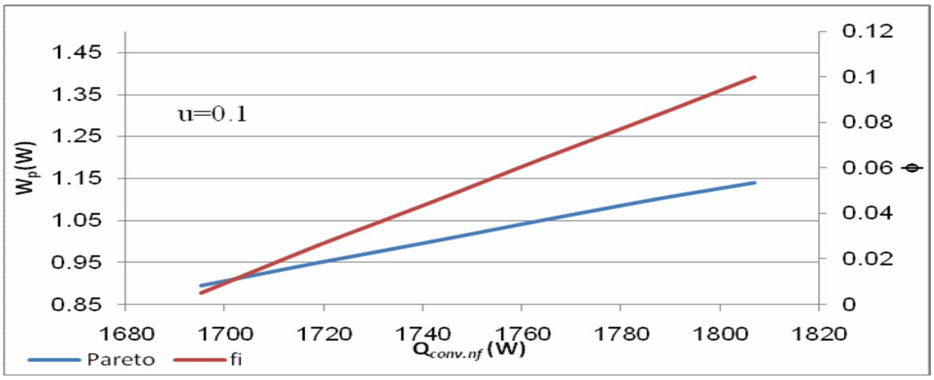
As Figure 3 shows, minimum pumping power occurs with keeping the nanoparticles concentration as low as possible, and at the same time increases the velocity to augment the heat transfer. This is applicable if there is no limit on the employed velocity, but in most of the real cases the velocity is controlled by the required flow rate that may not be allowed to be changed.

Figure 3. Optimum Pareto curve plotted at different nanofluid velocities (u) and the nanoparticles concentrations (fi)



Thus, Pareto front has been plotted again with attaining the fluid velocity at a specific value and manipulating the nanoparticles concentration. Figure 4 illustrates that the impact of the nanofluids start to appear, and to increase the convective heat it becomes a necessity to increase the nanoparticles concentration.

Figure 4. Pareto front with the optimum the nanoparticles concentrations (ϕ) at a velocity (u) of 0.1 m/s



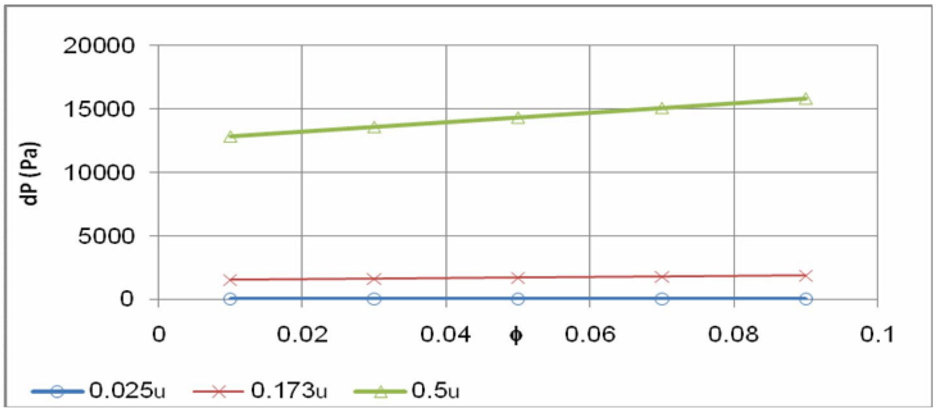
The increase in the pressure drop accompanied the enhanced convective heat transfer can be explained by looking at the change in the thermophysical properties by the dispersed nanoparticles. The next following figures highlight the enhancement in the thermophysical properties over a range of the nanoparticles concentrations.

Pressure drop and pumping power analysis

In this section the effect of the different conditions affecting the pressure drop and pumping power are analyzed.

Figure 5 illustrates the mutual effect of the operating conditions on the pressure drop. Not only the nanoparticles concentration affects the pressure drop, but the velocity has an obvious effect. Thus investigating the nanofluids shall be done with manipulating the velocity of the flow; otherwise misleading findings can be obtained.

