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Experimental study of friction factors of multi-walled carbon nanotubes/water flow inside helical double-pipe heat exchangers

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Abstract

This study presents the findings of experiments on the impact of multi-walled carbon nanotubes on the pressure drop of the flow in helical annuli. The exterior of the heat exchanger is insulated. The nanofluid travels through the annulus as hot water flows through the inner helical tube. Two double-pipe cases are produced, each with a different curvature ratio. Several experiments are conducted to assess the effect of the coiled annuli geometry on the flow pressure drop. Additionally, the effects of the Dean Number and nanotube concentration are examined. The results indicated that the friction factors related to the nanofluid flow are higher than those of water, but our previous study demonstrated that they have superior heat transfer coefficients. Therefore, the performance evaluation criteria are achieved. In all the cases, they are higher than unity showing the superiority of this kind of heat exchanger.

Keywords: Friction Factor; Helical Annuli; Nanofluid; Multi-Walled Carbon Nanotube, PEC.

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1. Introduction

Active and passive techniques, respectively, are used to increase heat transfer rates. Unlike passive methods, active methods rely on external energy sources to enhance heat transfer. Helix passages are a notable example of passive flow swirling. As a result, curved tube heat exchangers have been widely used in both industry and research [1]. However, one of the drawbacks of these systems is the augmentation in adherent pressure drop. Several studies have been conducted to comprehend the heat transfer and pressure drop of flows inside curved tubes [2]. Salimpour conducted experimental studies on the flow and convective heat transfer inside a shell and coiled tube heat exchangers [3, 4]. He employed some correlations to assess the convective heat transfer coefficients on the inner and outer walls of the coiled tubes. Shokouhmand et al. [5] applied Wilson plots to assess the convective heat transfer coefficients based on experimental and empirical data. Cioncolini and Santini reported that the curvature ratio of the coils in helical tubes affects when a system transitions from a laminar to a turbulent state [6]. Using CFD and experimental methods, Jayakumar et al. studied convection heat exchangers which were helically coiled. [7]. The boundary conditions for the heat exchangers' constant heat flux and constant wall temperature were taken into account.

It has been made possible to create new fluids with improved thermal properties by utilizing nanoparticles and nanotubes. These fluids, also referred to as nanofluids, are more thermally conductive than the base fluid while maintaining a pressure loss that is not appreciably higher [8]. Several studies have reported that nanofluids have better thermal properties than base fluids [9-11]. By analyzing the heat transfer convection of nanofluid flow through the tubes with constant boundary conditions, Akhavan-Behabadi et al. [12] investigated the simultaneous effects of the addition of nanoparticles and the use of curved pipes on heat transfer and pressure drop. The study revealed that higher heat transfer rates are possible when both enhanced techniques are used. In another study Hashemi and Akhavan-Behabadi [13] investigated the convection and pressure loss of a copper oxide/oil nanofluid flow in a coiled tube. The experiments made use of a boundary condition with constant heat flux. Kahani et al. investigated the impacts of metal oxide nanoparticles on the thermal characteristics of fluid flow inside curved tubes. Using their findings as a foundation, some correlations were developed to assess the pressure drop and Nusselt number of nanofluids.

Cylindrical carbon atom structures form carbon nanotubes. They are made by rolling a nanometer diameter sheet of graphite into a tube. Carbon nanotubes have exceptional mechanical, electrical, thermal, and chemical properties [15].

The effect of adding CNT on the thermal properties of the base fluids has been the subject of numerous studies. Assael et al. [16, 17] studied how the use of different surfactants affects the thermal conductivity of CNT nanofluids. Similar studies were done by Ding et al. [18] in their study. They used gum Arabic as a surfactant.

To determine how the addition of carbon nanotubes at different temperatures and concentrations affected the heat transfer behavior of MWCNT/water nanofluid containing gum Arabic, Indhuja et al. [19] used experimental techniques.

The effects of a magnetic field on the viscosity and thermal conductivity of a carbon nanotube magnetic nanofluid were reported by Shahsavar et al. examined [20]. They have also investigated the effects of applying magnetic fields on the flow of ferrofluid containing carbon nanotubes in both alternating and constant magnetic fields [21]. In another study, Moradi Fard et al. [22] investigated the convection of CNT nanofluid inside spiral tubes. Curved tubes and the addition of CNT have been found to significantly improve heat transfer.

