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Numerical Study of New Small-twist Tape Insert on Heat Transfer and Pressure Drop for Laminar Flow Inside Circular Pipe

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ABSTRACT

In this study, thermal performance of the laminar flow inside pipe with proposed small twisted tape insert is studied numerically by using computational fluid dynamic software. The proposed insert consists of three- and five-small twisted tapes insert that are arranged in radially symmetry pattern. These group of inserts are then arranged along the pipe with gap spacing S to generate continuous flow disturbance. The inserts are proposed to be modelled as zero-thickness layer to reduce the computational cost. The proposed zero-thickness model is validated by compare the with the results of 1mm-model and reference experimental results. The zero-thickness model is then implemented on the proposed insert design for numerical study. Compare with plain twisted tape insert, Nusselt number of the new design is increases by the range of approximately 0.07-42.7% for three-small tapes design, and 4.7-48.0% for five-small tapes design. Performance evaluation criteria (PEC) of present design ranging from 2.2-3.7 for three-small tapes design, and 2.65-3.65 for five-small tapes design. The proposed insert is found to have more advantage over plain twisted tape at lower Reynolds number, reflected by more significant increase in PEC at lower Reynolds number. From the result of friction factor and PEC, the optimum gap distance of insert group is found to be 50 mm.

1. Introduction

Heat exchangers have become an essential part of cooling and heating system, and are very important components of many industrial applications. Several techniques have been employed to enhance the rate of heat transfer by increasing flow disturbance, such as by the use of baffle, modify the shape of pipe surface, and by using pipe inserts [1-10].

Inserts are place inside a pipe to act as vortex generators by generating swirling flow to enhance the rate of heat transfer when the fluid is flow inside pipe. The most common type of insert is twisted tape insert, due to the relatively easy to install and maintain. This twisted tape insert guided the flow to flow in swirling motion, and create disturbance near the wall of pipe to enhance the rate of heat transfer. Due to the importance of twisted tape in heat exchanger application, it has been studied

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extensively in past research through experimental, mathematical correlation, and numerically [11-15]. The enhancement of heat transfer varies by the use of different pitch and twist ratio, where pitch is defined as the distance between two co-planar consecutive point along the axis of twisted tape, and twist ratio is the ratio of pitch to width of insert.

Modification on twisted tape geometry has also been studied. Small features are introduced on the twisted tape to induce additional fluid disturbance, and hence, achieve better fluid mixing and heat transfer enhancement with slight increase in friction penalty. Thermal-hydraulic performance of perforated, notched, and jagged twisted tape are compared in the study by Rahimi *et al.,* [14], and twisted plate with jagged cut was found to give highest rate of heat transfer. Group of Murugesan *et al.,* [16,17] have studied the effect of square-cut and V-cut, and both gives improvements in term of thermal performance factor over plain twisted tape. Improvement of heat transfer by adding serrated edge on the twisted tape was also reported by Chang *et al.,* [18], Eiamsa-Ard and Promvonge [19], respectively. However, in most of the cases, the thermal performance factor is decreased with the increase of Reynolds number in the turbulence flow. This suggested that in high Reynolds number flow, turbulent induced is no longer significant to enhance the rate of heat transfer for the increase in friction.

Apart from the insert based on twisted tape, other type of inserts has also been studied. Tusar *et al.,* [20] have numerically studied the performance of laminar flow in pipe with helical screw tapes. Fan *et al.,* [21] and Liu *et al.,* [22] have studied conical strip insert to enhance the rate of heat transfer without significant increase in pressure drop. In their observation, slant angle of the conical strip plays a more important role than pitch in heat transfer performance, and slant angle of $30°$ is found can gives better heat transfer performance over other slant angles. Regardless of pitch and slant angle, moderate Reynolds number of 17000-25000 will gives higher thermal performance. When Reynolds number is increases further, the thermal performance deteriorated rapidly.

Tu *et al.,* [23,24] have numerically studied the heat transfer performance of small pipe insert for both laminar and turbulence flow. Both studies have found that the decrease in dimensionless spacer length result in increase in heat transfer. In their study on turbulence flow in Tu *et al.,* [24], inserts with three- and four-small pipes are compared, and they reported that despites have higher friction factor, insert with four-small pipes gives better thermal performance over three-small pipes setup. Group by Bhattacharyya *et al.,* [25] and Bhattacharyya and Paul [26] have also studied different type of inserts, such as square extruded bluff cylinder inserts and circular hole spring tape with promising results. Their group has also studied the use of magnetic baffle to generate vortices in magnetic nanofluid instead of physical insert [27].

In the numerical studies in the literatures, the thickness of the insert is always modelled in geometry. Although this is more accurate representation of actual insert, small elements need to be generated to capture the thickness of the insert, and this increases the overall number of elements. Although it is obvious that the number of elements can be reduced when the thickness of insert is neglected, there is yet any study on the impact of this geometry simplification to the accuracy of the simulation result.

In this work, a new type of small twisted plate insert is proposed to enhanced the rate of heat transfer in laminar flow. The new insert consists of few small twisted tapes inserts that are arranged in radial symmetry direction to create swirling and flow disturbance between center and wall of the pipes to enhance heat transfer. Thermal performance of proposed insert is to be studied numerically by using ANSYS Fluent CFD software. The feasibility of model the tape insert by using zero-thickness geometry is also studied. The aim is to reduce the computational cost by reducing the number of elements needed to model the flow domain after the plate thickness is simplified.