Figure 5. Effect of the nanoparticles concentrations (x-axis) on the pressure drop (y- axis) at three different velocities (u) namely 0.025, 0.173, and 0.5 m/s (the three lines).



At nanofluid velocity of 0.5 m/s, with increasing the nanoparticles concentration the pressure drop increased up to 30%; at a velocity of 0.137m/s the pressure drop was typically less than 10%; the pressure drop was almost negligible at a velocity of 0.025m/s. Based on these results, a relation between the maximum pressure drop accompanied nanofluids (*Max (ΔP)*) expressed in Pa and the velocity (*u*) of the nanofluid in m/s is drawn as follows:

$$Max\ ((P) = 60.766(u)$$

Thermophysical properties

The reasons beyond raising the pressure drop are increasing the viscosity and the density of the nanofluid by the dispersed solid nanoparticles, as shown in Figure 6. This increase in the pressure drop requires higher pumping power to maintain the flow at the designed value.

Figure 6. Viscosity and density change of the nanofluid at different concentration of nanoparticles (ϕ).

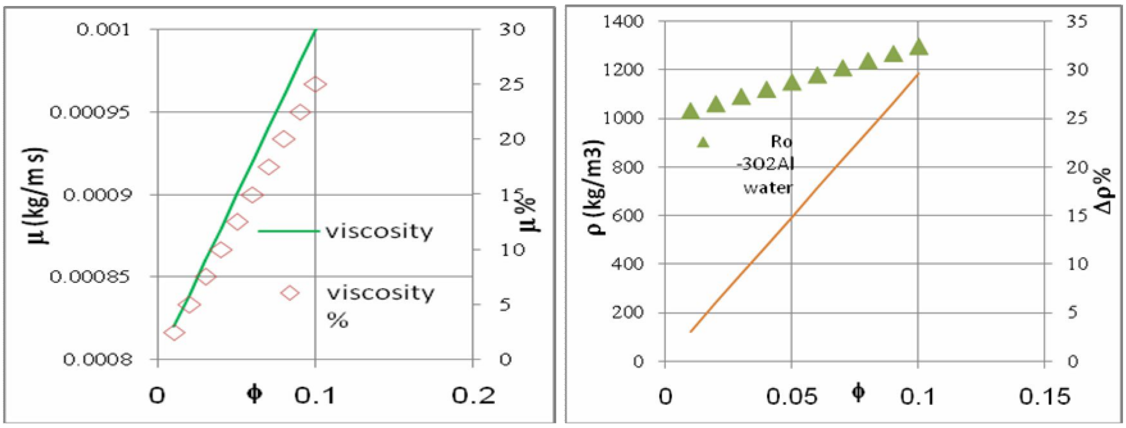
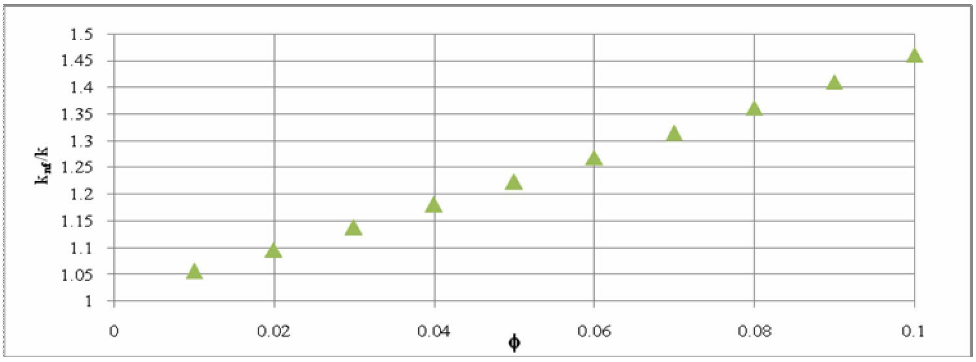


Figure 7 demonstrates that the thermal conductivity of the nanofluids increases with the nanoparticles concentration. An enhancement of 50% occurs at 0.1 vol. % and consequently the convective heat transfer coefficient rises according to the relation (h = Nu k /D).