In a previous study [23] we used an experimental approach to investigate how the addition of SWCNTs and MWCNTs to distilled water affects the convective heat transfer coefficients. CNTs have been found to significantly increase the heat transfer coefficients of distilled water. In addition, it is necessary to calculate the convective heat transfer coefficients of the flow based on an empirical correlation.

A literature review shows that recent research has mainly focused on the pressure drop and heat transfer coefficients of nanofluids in curved tubes. However, it has not been studied how the presence of MWCNTs in combination with distilled water affects the performance standards and friction parameters of flow in helical rings. Experiments are performed to determine how addition of multi-walled CNTs, curvature ratio, curved ring geometry, CNT concentration, and mass flow rate affect the coefficient of friction. Then, based on the heat transfer data from our recent study [23], a form of performance metric is evaluated to assess the usefulness of this type of advanced heat transfer device

2. Experimental Apparatus

2.1. Preparation of CNT nanofluid

Gum Arabic (GA), multi-walled CNT, and distilled water are used to make CNT nanofluid. The nanotubes used are 10 m long and have an outer diameter of 10 to 30 nm. Gum Arabic and distilled water are combined with carbon nanotubes and then the combination is sonicated to produce a consistent and stable nanofluid.

2.2. Experimental setup

The aim of this study is to design and set up an experimental test rig for investigating the friction factor of flowing working fluids. Figure 1

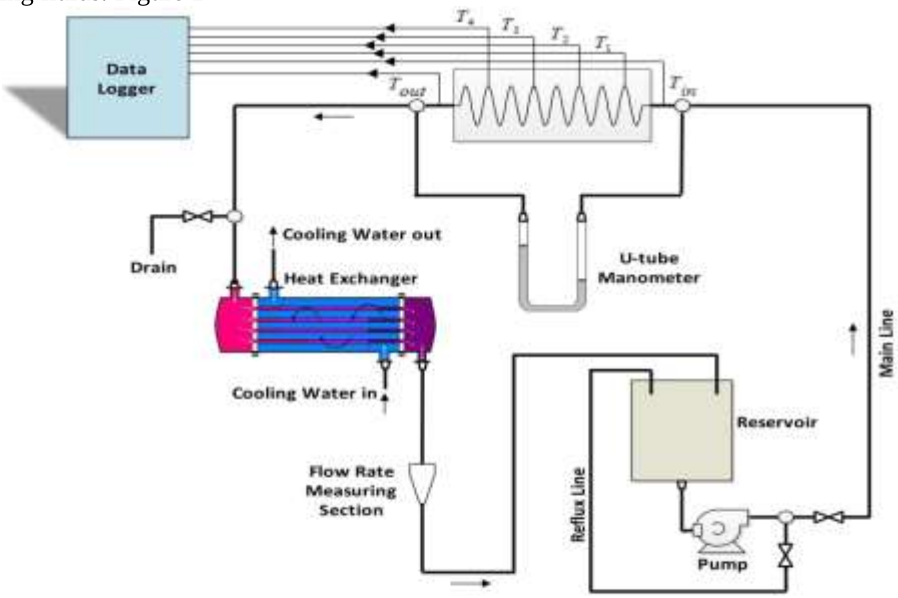

Figure 1. Schematic diagram

Three different spiral annuli sets were used at the test section (Fig. 2). Table 1 gives the geometric dimensions of various coiled annuli considered in this study. The method of constructing the coiled annuli is mentioned in our previous article. In order to accurately assess the properties and flow of fluids, it is necessary to know their temperatures. Four calibrated RTDs with an accuracy of 0.1 °C are used for this. These RTDs are used to measure the temperature of the hot water and the inlet and outlet temperatures of the working fluids. A digital display is connected to each RTD. In order to achieve the desired flow rates, both the main line and the return line have adjustable valves. The observations show that the system reaches a steady state after 30 minutes. This condition is a must for reliable measurements.