2. Simulation Setup and Boundary Condition

The pipe with length of $L = 1$ m and diameter of $d = 19$ mm, following the geometry setup in experiment by Wongcharee and Eiamsa-Ard [28]. The range of Reynolds number of 800-2000 are to be simulated, which are in range of laminar flow. Water is used as working fluid, and the default fluid properties are applied. The fluid properties are assumed to be temperature independent and are remain constant through the simulation. In this study, steady state incompressible solver is used, with the convergence criteria are set at 1e-7 for energy equation, and 1e-3 for other equations. SIMPLE algorithm is used for pressure-velocity coupling, and second-order scheme for momentum and energy equations.

For the boundary condition setting, parabolic velocity profile is applied at the inlet through the implementation of user defined function, in order to minimize the entrance effect. Outflow is set as pressure outlet with constant pressure. In this study, thickness of the pipe wall is not modelled. The heat is assumed to be directly transferred to the fluid through the inner wall of the pipe. Hence, constant heat flux is applied at the inner wall of the pipe for all simulations. On the other hand, the surface of the insert is modelled as insulated wall. The geometry and boundary conditions applied are shown in Figure 1.

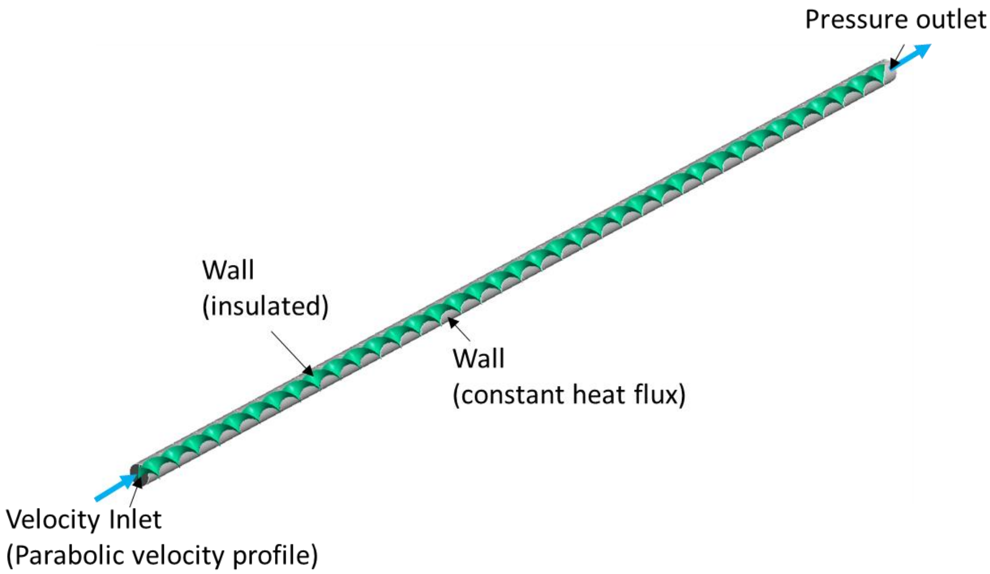


Fig. 1. Geometry and boundary conditions of the simulations

Tetrahedral element is chosen as the grid type for the domain, due to adaptability of tetrahedral shape in complex geometry. The skewness of the grid is controlled to be lower than 0.8. Example of grid generated for 1mm-thickness and zero-thickness model are shows in Figure 2 and Figure 3, respectively. Both example grids shown have around 1 million elements.

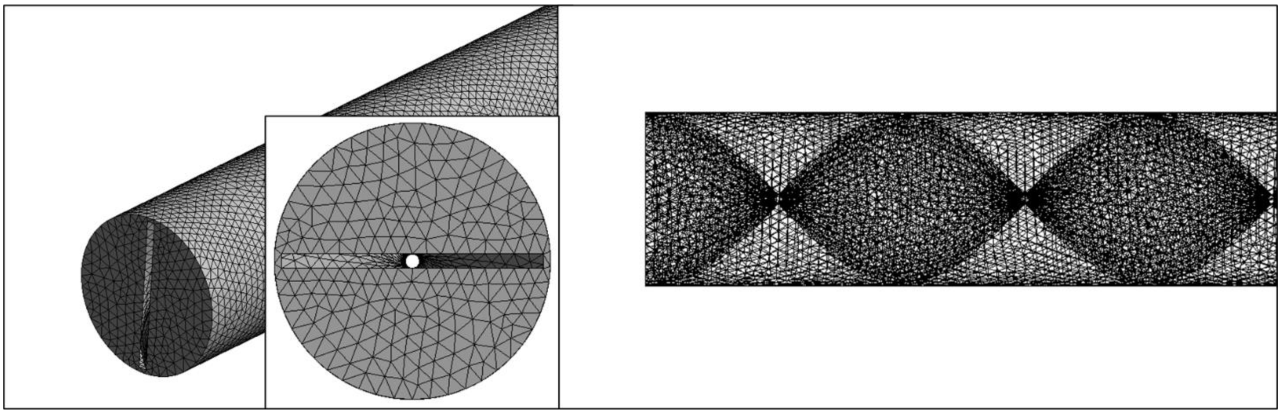


Fig. 2. Grid generated for 1mm-thickness model (number of elements 1.29M, highest skewness 0.798)

