Heat Transfer Enhancement of a Biodiesel Heater

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HEAT TRANSFER ENHANCEMENT OF A BIODIESEL HEATER

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ABSTRACT

Issues of fuel preparation are quite crucial in many industrial/transport applications. Some fuels may not be ready to use in their raw state and hence are required to pre-processed, particularly to increase the temperature to the required level, prior to the combustion stage. For this purpose, two major types of fuel heaters are used: in-line type that attached to the fuel pipes and off-line type that attached outside the fuel tank. This work is aimed to consider an in-line counter flow heater used in marine applications and to propose modifications to improve its performance. After considering several heat transfer enhancement techniques, a twisted-tube insert was chosen to be used. Then, theoretical calculations were performed with and without heat transfer enhancement for a set task. The results showed that the required length of the heater can be reduced by 83.9% only introducing a twisted-tube instead of a plain tube. Usually, pressure drop increases with a twisted-tube but a reduction of pressure drop also can be observed in this work due to the reduction of the required length of the heater. Also, a reduction of the heater's manufacturing cost should be achieved with a twisted-tube to perform the same task compared to a plain tube. Therefore, the use of twisted-tubes within these type of heaters will provide substantial benefits particularly to design compact heat exchangers but with improved performance.

Keywords: Heat exchanger, Heat transfer enhancement, Biodiesel, Modelling, Twisted-tube

NOMENCLATURE

A	[m^2]	Surface area
C_p	[J.kg^{-1}.K^{-1}]	Specific heat capacity at constant pressure
d	[m]	Diameter
h	[W.m^{-2}.K^{-1}]	Convective heat transfer coefficient
k	[W.m^{-1}.K^{-1}]	Thermal conductivity
L	[m]	Length
$\dot{m}$	[kg. s^{-1}]	Mass flow rate
Nu	[-]	Nusselt number
Pr	[-]	Prandtl number
$\dot{q}$	[W]	Heat transfer rate
Re	[-]	Reynolds number
t	[m]	Thickness
T	[^{o}C]	Temperature
ΔT_{lm}	[^{o}C]	Log mean temperature difference
U	[W.m^{-2}.K^{-1}]	Overall heat transfer coefficient
V	[m.s^{-1}]	Velocity
ρ	[m^3/kg]	Density
μ	[Pa.s]	Viscosity

Subscripts and Superscripts

c	Cold fluid flow
h	Hot fluid flow
i	Inlet conditions
o	Outlet conditions

1. INTRODUCTION

Heat transfer can occur through several mechanisms such as conduction, convection, radiation, etc. Usually, the heat is naturally released to the surroundings from systems/machines by means of one or many of these ways. However, the forced cooling is a requirement of removing the additional heat generated in some applications to ensure the effective/efficient operation. In such applications, heat exchanges are commonly used for removing the additional or unnecessary heat. Usually, heat exchangers remove the heat of a particular medium by allowing it to absorb into another heat transfer medium such as water, oil, air, etc. Currently, numerous heat exchanging techniques are available and are widely used in the applications such as refrigeration, air conditioning, automobiles, process industry, solar water heating, thermal power plants, and so forth. In some particular applications, heat exchangers which are bulky in size have to be used based on the amount of the heat required to be removed or added for a given time to maintain the desirable temperature limits. However, the size of the components or machines has become a major consideration in the modern industrial world due to the constraints such as space limitations, maintenance requirements, manufacturing cost, portability, appearance, etc. Therefore, the size of the heat exchangers has also become a critical factor which would decide the size of some particular machines/plants. Under such circumstances, extensive researches have been focused over the last few decades to reduce the size and fabrication cost of the heat exchangers [1-7].

This work is aimed to explore the possible strategies of enhancing the performance of a biodiesel heater (used with internal combustion engines) to reduce its typical size while maintaining its efficiency in the same or a higher level. The typical low- or medium-speed marine engines use fuel heaters which are quite large in size and hence the possible reductions of their sizes and weight, while having the same/higher performance, would be invaluable. A biodiesel heater was considered due to its timely importance of using more green fuels particularly in marine applications. Currently, a number of heat transfer enhancement techniques are used in practical applications. However, some of these heat transfer techniques may not be used with biodiesel heaters due to the constraints such as high viscosity and density of the biodiesel. After choosing a suitable heat transfer enhancement technique, theoretical calculations can be performed to determine the required length of the heater with and without the enhancement technique to evaluate the efficacy of the selected technique. Regardless the possible improvements of heat transfer performance (i.e., the reduction of the length), pressure drop may be increased and this may cause to increase the required pumping power. Hence, the increase of both the heat transfer performance and the pumping power should be estimated and compared before making any judgement on the overall worthiness of the newly proposed technique.