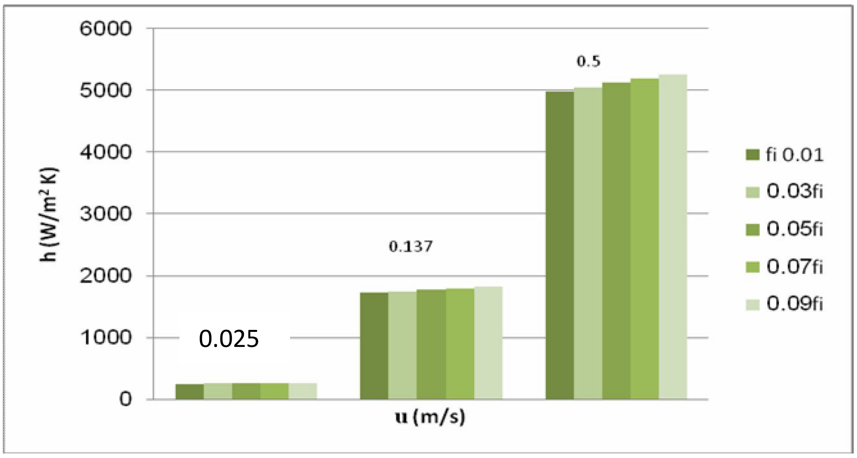
Figure 7. Thermal conductivity of Al_2O_3- water at different nanoparticles concentrations (ϕ)



Convective heat transfer

The increase in the convective heat transfer under three different flow velocities (0.025, 0.173, and 0.5 m/s) is analyzed and the results are represented in Figure 8. These velocities have been selected to represent the turbulent flow at Reynolds numbers of 4708, 32583, and 94170 respectively.

Figure 8. The mutual effect of the velocity (u) and the nanoparticles concentration (fi) on the convective heat transfer coefficient (h)



The results indicate low velocity is not in favor of the heat transfer performance; however, the dispersed nanoparticles can enhance the heat transfer characteristics at the same velocity.

Conclusions

Galvanized iron pipes that have many applications such as in flat plate solar collectors and fluid transport networks and characterized by its internal rough surface are investigated. Al_2O_3-water nanofluid is flowing inside galvanized pipes under fully developed turbulent flow conditions. The simultaneous pressure drop and convective heat transfer of the nanofluid are optimized through ε method under different values of the nanoparticles concentrations and fluid velocities. Some points are concluded are follows:

- There is a linear relationship between the nanofluid velocity and the maximum pressure drop.
- In case of nanofluids running in commercial rough pipe, the pressure drop can be up to ten folds of that in the smooth pipes.
- The roughness of the commercial pipes may act as baffles but at the micro level which improves the convective heat transfer.
- Significant enhancement in the convective heat transfer can be attained via dispersing Al_2O_3 nanoparticles in the water, and the pressure drop can be controlled under acceptable value via selecting the optimum operating conditions of flow velocity and the nanoparticles concentration together.
- The same enhancement in the convective heat transfer and decrease in the pressure drop can be achieved through two different routes namely the implemented velocity and the nanoparticles concentration. In case of nanofluids, the velocity of the flow and the nanoparticles concentration effect shall be studied simultaneously; otherwise misleading conclusion may be drawn.

Conflict of interest

The author declares no conflict of interest.

Nomenclature

As	surface area, m^2
Cp	specific heat of nanoparticles, J/kg. K
Cpbf	specific heat of the base fluid (water), J/kg. K
Cbnf	specific heat of the nanofluid (Al_2O_3-water), J/kg. K
D	inner diameter of the pipe, m
e	average roughness, mm

f	friction factor
h	convective heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	length of the pipe, m
Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number
ΔP	pressure drop, Pa
Q	convective heat transfer rate, W
u	velocity, m/s
W	pumping power, W

Greek Symbols

ϕ	nanoparticles volume concentration, %
ρ	density, kg/m^3
μ	viscosity, Pa.s

Subscripts

s	surface
bf	base fluid
nf	nanofluid
p	nanoparticles

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