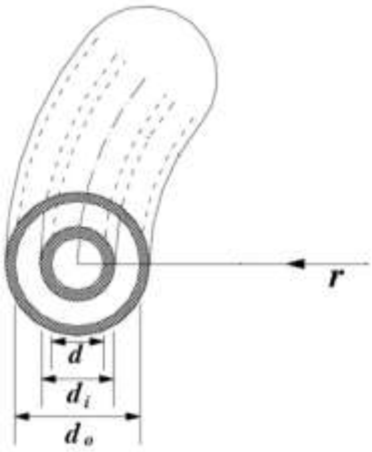

Figure 2. Schematic representation of a helical double-tube heat exchanger

Table I. Geometrical dimensions of the coils

Coil No.	d(mm)	d_i(mm)	d_o(mm)	D(mm)	b (mm)	$\delta = d/D$	L(mm)	N
coil 1	4.2	6.2	10.4	112	30	0.0375	2914	8
coil 2	8	10	18	112	30	0.071	3062	8

2.3. Data reduction

It was decided to use a Paar of Physica MCR 300 parallel disk rheometers to measure the viscosity of the carbon nanotube nanofluids. A KD2-pro was also used to evaluate the thermal conductivity of the fabricated nanofluids. A differential scanning calorimeter was used to determine the specific heat of the nanofluids and a liquid density gravometer to determine their density. The experimental fanning friction factor, f, has been determined using the following Equation.

$$f = \frac{\Delta P . d_h}{2 \rho u_m^2 L} \qquad \text{Eq. (1)}$$

Here, ΔP indicates the pressure drop, d_h is the hydraulic diameter of the annulus, ρ is the density of the liquid and L is the length of the annulus passage.

To ensure the reliability of the experimental setup, data for the flow of pure water inside a helical tube have first been collected. The friction factors obtained for this flow are compared with those anticipated by Manlapaz and Churchills [24]. The results are shown in figure 3. This figure represents an excellent between the present results and those of ref. [24]. Therefore, the integrity of the experimental set-up is verified.

Table 2. Uncertainty factor of measurements

Instrument and parameter	Uncertainty
Density [kg/m^3]	0.05
ΔP [Pa]	3.0
Flow meter [kg/s]	4%
Length [m]	0.001

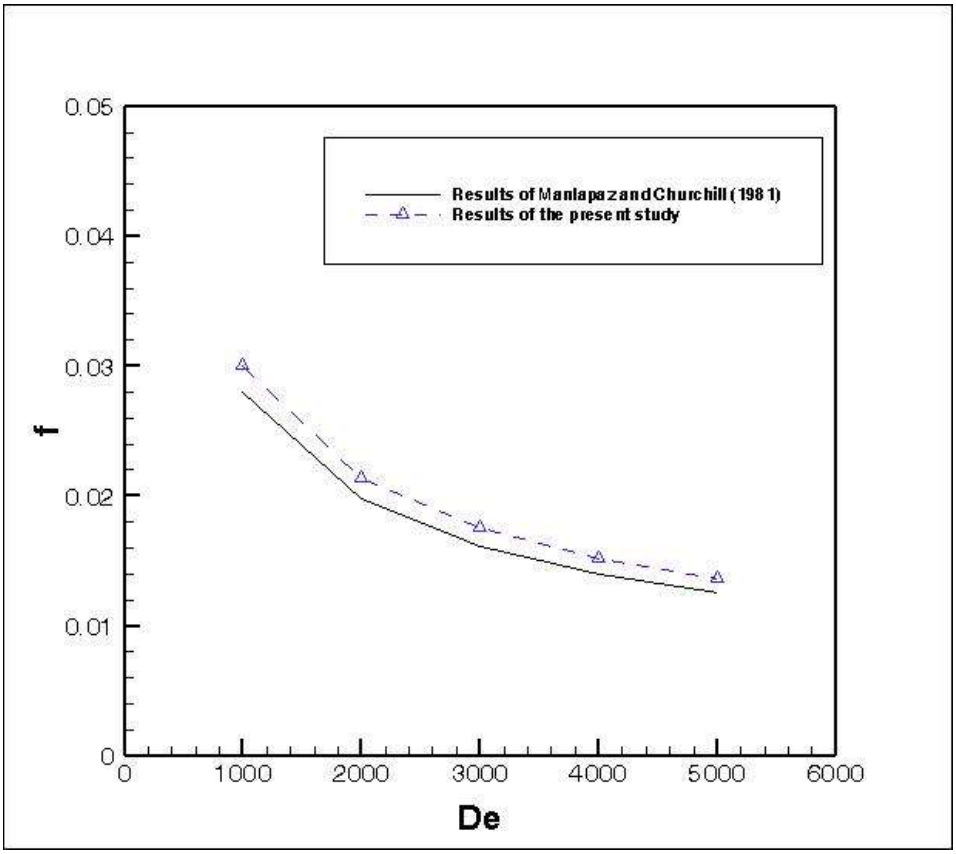

Figure 3. Comparison of the results with those predicted by Manlapaz and Churchill [24]