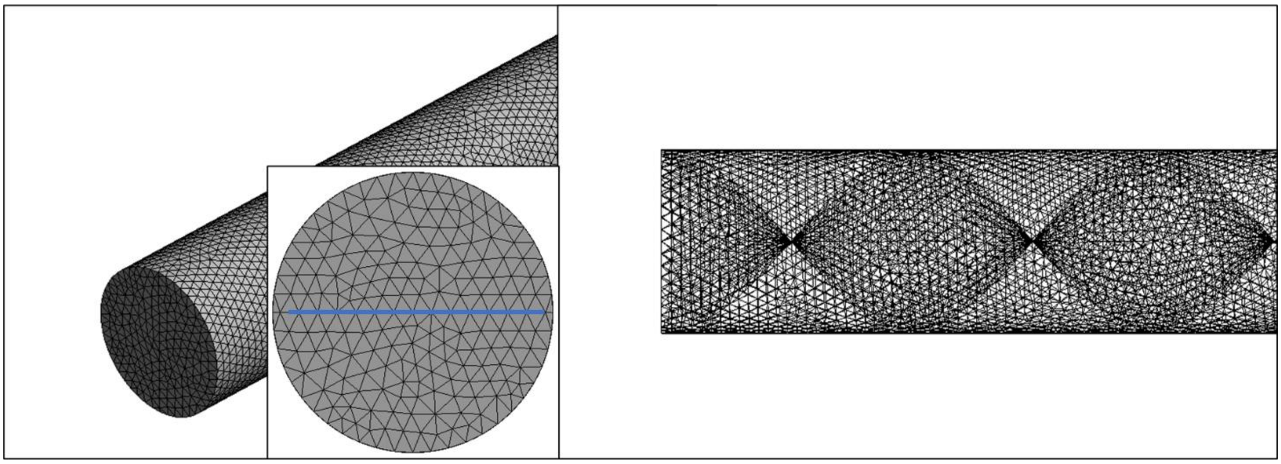


Fig. 3. Grid generated for zero-thickness model (number of elements 975k, highest skewness 0.799). Blue line indicates the position of zero-thickness layer

3. Data Processing

After the numerical simulation, the processing of the results obtained are summarized in this section. The heat flux transferred to the pipe through convection is governed by Eq. (1):

$$q = h(T_s - T_b) \tag{1}$$

Where T_s is the temperature at the inner surface of the pipe, and T_b is the bulk temperature of the fluid. In this study, the bulk temperature T_b is obtained by calculate the mass average temperature throughout the domain, and surface temperature T_s is calculated by area-weight averaged the temperature at the inner wall of the pipe. The convective heat transfer coefficient h can then be calculated as:

$$h = \frac{q}{T_s - T_b} \tag{2}$$

The improvement of the heat transfer with different insert is evaluate by comparing the Nusselt number of each case:

$$Nu = \frac{hd}{k} \tag{3}$$

The diameter d in the Eq. (3) above is an inner diameter of the pipe, and k is the thermal conductivity of the fluid. The corresponding friction factor is calculated by using Darcy-Weisbach equation as:

$$f = \frac{\Delta p}{\rho}\frac{d}{L}\frac{2}{\bar{u}^2} \tag{4}$$

Where Δp is pressure drop across the pipe, ρ is density of the fluid, $\bar{u}$ is the mean velocity of the fluid inside pipe. The improvement of rate to the heat transfer is often comes with the price of higher friction factor. To measure the overall performance is evaluated by using a performance evaluation criteria (PEC), also called thermal performance factor, that is calculated as:

$$PEC = \frac{\left(\frac{Nu}{Nu_0}\right)}{\left(\frac{f}{f_0}\right)^{1/3}} \tag{5}$$

Where Nu_0 and f_0 are theoretical value of Nusselt number and friction factor for flow inside plain tube. The value of $Nu_0 = 48/11$ and $f_0 = 64/Re$ is used in this study.

4. Numerical Test

4.1 Grid Independent and Verification Study

For this grid independent and verification is done to prove that the geometry simplification by using zero-thickness layer to model the insert will still give results that within tolerable accuracy. In this verification study, plain twisted tape with width of 18mm and thickness of 1 mm is used. The twist ratio is set as $y/W = 3$, where y is the pitch distance, and W is the width of the insert. The Reynolds number of the case is set as $Re = 1500$.

Figure 4 shows the value of Nusselt by using different number of elements for both zero-thickness insert and 1mm thickness insert. It is found that both converged to approximately Nu=21-23. The optimum number of elements for zero-thickness insert is taken to be 975k (1.2% different with result of 1.65M elements), and the 1mm-thickness model is 3.33M element (1% different with the result of 4.8M elements). The number of elements needed for 1mm-thickness model is relatively large as finer elements need to be used alongside the thickness of the insert to avoid skew element, that will reduce the stability of numerical simulation. The result of zero-thickness layer model only has approximately 5% difference with 1mm-thickness model, and only takes 30% of the grid required of the later. Hence, we can conclude that there is no significant change on the Nusselt number after the insert is modelled with zero-thickness layer.