1.1. Biodiesel

Biodiesels are type of environmentally friendly biofuels which are made from vegetable oils (e.g., rapeseed, soy, palm, coconut, etc. oils) or animal fat and are used to replace petroleum diesel fully or partially. They are good alternatives to conventional fuels due to their environmental friendliness [8] and the best fit with new regulations imposed by International Maritime Organisation (IMO) [9]. From chemical standpoint, biodiesel is a mixture of methyl and/or ethyl monoalkyl esters of long-chain fatty acids (saturated and unsaturated). Also, it can be used in pure or blended form with petrol/diesel [10]. Depending on the amount of the biodiesel in the blend it has different commercial names:

- B100: 100% biodiesel
- B20, B5, B2: 20%, 5%, 2% of biodiesel with 80%, 95%, 98% of petro-diesel, respectively.

Blends with low biodiesel content (2-20%) could be used in normal diesel engines without any modifications. Others require certain engine modifications to avoid troubles during performance and maintenance [11]. Biodiesels are light solvents and hence they keep fuel tank and feed/injection systems clean. Moreover, because of their acidic nature, they require storage tanks and supplying systems made from corrosion-resistant materials or with a specific coating. Moreover, biodiesels' lubricity help to reduce engine wear and hence to increase its lifetime. It was indicated that B5 blend provides 50% of less wear scars than petro-diesel. Higher Cetane number and oxygen content (11%) provide better combustion as well as a shorter ignition delay and hence a lower emission rates [10]. The overall impact of biodiesels on engine performance is well-described by BioMer [10]. Apart from the toxicity and the pre-preparatory requirements, another limitation of the biodiesels is the cost. The average price of B100 is 3.08 $/Gal when diesel costs 2.54 $/Gal. Blends B5 and B20 are quite cheaper (2.55 and 2.69 $/Gal, respectively) but still expensive than diesel. Moreover, it requires special engine modifications, which incur extra cost, that provides high resistant to corrosion, additional fuel preparation processes, etc [11]. However, wide spreading of biodiesels as a marine fuel is ensured by its low emission rate. The National Renewable Energy Lab [11] has reported that the use of biodiesel in conventional diesel engines provide significant reduction of unburned hydrocarbons (HC), exhaust (i.e., particulate matter) and carbon monoxide (CO) in comparison with the emissions from high sulphur diesels which occurs due to 11% of oxygen (by weight) in biodiesel fuels that allows the complete burning of fuel. Also, the use of biodiesel has been become much popular due to the strict regulations imposed recently by the IMO [9]. These regulations have significantly reduced the allowed SO_x and NO_x pollution levels and consequently, they force to consider of minimizing the use of conventional marine fuels. New regulations state that NO_x emissions in new ships that would be built in 2016 should be reduced almost in 5 times comparing with those that exist from year 2000. A 3 times of reduction of SO_x emissions is also expected during the same time period. In fact, some marine engine manufactures have already been preparing for using biodiesel fuels [11]. However, most of them have been using blends that contain only 5-20% of the biodiesel.

1.2. Biodiesel heating

As was mentioned earlier, biodiesels' cloud point is usually higher than petro-diesels and hence the use of various additives as well as heating during exploitation should be required, particularly in cold weather conditions. Previous studies [12] recommended that heating of biodiesel in tanks, pipes and separators or using of chemical additives prior to use in ship power plants. Also they have proposed a number of possible heating techniques. One possibility is that a heater attached on the outer surface of the fuel tank as shown in Figure 1.

Figure 1: Heater for biodiesel storage tanks [12]

This heater is made as a flexible wide ribbon worn on the fuel tank externally. It comprises a heating element sandwiched between two layers of fiberglass with silicone rubber. These types of heaters do not need to be installed in the fuel system and they are compact, corrosion/moisture/chemical resistant. However, they can be used only on small vessels powered by biodiesel. Also, typical electrical heaters that can be attached to any metal surface would also be used in fuel heating. Their aluminium heat exchange surface can heat the fuel by converting it from gel to a liquid and to maintain the fuel at the desired temperature.