The accuracy of the current study is ensured in part by calculating the level of uncertainty in the results. This is achieved by using the measurement uncertainty presented in Table 2. The maximum uncertainty for the friction factor is 5.5% when using the reference method [25].

3. **Results and discussion**

Due to the fact that coil pitch had a lower significance on pressure drop than curvature ratio in the current study, all tested coils' pitches were kept constant and set to 30 mm (Table 1). Figure 4 depicts the change of the friction factor in Case I versus the Dean number. The results indicate that as Dean numbers increase, the friction factor tends to go down. The relationship between the flow's Reynolds number and the passage's curvature ratio is simultaneously shown by the Dean number. The friction factor decreases as the curvature ratio increases because the centrifugal force that creates the secondary flow is amplified. The addition of nanotubes increases the friction factor, which has also been observed. Also, the gain is higher at higher volume concentrations of the nanotubes. The higher friction is a result of the chaotic motion of carbon nanotubes at higher Dean numbers. This is consistent with our earlier finding (ref. [23]) where higher heat transfer coefficients are observed at higher curvature ratios.

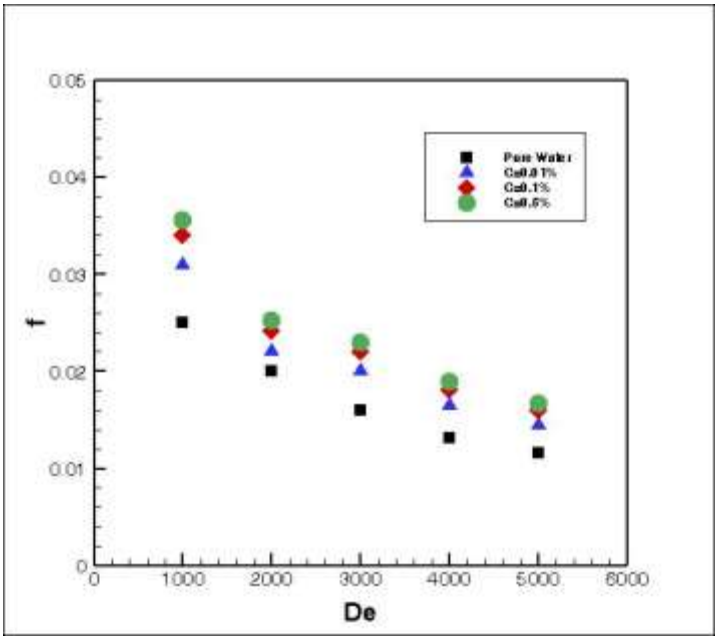

Figure 4. Variations of friction factor with Dean number for Case I at different CNT volume fractions

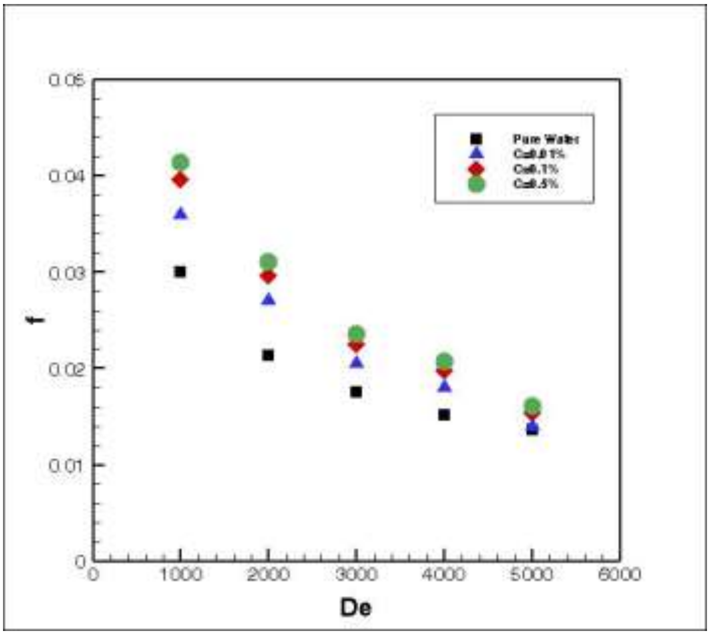

Figure 5. Variations of friction factor with Dean Number for Case II at different CNT volume fractions