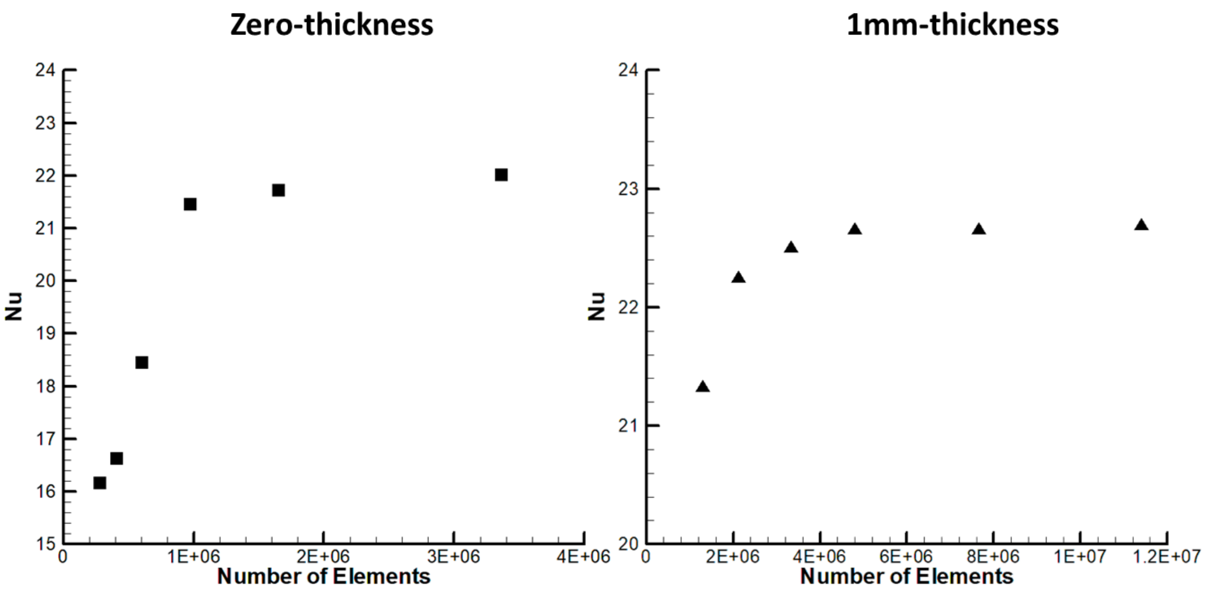


Fig. 4. Grid independent test result for zero-thickness (left) and 1mm-thickeness model (right)

Simulations for both zero-thickness and 1mm-thickness model at different Reynolds number are done by using their respective optimum number of elements found from grid independent study above. The Nusselt number at different Reynolds number are compares with the experimental result reported by Wongcharee and Eiamsa-Ard [28] (for twist ratio 3.0), that is shows in Figure 5. It can be seen from the plot that the numerical results are slightly lower than the result of experiment. The trend of both numerical results is similar, and the discrepancy between both numerical results is from 3.4-11.8%. Trendline is fitted for reference experimental data, and the Nusselt numbers obtained from trendline equation are compared with the value obtained from numerical simulations. The discrepancy between zero-thickness model and experimental data is from 2.5-8.6%, whereas for 1mm-thickness model is 2.9-13.7%. Since both results are consistent, this error might due to the simplification of geometry that does not take the wall of pipe into account.

The plot of friction factor versus Reynolds number is shows in Figure 6. The friction factor obtained by zero-thickness model is found to be lower than both experimental and 1mm-thickness model. Nevertheless, the trend of friction factor from numerical results is also similar than of experimental results. By comparing to fitted trendline of experimental data, the percentage error of the result obtained by zero-thickness model is between 0.4-3.0%. This shows that despites that the geometry of the insert is simplified in zero-thickness model, the result is not deteriorated much from this simplification.

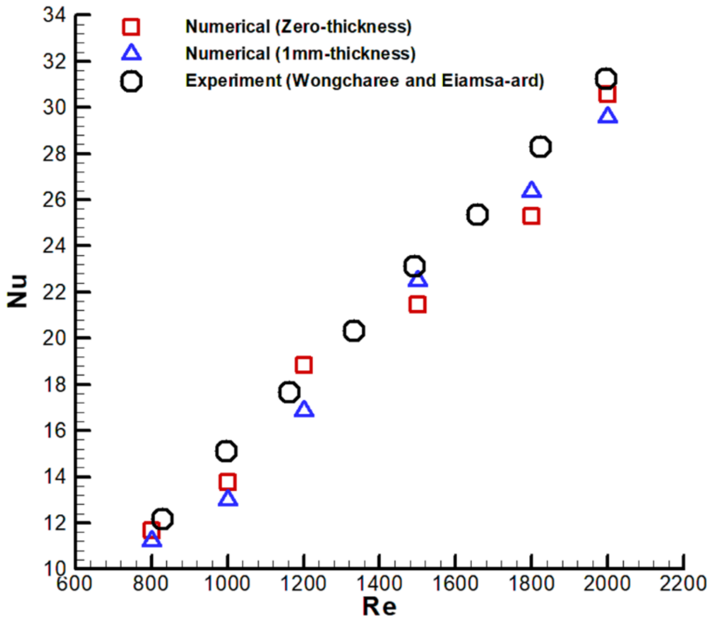


Fig. 5. Nusselt number vs Reynolds number for zero-thickness model (square), 1mm-thickness model (triangle), and experiment result (circle) [28]