ArcticFox Company has introduced pipes with integrated heating elements which prevent solidification of the fuel inside pipelines. These in-line fluid warmers are double-pipe shell-and-tube heat exchangers and the warm water is taken from the engine cooling system which flows in the inner tube while heating biodiesel fuel that flows in the shell-side. All surfaces in contact with the biodiesel are made from stainless steel to avoid corrosion and to eliminate contamination of the fuel. This construction is fairly simple in manufacturing, installation and maintenance. Moreover it uses the heat removed by the engine cooling system (hence to save the power required for heating) that would be otherwise lost [13]. Stainless steel (at least 11% of Chromium by weight) is the most commonly used material for biodiesel fuel system/equipment while Nickel or Molybdenum also could be added for improving the corrosion resistance [14].

2. ADDITION OF SWIRL TO THE SHELL-AND-TUBE HEAT EXCHANGERS

In general, heat transfer enhancement methods can be classified into three major types [15, 16]:

Active methods: These involve in improving the heat transfer rate via techniques that require extra external power sources, for example, mechanical aids, injection and suction of the fluid, surface-fluid vibration, jet impingement, use of electrostatic fields, etc. However, these methods may have limitations in practical applications due to their requirement of external power sources.

Passive methods: These perform their function passively (i.e., without any involvement of external power sources) by enhancing the heat transfer with various possible techniques such as the use of surface coatings, rough/extended/twisted surfaces, swirl-flow generators across the flow, additives with heat transferring mediums, etc. These methods seem to be attractive in practical applications particularly due to their simplicity and low cost.

Compound methods: If a system uses any two or more active or passive methods to improve the rate of heat transfer, it is known as a compound method.

In fact, the performance of heat exchangers can be improved passively by addition of swirl [17]. The use of twisted tapes/tubes is a good way of adding swirl to the fluid flow and two types of swirl flow devices are widely popular in the industry: continuous and decaying swirl flow devices. In a continuous swirl flow, the swirling motion exists over the whole length of the tube (e.g., twisted-tapes, twisted-tubes and wire coil inserts) while the heat transfer coefficient and pressure drop keep constant with the axial distance [18-21]. In a decaying swirl flow, the swirl motion is generated at the entrance of the tube and decays along the flow path (e.g., radial guide vane swirl generators, snail swirl generators and the tangential flow injection devices) while the heat transfer coefficient and pressure drop decrease with the axial distance [22-23]. To enhance the rate of heat transfer, it is required to increase the convective heat transfer coefficient and this can be achieved by increasing the convection coefficient or/and by increasing the convective surface area. Schematic diagrams showing some of the possible methods of improving the rate of heat transfer are presented in Figures 2-8.