The variations in friction factor for Case II, which has higher curvature ratio values, are shown in figure 5. As the graph shows, the friction factor increases with increasing curvature ratios. For a concentration of 0.5% nanotubes, case II is observed to have the highest friction factor with a curvature ratio of 0.071 while the Dean number is kept constant.

Figure 6 compares the friction factors of cases I and II for carbon nanotube concentrations of 0.1%. The impact of the curvature ratio is more apparent at lower Dean Numbers, as shown by figure 6. That is, when De is high, the increment of fluid velocity balances the weakness of the secondary flow; however, the impact of secondary flows on pressure drop is stronger than the main flow velocity at lower Dean Numbers.

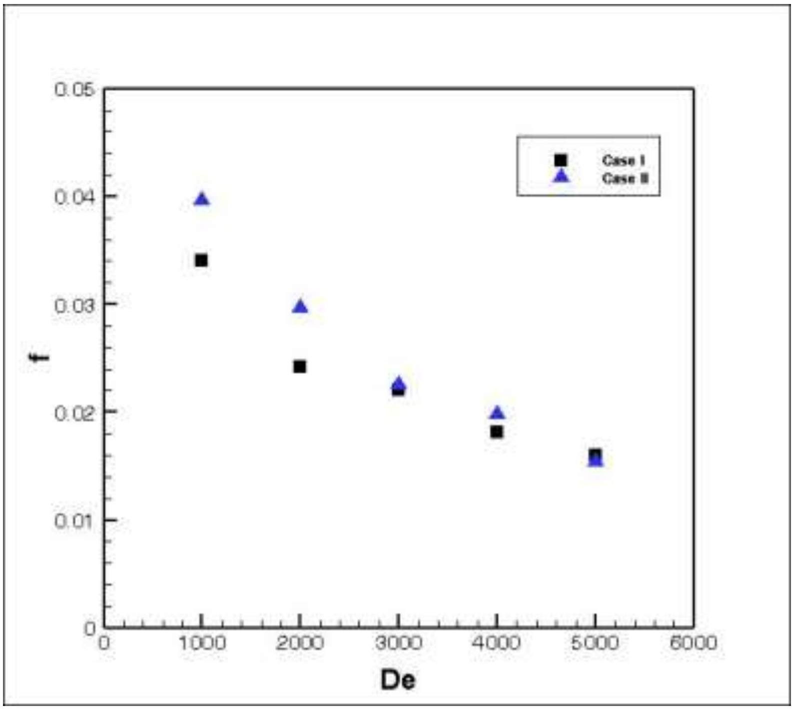

Figure 6. Comparison of friction factors of Cases I and II for C=0.1%

To account for the advantages of curved geometry (improved heat transfer) as well as the drawbacks, a performance criterion is used (increased pressure drop). Here are some ways that performance evaluation criteria, or PEC, are employed:

$$PEC = \frac{Nu_{nf}/Nu_{bf}}{\left(f_{nf}/f_{bf}\right)^{1/3}} \quad \text{Eq. (2)}$$

In order to evaluate the PEC, we need heat transfer coefficient data. For this purpose we used the data that we obtained during our experiments [23]. If the value of PEC is higher than unity, it means that using the improved method is advantageous. Figure 7 illustrates the value of PEC for different Dean Numbers and concentrations of nanofluids of Case I. It shows that PECs are higher than unity at all the cases, implying that the use of coiled passages is useful. Additionally, higher carbon nanotube concentrations are seen to have better merit figures. Because, their heat transfer coefficient enhancements are higher than their friction factor increments. Moreover, it is observed that the best condition for case I happens at *De=2000* and *C=0.5%* which is about *1.29*.