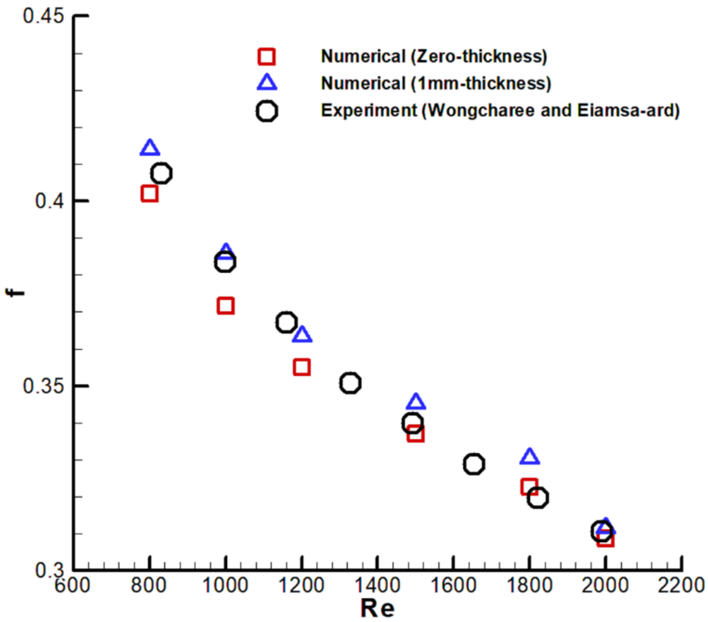
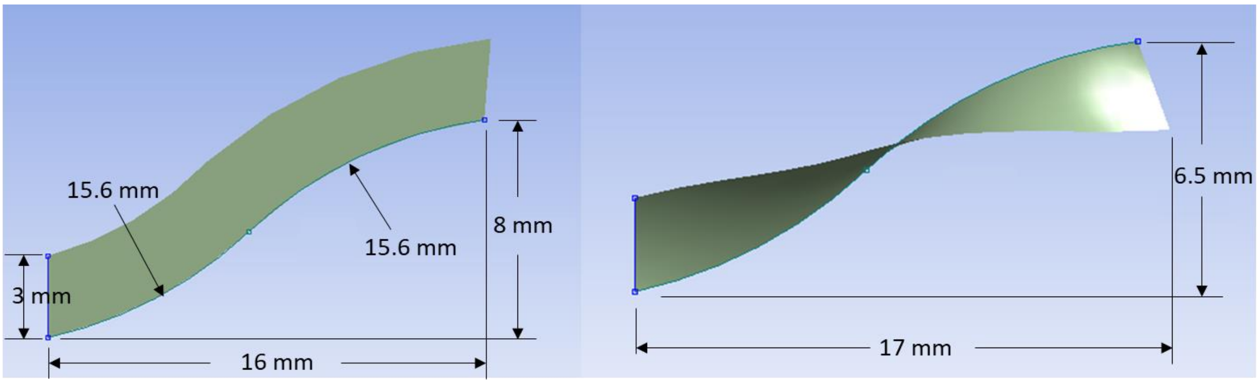


Fig. 6. Friction factor vs Reynolds number for zero-thickness model (square), 1mm-thickness model (triangle), and experiment result (circle) [28]

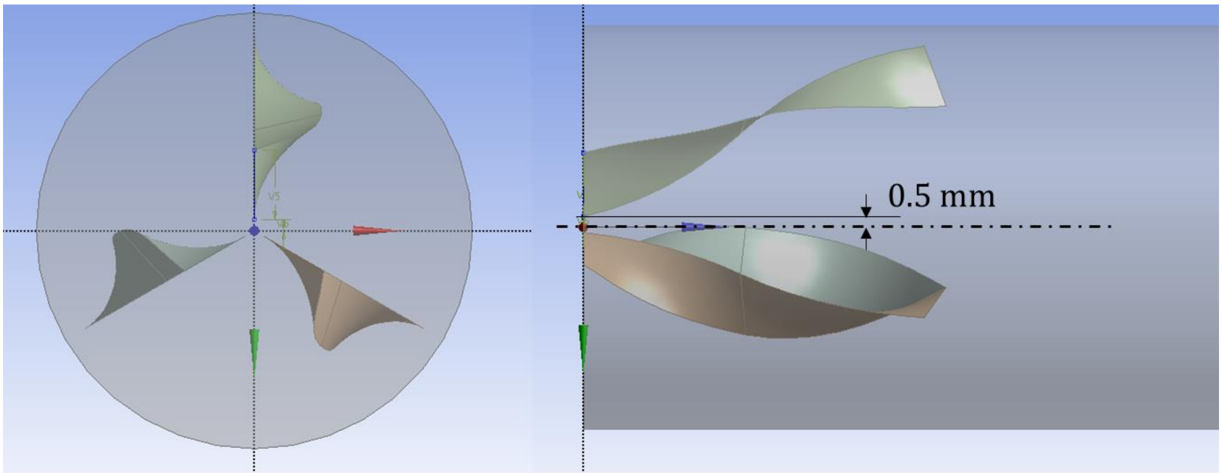
4.2 Proposed Design of Small Twisted Tape Insert

The proposed design of insert consist of small twisted tape is in "S" shape pattern as shows in Figure 7, from center towards the radial direction of the pipe. The "S" shape tape is twisted by half turn, as in Figure 5(b). The purpose is to create swirling pattern that can guide the direction of the flow from the center towards the wall of the pipe. The inserts are then arranged in radially symmetry pattern similar to small pipe insert by Tu *et al.,* [23,24]. The purpose of slight twist and arrangement of the tapes are able to guide the flow at the center of the pipe towards the wall of the pipe. Example of three-small twisted tape inserts arranged in radially symmetry pattern is shows in Figure 8.



(a) (b)

Fig. 7. Design of present small twisted tape (a) initial dimension of the plate, (b) plate after twisted by 0.5 turns



(a) (b)

Fig. 8. Arrangement of the three small twisted tapes inserts in radially symmetry pattern. (a) view from the inlet of the pipe, (b) view from side of the pipe.

Thermal performance of small twisted tapes is numerically studied for the configuration of three- and five-small twisted tapes. The tapes group are separated by a gap distance S as shows in Figure 9. In this study, three different values of $S = 60, 50, 40$ mm are used.