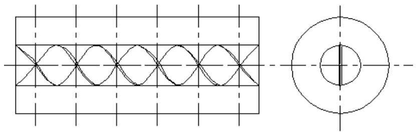


Figure 2: A twisted-tape placed inside the tube

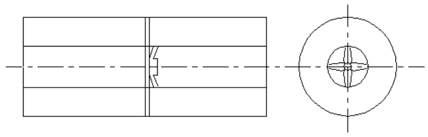


Figure 3: A propeller placed inside the tube

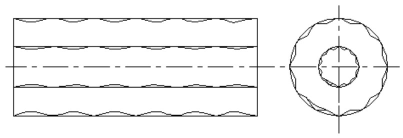


Figure 4: A shell and a tube with wavy surfaces

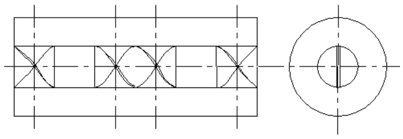


Figure 5: Spiral windings placed inside the tube

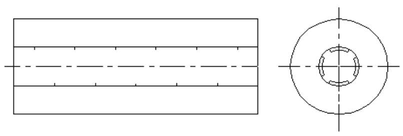


Figure 6: A tube surface with obstacles

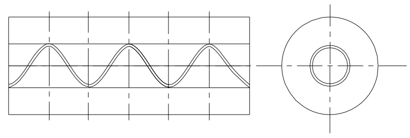


Figure 7: A helical coil placed inside the tube

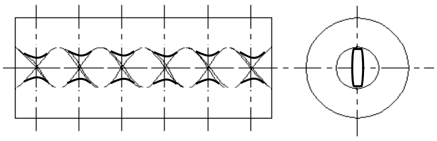


Figure 8: A twisted-tube inside the shell

In this study, a passive heat transfer enhancement method was used particularly due to its simplicity and low implementation cost. After evaluating several possibilities, a twisted-tube insert was identified as an efficient method as it can increase the convection coefficient by introducing swirl into both fluid flows inside the tube and shell. A twisted-tube is a periodically twisted pipe through 360º which can be fabricated relatively easily and economically and provides good heat transfer performance as well [10]. Here, the introduction of a tangential velocity component increases the speed of the flow. Therefore, twisted-tubes would be an economical, simple and efficient way of adding swirl to the fluid flows. In this work, the heat transfer enhancement of a double-tube biodiesel heater is considered with a twisted inner tube. In fact, such a technique could also be applied in multi-tube heaters as well (Figure 9). Evidently, due to the space limitations, it would be difficult to use the baffles in this type of heat exchanger. Therefore, the tubes should be subjected to a unique forming process that provides an oval cross-section with a superimposed helix as shown in Figures 9 and 10. Then, each tube is firmly supported by the adjacent tubes without baffles (i.e., baffle free tube support) while allowing the fluids to swirl freely along the outer surface as shown in Figure 9. Tube forming process ensures that the tube wall thickness stays constant as well as the material yield point is not exceeded thereby retaining mechanical integrity. By allowing required connections with other systems, tube ends are formed in round shape.

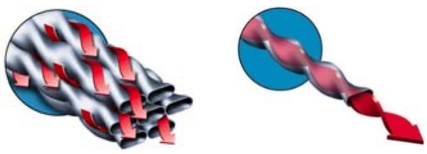


Figure 9: Schematics showing the flow arrangements inside and outside of a twisted-tube [10]

There are a few possible ways of assembling twisted-tubes in a bundle and seven possible constructions are shown in Figure 10. As was mentioned by Morgan [10], some bundles can include up to 5000 tubes leading of up to 1.8 m in diameter and length of up to 2.5 m.

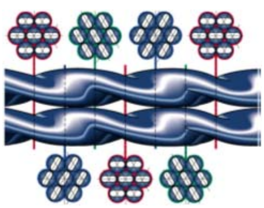


Figure 10: Arrangements of twisted-tube bundles [10]

Some of the major advantageous of heat exchangers with twisted-tubes are that they do not have baffles and hence a less pressure drop and also can have significant reduction of tube vibrations which is a common problem of other types. Also, they are good in thermal effectiveness and less susceptible to fouling. Furthermore, comprehensive review studies on the methods of enhancing of heat transfer with swirl generators [16] and also other possible techniques in heat transfer augmentation [24-29] can be found in the literature.

3. MODELLING

3.1. Case study details

A schematic of the double-pipe biodiesel heater considered in this work is shown in Figure 11.

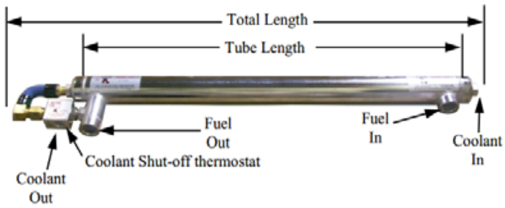


Figure 11: ArcticFox LCC in-line fluid warmer [13]

Heat exchanger type: a double tube heat exchanger with a concentric flow and concentric pipes
Fluid inside the inner tube (hot fluid): water from the engine cooling system
Fluid inside the shell (cold fluid): biodiesel B100
Material (tube and shell): stainless steel
Enhancement technique: twisted inner tube

Table 1. Major parameters of the heat exchanger

Parameter	Unit	Water (Hot fluid)	Biodiesel (cold fluid)
Diameter of the tubes (d_i ,d_o)	m	0.028	0.05
Mass flow rate (m)	kg/s	0.1	0.04
Inlet temperature (T_i)	^{o}C	85	30
Outlet temperature (T_o)	^{o}C	-	80
Specific heat capacity (C_p)	kJ/kg·K	4197	2067
Prandtl number (Pr)	-	2.22	5.66
Viscosity (μ)	10^{-6} Pa·s	355	1,383
Thermal conductivity (k)	W/m·K	0.670	0.154
Density (ρ)	kg/m^3	972	875

Assumptions:

- Negligible heat losses to the surroundings.
- Negligible kinetic and potential energy changes.
- Constant properties of fluids and fully-developed conditions for the cold and hot fluid flows.
- Negligible fouling factors.