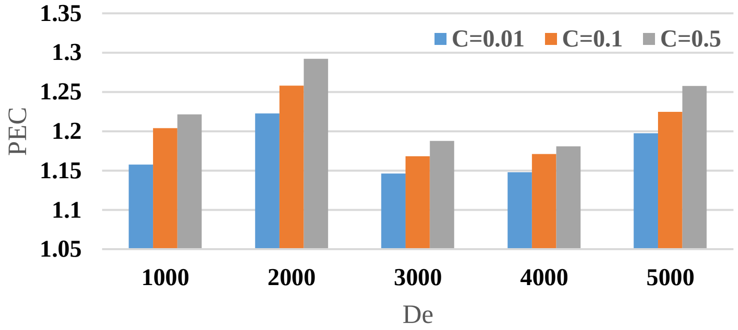

Figure 7. Comparison of PEC values of Case I for different concentrations of CNT

In order to investigate the influence of the curvature ratio on the overall parameter of the PEC, the figure of merit for case II is given in Figure 8. Similar to Figure 7, this figure variation in the PEC trend follows the same pattern. However, the difference here is that the PEC is higher at the 1000 Dean number and the PEC of nanofluid are comparable at 0.5% at both the 1000 and 2000 Dean numbers. The other notions are similar.

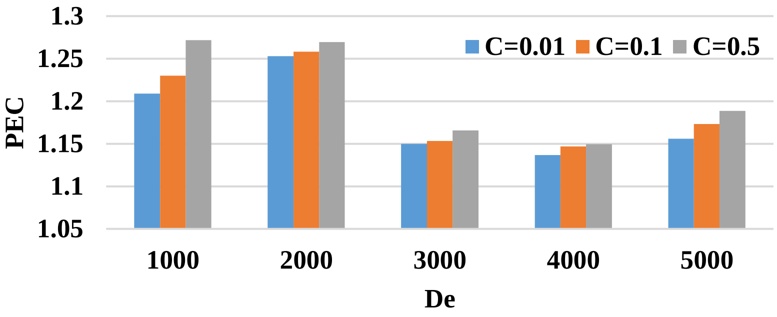

Figure 8. Comparison of PEC values of Case II for different concentrations of CNT

To get a better insight, the PEC values of two different curvature ratios for a carbon nanotube concentration of 0.5% are plotted on the same diagram in Figure 9. Figure 9 shows that except for De = 1000, the first case with a lower curvature ratio has higher performance. Furthermore, the best optimal value of PEC belongs to De = 2000

4. Conclusion

The friction between distilled water and MWCNT/water-based nanofluids flowing through twisted annuli was examined in this study. For this research three volume concentrations were utilized. The findings of this investigation led to the following conclusions.

1) The flow of nanofluid has higher friction factors than the flow of distilled water. This applies to all carbon nanotube concentrations.
2) As the curvature ratio increases, the coefficient of friction increases.
3) As the concentration of nanotubes rises, the friction factors rise as well.
4) In the largest range of Dean numbers, lower curvature ratios have higher PECs.
5) In all the test runs of this study, the PECs are higher than unity implying that the usage of them are beneficial.
6) The maximum value of PEC is achieved at *De=2000* and *C=0.5%*.

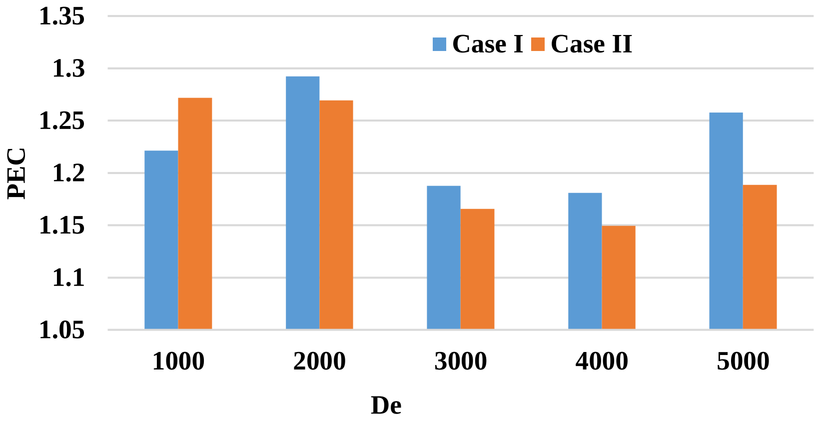

Figure 9. Comparison of PEC values of Cases I and II for C=0.5%

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