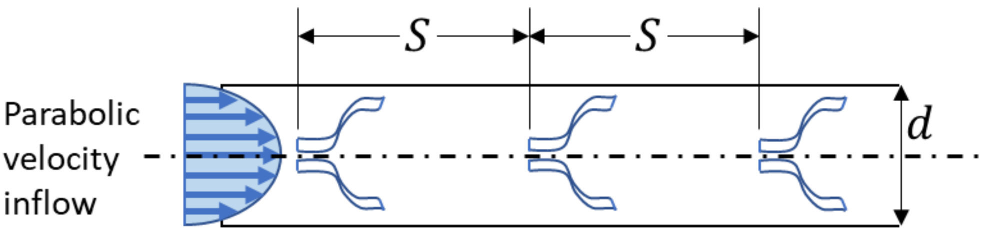


Fig. 9. Arrangement of the small twisted tapes in the pipe

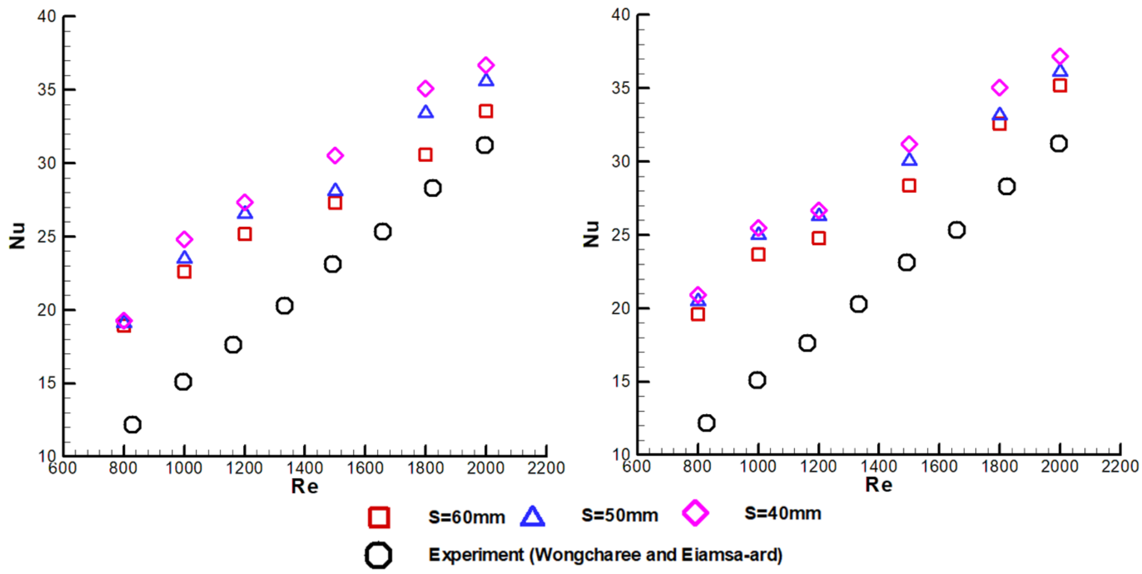
Figure 10 shows the plot of Nusselt number versus Reynolds number for the proposed three- and five-small twisted tape insert. From the plot, it is clear that the Nusselt number increase with the reduce of gap distance S. Although in general, more significant increase of Nusselt number is observed when gap spacing reduces from $S = 60\ \mathrm{mm}$ to $S = 50\ \mathrm{mm}$. This can be clearly seen from the plot of percentage increase of Nusselt number in Figure 10(b). The percentage error is calculated with respect to reference value Nu_{ref} as in Eq. (6):

$$\text{Percentage} = \frac{Nu_{numerical} - Nu_{ref}}{Nu_{ref}} \times 100 \tag{6}$$

The reference value Nu_{ref} is calculated from the trendline curve fitted to the experimental result by Wongcharee and Eiamsa-Ard [28] (plain twisted tape insert with pitch ratio of 3), that is taken in the form of $Nu = 0.0162Re - 1.187$.

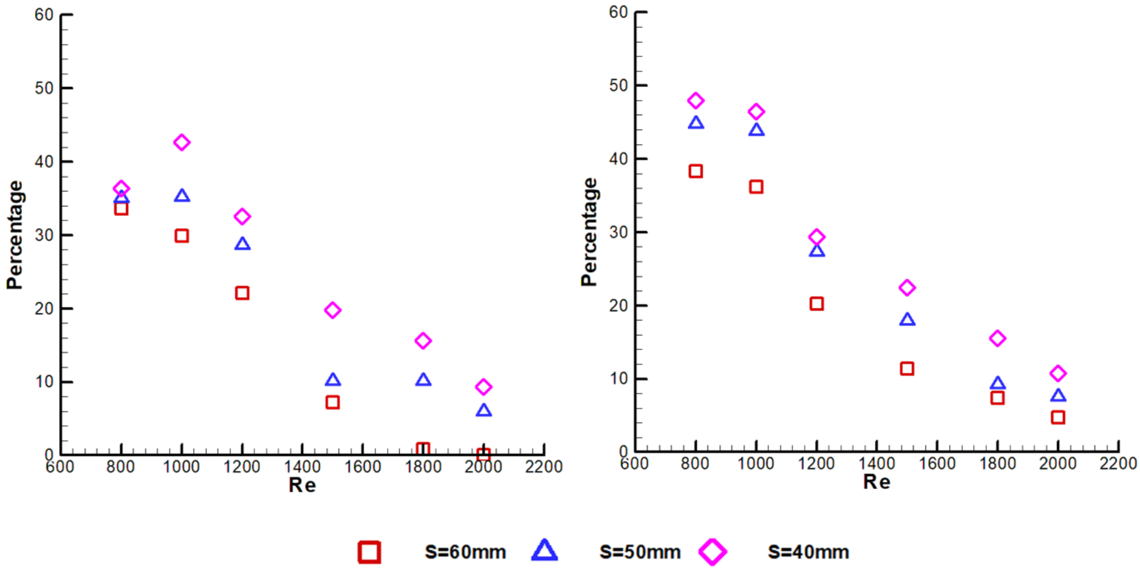
It is observed at lower Reynolds number, the proposed insert clearly has more advantage over the plain twisted tape insert (with pitch ratio of 3.0). As Reynolds number increases, the gap between reference experimental data and present numerical result decreases. For three-small tapes insert, the lowest percentage increase of Nusselt number is only at 0.07% when $S = 60\ \mathrm{mm}$ and Reynolds number 2000. Highest increase of Nusselt number is 42% at $S = 40\ \mathrm{mm}$ and Reynolds number 1000. The minimum and maximum percentage increase in Nusselt number for five-small tapes insert are 4.7% ($S = 60\ \mathrm{mm}, Re = 2000$)and 48% ($S = 40\ \mathrm{mm}, Re = 800$), respectively.