Shell and tube diameters were chosen according to the dimensions provided by the ArcticFox [13]. Mass flow rate of biodiesel was decided by fuel consumption requirements of the most widely-used marine internal combustion engines. The mass flow rate of the water (hot fluid) was chosen based on the heat transfer requirements to heat-up the biodiesel till the desired temperature [30]. Usually, B100 biodiesel blend is kept in storage tanks at 25-30 °C and must be delivered to engines at 70-85 °C to ensure the efficient performance of the engine [12]. Since the hot fluid is taken from the engine cooling system its temperature is also known and taken as 85 °C for this study. The outlet temperature of the hot fluid would be figured out later from the energy balance equation. Specific heat capacity, Prandtl number, viscosity and thermal conductivity values were taken from the literature [11, 31]. For calculations, it would also be necessary to know tubes' material parameters. The heat exchanger is made from stainless steel (thickness = 1 mm and thermal conductivity 16.5 W/m·K) due to its good resistance to corrosion. A schematic of the heat exchanger and the corresponding temperature-distance (T-x) graph are shown in Figure 12.

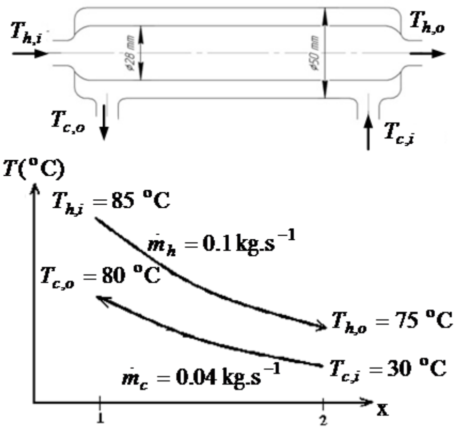


Figure 12: Model of the heat exchanger with the corresponding temperature-distance diagram

Flow conditions based on the Reynolds number (*Re*) [31-33]: Laminar flow: $Re < 2000$
Transitional flow: $2000 < Re < 4000$
Turbulent flow: $Re > 4000$

Dittus-Boelter (DB) correlations which represent the relationship between the Nusselt number (*Nu*), Reynolds number (*Re*) and Prandtl number (*Pr*) are given by Eqs. (1) and (2) [31]:

$$Nu = 0.023 \times Re^{0.8} \times Pr^{0.4} \text{ (Turbulent flows)} \quad (1)$$

$$Nu = 0.023 \times Re^{0.8} \times Pr^{1/3} \text{ (Transitional flows)} \quad (2)$$

3.2. Estimation of the heat exchanger length without an enhancement technique

The required rate of heat transfer, $\dot{q}$, (i.e., the heat that should be added to the cold fluid to reach the specified outlet temperature) can be obtained from the overall energy balance of the cold fluid, Eq. (3):

$$\dot{q}_c = \dot{m}_c \times C_{p,c} \times (T_{c,o} - T_{c,i}) \quad (3)$$

$$\dot{q}_c = 0.04 \times 2132 \times (80 - 30) = 4264 \text{ W}$$

By assuming that there is no any heat loss to the surroundings, $\dot{q}_h = \dot{q}_c$, and hence for the hot fluid:

$$\dot{q}_h = \dot{m}_h \times C_{p,h} \times (T_{h,i} - T_{h,o}) \quad (4)$$

$$4264 = 0.1 \times 4197 \times (85 - T_{h,o})$$

$$T_{h,o} = 74.9 \text{ °C} \approx 75 \text{ °C}$$

Then, the log-mean temperature difference is:

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{ln\left(\frac{(T_{h,i} - T_{c,o})}{T_{h,o} - T_{c,i})}\right)} \quad (5)$$

$$\Delta T_{lm} = \frac{(85-75)-(80-30)}{ln\left(\frac{85-75}{80-30}\right)} = 24.9 \text{ °C}$$

Reynolds number of the hot fluid inside the tube:

$$Re = \frac{4 \times \dot{m}_h}{\pi \times d_i \times \mu_h} = \frac{4 \times 0.1}{\pi \times 0.028 \times 313 \times 10^{-6}} = 14{,}528 \quad (6)$$

Therefore, the hot fluid flow is turbulent and hence the Nusselt number is given by Eq. (1):

$$Nu = 0.023 \times Re^{0.8} \times Pr^{0.4}$$

$$Nu = 0.023 \times 14{,}528^{0.8} \times 2.22^{0.4} = 67.6$$

Then, the heat transfer coefficient for water (hot fluid) in the inner tube can be obtained by Eq. (7):

$$h_h = \frac{Nu \times k_h}{d_i} = \frac{67.6 \times 0.670}{0.028} = 1{,}617.6 \text{ W.m}^{-2}\text{.K}^{-1} \quad (7)$$

For the cold fluid flow (biodiesel) inside the shell:

$$Re = \frac{4 \times \dot{m}_c}{\pi \times (d_i + d_o) \times \mu_c} \quad (8)$$

$$Re = \frac{4 \times 0.04}{\pi \times (0.028 + 0.05) \times 1383 \times 10^{-6}} = 472.1$$

Therefore, shell flow is laminar and Nusselt number was chosen from the tables provided in the literature [1] which was noted as 5.63. Then, heat transfer coefficient is given by Eq. (9):

$$h_c = \frac{Nu \times k_h}{(d_o - d_i)} = \frac{5.63 \times 0.154}{(0.05 - 0.028)} = 39.4 \text{ W.m}^{-2}\text{.K}^{-1} \quad (9)$$

Eventually, the overall convection coefficient (*U*) could be obtained from Eq. (10):

$$U = \frac{1}{\left(\frac{1}{h_h}\right) + \left(\frac{1}{h_c}\right) + \left(\frac{t_{tube\,wall}}{k_{tube\,wall}}\right)} \quad (10)$$

$$U = \frac{1}{\left(\frac{1}{1618}\right) + \left(\frac{1}{39.4}\right) + \left(\frac{0.001}{16.5}\right)} = 38.4 \text{ W.m}^{-2}\text{.K}^{-1}$$

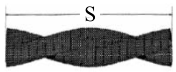
where $t_{tube\,wall}$ is the thickness of the tube wall and $k_{tube\,wall}$ is the thermal conductivity of the tube material. Therefore, the required length (*L*) of the heat exchanger tube for this particular set task is:

$$L = \frac{q}{U \times \pi \times d_i \times \Delta T_{lm}} \quad (11)$$

$$L = \frac{4264}{38.4 \times \pi \times 0.028 \times 24.9} = 50.7\ m$$

3.3. Estimation of the heat exchanger length with an enhancement technique

In this work, inserting of twisted-tubes was used as the heat transfer enhancement technique. By using twisted-tubes instead plain tubes, Nusselt number can be increased in both fluid flows and hence the heat transfer rate would increase. The relationship between Nusselt number and Reynolds number for twisted-tubes with different twisting ratios (S/d) is illustrated in Figure 13.



S – Pitch, S/d – Twisting Ratio

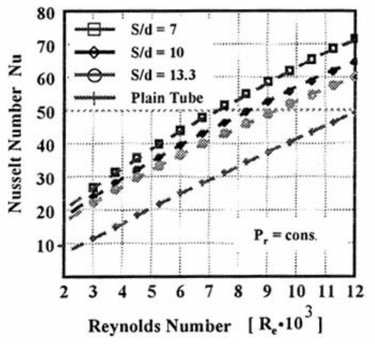


Figure 13: The dependence of Nusselt number *(Nu)* on Reynolds number and twisting ratio [2]

The percentage increase of Nusselt number with different twisting ratios (S/d) can be determined as below based on the information given in Figure 13.

For the hot fluid inside the tube (Re = 14,528):

$$S/d = 13.3$$

$$\%\,increase\,of\;Nu = \left(\frac{71-60}{60}\right)\times 100\% = 18.3\%$$

$$S/d = 10$$

$$\%\,increase\,of\;Nu = \left(\frac{75-60}{60}\right)\times 100\% = 25.0\%$$

$$S/d = 7$$

$$\%\,increase\,of\;Nu = \left(\frac{83-60}{60}\right)\times 100\% = 38.3\%$$

For the cold fluid inside the shell (Re = 472.1):

$$S/d = 13.3$$

$$\%\,increase\,of\;Nu = \left(\frac{6-1}{1}\right)\times 100\% = 500\%$$

$$S/d = 10$$

$$\%\,increase\,of\;Nu = \left(\frac{8-1}{1}\right)\times 100\% = 700\%$$

$$S/d = 7$$

$$\%\,increase\,of\;Nu = \left(\frac{10-1}{1}\right)\times 100\% = 900\%$$

Then, by following the same method presented in section 3.2, the required length of the heat exchanger with twisted-tubes can be calculated, with new Nusselt numbers achieved with different twisting ratios, for the same task.

The use of twisted-tubes to increase the heat transfer rate will affect the axial pressure drop along the heat exchanger. The change of friction factor (f) with Reynolds number and twisting ratio is given in Figure 14 [2]. The pressure drops (ΔP) along the heat exchanger with a plain tube and twisted-tubes were also calculated (for Re = 14,528 and Re = 472) with Darcy-Weisbach equation given in Eq. (12):

$$\Delta P = f\times\frac{L}{d}\times\frac{\rho}{2}\times V^2 = f\times\frac{L}{d}\times\frac{\rho}{2}\times\left(\frac{\dot{m}}{\rho A}\right)^2$$

$$\Delta P = \frac{f\times L\times \dot{m}^2}{2\times d\times\rho\times A^2} \quad (12)$$

Then, new values calculated for twisted-tubes with different twisting ratios are presented in Table 2.

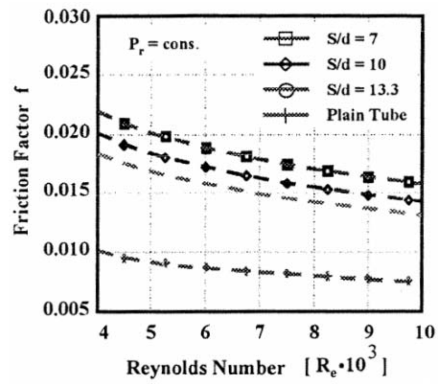


Figure 14: The dependence of friction factor on Reynolds number and twisting ratio [2]

Table 2. Parameters of the heat exchanger after adding a twisted-tube

S/d	**13.3**	**10**	**7**
	Tube flow (hot fluid)		
Nu	79.97	84.05	93.49
h_h (W.m^{-2}.k^{-1})	1914	2022	2237
ΔP (Pa)	66.67	53.25	48.67
	Shell flow (cold fluid)		
Nu	28.15	39.41	50.67
h_c (W.m^{-2}.k^{-1})	197.1	275.9	354.7
ΔP (Pa)	6.42	5.21	4.52
U (W.m^{-2}.k^{-1})	176.7	239.2	300.6
L (m)	11.01	8.14	6.48

4. DISCUSION

A comparison of the required heat exchanger length with and without heat transfer enhancement to perform the same task is shown in Figure 15. Clearly, the heat exchanger length has reduced considerably with twisted-tubes where the higher the twisting ratio the lower the required length. Also, with twisted-tubes, the axial pressure drops along both the shell and tube show reductions as shown in Table 2 and Figure 16 which should lead to decrease the required pumping power as well.

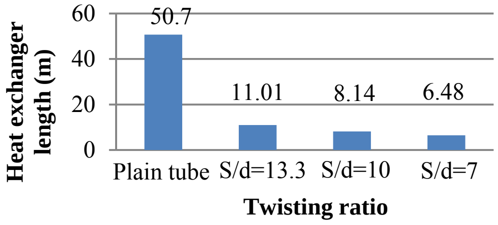


Figure 15: The required length of the heat exchanger with different tubes to perform the same task

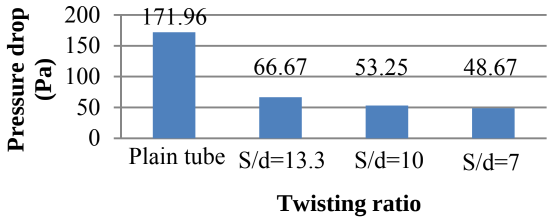


Figure 16: The axial pressure drop along the different tubes to perform the same task

A comparison of the major parameters of the heat exchanger with a plain tube and a twisted-tube with a twisting ratio (S/d) of 10 is given in Table 3.