From the plot of friction factor versus Reynolds number in Figure 12, it is not surprise to found that the friction factor increased as the gap distance S reduced, due to the flow disturbance that caused higher pressure drop. Five-small twisted tape insert has higher friction factor than the three-small twisted tape type especially for low Reynolds number. It is also found that the increase of friction factor is more significant when gap spacing is reduces from $S = 50\ \mathrm{mm}$ to $S = 40\ \mathrm{mm}$, compare to when S is reduces from $60\ \mathrm{mm}$ to $50\ \mathrm{mm}$.



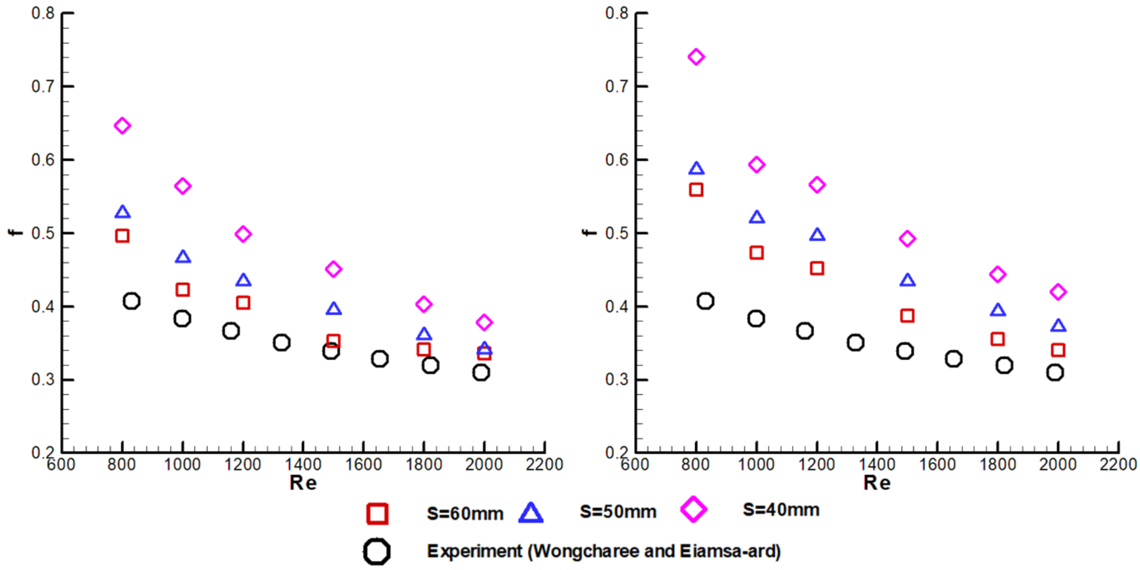
(a) Three-small tapes (b) Five-small tapes

Fig. 10. Plot of Nusselt number versus Reynolds number for (a) three-small twisted tapes, and (b) five-small twisted tapes insert with different gap distance S. The results are compared with experimental result of Wongcharee and Eiamsa-Ard [28] for pitch ratio of 3.0



(a) Three-small tapes (b) Five-small tapes

Fig. 11. Plot of percentage increase of Nusselt number versus Reynolds number for (a) three-small twisted tapes, and (b) five-small twisted tape insert with different gap distance S



(a) Three-small tapes (b) Five-small tapes

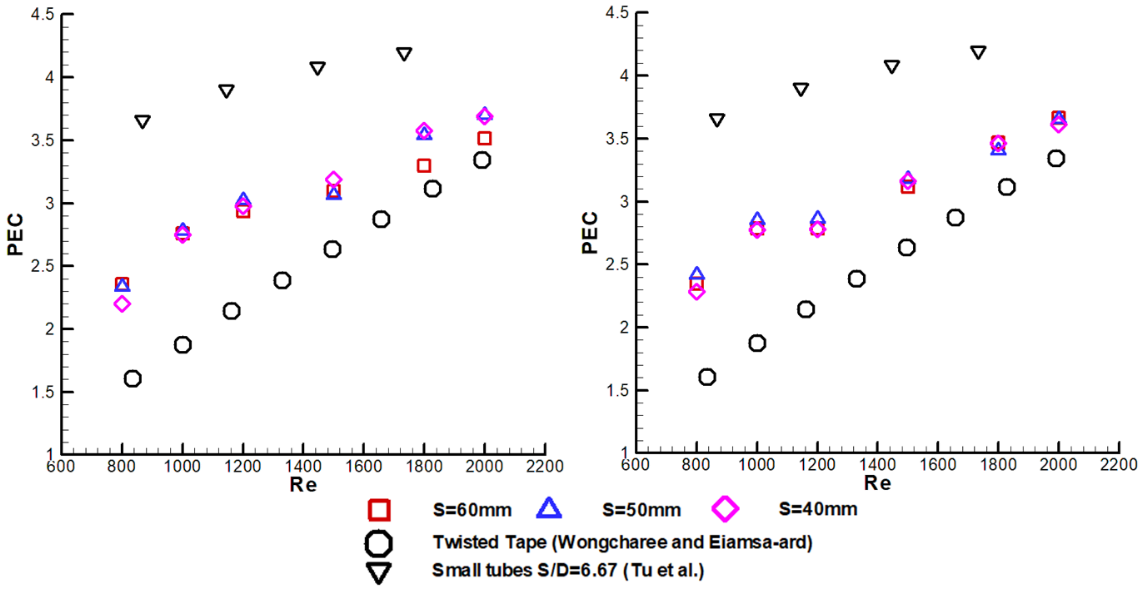
Fig. 12. Plot of friction factor versus Reynolds number for (a) three-small twisted tapes, and (b) five-small twisted tape insert with different gap distance S. The results are compared with experimental result of Wongcharee and Eiamsa-Ard [28] for pitch ratio of 3.0

The performance evaluation criteria (PEC) of the results are evaluated by using the Eq. (5) described in section 3. The PEC versus Reynolds number for both inserts are shows in Figure 13. In general, PEC increase with Increase of Reynolds number. As the gap distance S reduced, the value of PEC is increases due to the increase in Nusselt number.

It is interesting to note that despite the difference in Nusselt number and friction factor, the value of PEC for three- and five-small tapes at highest Reynolds number of 2000 are converged to roughly same value around 3.5. When compare the plot of Nusselt number in Figure 10, at highest Reynolds number of 2000, decrease the gap distance from $S = 60$ mm to $S = 50$ mm yield more significant increase in Nusselt number, as compare with decrease from $S = 50$ mm to $S = 40$ mm. This shows that for current design of insert, the optimum gap distance is around $S = 50$ mm instead of smaller gap distance.

The PEC of small pipe inserts proposed by Tu *et al.,* [23] in included as the reference to compare with present design. The small pipe design with spacing value of 6.67 has superior thermal-hydraulic performance than present design, even though the present design adopted the same concept to divert the flow from center of the pipe towards the outlet of the pipe. The slight twisted design of the small tapes can only guide the flow to certain extend, which is different than small pipe insert design that allows the colder fluid from center to be discharged to near pipe wall and greatly enhance the heat transfer.

For the proposed insert in this study, the length and degree of twist are fixed. It is expected that the length and number of turns of the small-twisted tape will plays an important role in heat transfer performance as both increase the level of flow disturbance. Another possible improvement is by introducing twist angle between two consequence inserts group to further enhance the flow disturbance. These will be considered in future study.



(a) Three-small tapes (b) Five-small tapes

Fig. 13. Plot of performance evaluation criteria (PEC) versus Reynolds number for (a) three-small twisted tapes, and (b) five-small twisted tape insert with different gap distance S. The results are compared with experimental result of Wongcharee and Eiamsa-Ard [28] for pitch ratio of 3.0, and result of small tube insert by Tu *et al.,* [23] for spacing value of 6.67

5. Conclusions

In this paper, a new type of small twisted tape insert has been studied numerically at different gap distance. The twisted tape is modelled by using zero-thickness model is proposed. The feasibility of the zero-thickness model was first verified by compare the numerical result with both 1mm-model and experimental result. Then is followed by the modelling of new insert by using the zero-thickness model. The design of new insert consists of three- and five-small twisted tapes arranged in radially symmetry layout. The insert groups are separated by different gap distance S, and the heat transfer performances were studied for different arrangement. The following conclusion can be drawn:

a) The purpose of use of insert is to guide the flow in a pipe to flow in swirling motion, and create disturbance near the wall of pipe to enhance the rate of heat transfer.
b) The discrepancy between the result by zero-thickens model and reference data is 2.5-8.6%. Hence, it is safe to conclude that the modelling of plate inserts by using zero-thickness model will still give the results with acceptable accuracy with smaller number of elements.
c) Compare with plain twisted tape insert, Nusselt number of new insert design increases by the range of approximately 0.07-42.7% for three-small tapes design, and 4.7-48.0% for five-small tapes design. Thermal performance of present design ranging from 2.2-3.7 for three-small tapes design, and 2.65-3.65 for five-small tapes design.
d) For both three- and five-smaller tapes design, the performance evaluation criteria are found to be increasing in a smaller rate than the plain twisted tape. This shows that present design has higher advantage over plain twisted tape at lower Reynolds number, but deteriorating as the flow speed increasing.
e) For the current design of half-turn small twisted tapes, the optimum gap distance between insert groups has found to be 50 mm, as the friction factor increase drastically when the gap distance reduces to below 50 mm.

In the plot of friction factor in the present study, the pressure drop is found marginally higher than of twisted tape insert, hence, impacting the overall PEC. One of the possible directions for future study is by investigate configuration of the insert arrangement, such that it is in a more streamwise pattern to reduce the pressure drop without having to much impact on heat transfer.

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Conflicts of Interest
The authors declare that they have no conflicts of interest to report regarding the present study.

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