Table 3. Parameters of the heat exchanger with a plain tube and a twisted-tube (S/d=10)

Parameter	Plain tube	Twisted-tube (S/d=10)	Reduction or Increment (%)
U (W.m^{-2}.K^{-1})	38.4	239.2	↑ 522.9
Nu - tube flow	67.6	84.05	↑ 24.3
Nu - shell flow	5.63	39.41	↑ 600
ΔP- tube flow	171.96	53.25	↓ 69.0
ΔP- shell flow	18.56	5.21	↓ 71.9
Required Length, L (m)	50.7	8.14	↓ 83.9

The results show that the rate of heat transfer has increased by a percentage of 522.9% with a twisted tube (S/d=10) leading to a 83.9 % reduction of the required length of the heat exchanger to perform the same task. Therefore, it is clear that the inserting of twisted-tubes is an effective way to enhance the rate of heat transfer in heat exchangers and hence to reduce their size (i.e., heat exchangers which are compact in size) to perform a particular task. Moreover, the fabrication cost of the heat exchanger may be reduced considerably with the addition of swirl to the fluid flows inside the tube and shell. In fact, the case study presented in this work considered a heat exchanger with a single tube. However, the shell-and-tube heat exchangers which are commonly used in industrial applications include a number of tubes inside the shell. Thus, the addition of swirl to flows of such heat exchangers with multiple tubes may provide further improvements of the rate of heat transfer and hence further reductions to the fabrication cost as well.

The design and fabrication of twisted-tubes are relatively simple and also there is no need of any additional modification to the shell for inserting these tubes. Therefore, the inserting of twisted-tubes is a highly compatible technique for industrial applications. However, one of the disadvantages of this technique is that the possible increase of the pressure drop which should lead to demand more power to pump the fluid inside the tubes and shell. However, for this work, the pressure drops along both the shell and tube show reductions of 71.9% and 69.0% respectively with a twisted-tube (S/d=10) due to the reduction of the required length. In general, some of the major factors which should be taken into account as the addition of swirl for designing of compact heat exchangers are:

- The space requirements/limitations to position the heat exchanger
- Simplicity, effectiveness and the access requirements of the swirl generator/s
- Design and fabrication cost of the heat exchanger with and without swirl
- The level of increase/decrease of the pressure drop with the addition of swirl
- The level of increase/decrease of the required pumping power with the addition of swirl

Overall, it seems that the inserting of twisted-tubes is a cost effective and an efficient technique for enhancing the rate heat transfer and hence to design compact heat exchangers.

5. CONCLUSIONS

This study was mainly focused on investigating strategies to improve the performance of a biodiesel heater (i.e., a shell-and-tube heat exchanger) by the addition of swirl. A number of possible methods of adding swirl were evaluated and then a twisted-tube insert was selected to use. A case study was presented for calculating the increase of rate of heat transfer, the reduction of the required length of the tube and increase/decrease of the pressure drop with twisted-tubes with different twisting ratios. The results confirmed that the twisted-tubes are one of the simple and effective techniques to improve the rate of heat transfer without involving complex modifications to the typical design of shell-and-tube heat exchangers. In general, it showed that the size of the heat exchanger can be reduced considerably by introducing swirl to the tube and shell flows by inserting twisted-tubes and also the fabrication cost may be reduced significantly due to the reduction of the required length. Usually, the axial pressure drop along the tube and shell should be increased with a twisted-tube due to the increase of swirl motion and hence the required pumping power would also increase. However, the results of this work showed that the pressure drop has decreased with the twisted-tubes, due to the reduction of the heat exchanger length, to perform same task and hence the required power for pumping of fluids should also be decreased which is another advantage. Further studies are underway to explore more on the effective and economical strategies to enhance the rate of heat transfer to design compact heat exchangers. Also, computational fluid dynamics approaches will be used in the modelling work.

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