Comparison of Methods for Increasing Heat Transfer in Steam Generators in a CANDU Reactor using various forms of Twisted Tapes

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The efficiency of a nuclear reactor can be improved through an increase of heat transfer. Increasing the Nusselt (Nu) number is an effective way to increase the heat transfer coefficient (*h*). The Reynolds analogy states that as the shear stress of the flowing fluid increases, so must the Nu value, this is why promoting turbulence of the fluid through the use of twisted tape (TT) inserts has been observed. These TT's are available in numerous configurations and will have varying effects on the heat transfer coefficient dependent on the turbulence of the fluid. With the conditions tested, the helical twisted tape returned the largest Nu number (337.78) within the Reynolds number (Re) range of ~10000 to 20000. When observing the Re range of 2300 to 10000, using a clockwise/counter-clockwise tape will return the largest Nu value (162.3). These two tape inserts had the highest level of performance out of seven tape methods tested.

I. INTRODUCTION

Heat transfer enhancement has promising applications across a wide range of industries from automotive to nuclear. Increasing the amount of heat that can be transferred in the system will improve efficiency of the system as a whole.

In the case of a CANDU (CANada Deuterium Uranium) nuclear reactor specifically, the majority of necessary heat transfer occurs within the heat transport system. There are 4 steam generators that all contain a heat exchanger. These heat exchangers are comprised of numerous "U" shaped tubes to increase surface area for maximum heat transfer.

This follows directly from Newton's Law of Cooling where A is the surface area, ΔT is the change in temperature, h is the heat transfer coefficient, and q is the heat flux.

$$\frac{dq}{dt} = hA\Delta T \qquad (1)$$

In CANDU reactors the ΔT and A terms are fixed. To increase the heat flux, the heat transfer coefficient must be

Fig 1 – Reprinted with permission from (http://www.mountaineerfabricators.com/joomla/index.php/photo-gallery.html) Simple Heat Exchanger. This shows the "U" shaped tube bundles and that there is a large amount of tubing for every heat exchanger.

increased. Using a fundamental approach which relates momentum transfer of a turbulent fluid to the heat flux is known as the Reynolds Analogy

$$\frac{\tau_w}{\rho V^2} = \frac{Nu}{RePr} \qquad (2)$$

The more turbulent the fluid is, or the larger the Reynolds number ($Re = \rho VD/\mu$) the larger the shear stress (τ_w) will be at the wall of the tube. This causes more heat to flow across the material boundary. This is especially important when considering the Nusselt number ($Nu = hl/k$) as this dimensionless number relates the amount of heat transfer to both Re and the Prandtl number ($Pr = \mu\frac{cp}{k} = \frac{v}{\alpha}$). Pr is a relation between momentum diffusivity (v) and thermal diffusivity (α). It will be beneficial to define all above variables as; μ [Ns/m^2] is the dynamic viscosity, ρ [kg/m^3] is the fluid density, V [m/s] is fluid velocity, D [m] is pipe diameter, l [m] is the length of the pipe, k [W/mK] is the fluids thermal conduction coefficient.

Looking at the difference between a fully developed laminar flow (Re < 2000) and a fully developed turbulent flow will show the reason for larger heat transfer.
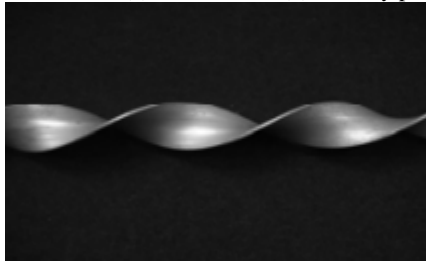
Fig 3 – Reprinted with permission from P.Murugesan, K.Mayilsamy, and S.Suresh, Chinese J. of Chem. Eng. **18**, 609 (2010)
Simple TT without any modifications[3].

The turbulent flow is more "flattened" compared to the parabolic laminar flow due to the higher τ_w. This causes more fluid particles to impact the wall transferring momentum.

A secondary way to approach this problem is to increase the friction factor (*f*) in the piping. Friction factor is a function of the Reynolds number as well as the relative roughness in the pipe. Relative roughness (ε/D) is the ratio of the average height irregularities in the pipe and the overall pipe diameter.

Directly increasing the friction factor does have some drawbacks as the major head loss in a piping network is directly coupled to the friction factor.

$$h_{major} = \frac{fl}{D}\frac{1}{2}\rho V^2 \qquad (3)$$

Even though increasing *f* would increase the heat transfer, a real engineering challenge is met in that it may cause the pumps not to be able to supply enough pressure and there would be no flow. This is an issue with every pump, as there will always be a head loss to the system and for a pump to be useable it must supply more pressure than the head loss. Head loss is commonly given in [m] so this can be rewritten as [Pa] through $h_{major}/\rho g$. To overcome this problem, numerous designs have been created to increase the heat transfer without deviating away from set pressure requirements. An effective and common way to achieve this is with the insertion of twisted tapes (TT) into each heat exchanger tube.

It is possible to modify these TT's to increase turbulence in the flow and as a result, heat transfer will increase.
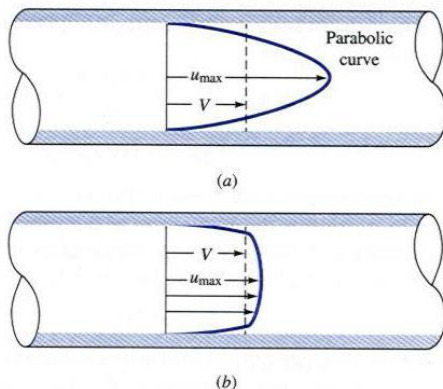
If in the event that a steam generator is disabled to be cleaned or have a component fixed, it may be worthwhile

to install TT in the heat exchanger. Knowing the limitations of each insert will help the engineer select an insert that does not cause too much head loss as to ensure the pumps cannot overcome this.

Multiple insert arrangements will be compared varying from the unmodified case shown in Fig 3.

II. METHODS

In Table I, there are numerous different ways to create a TT that can be inserted into the heat exchanger inside a CANDU steam generator. The primary comparison method will be based on how well each TT method increased the Nu number relative to each other. The Nu number will change based on each varying TT. It will provide a basis for comparison as the larger the Nu value, the larger the heat transfer coefficent will become since they are linearly proportional.
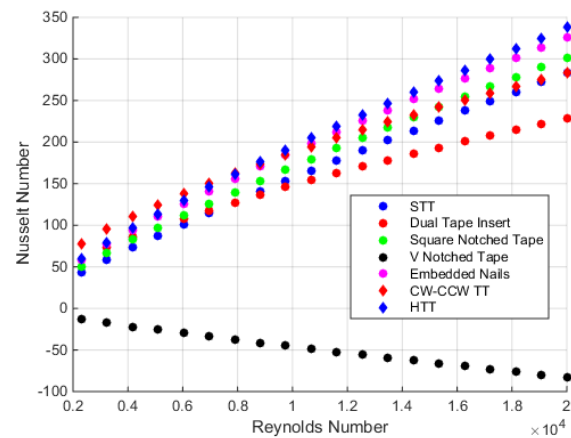

Fig 4 – Various TT Methods plotted with twist, depth, width, and pitch ratios = 1. The V notched tape must require varying depth and width ratios to positivly effect the system.

Table II will show a Nusselt number correlation for each of the 7 selected TT designs. Since the basis of the Reynolds analogy is that the flow is turbulent, these will be plotted against a Re number range of Re = 2300 to Re = 20000. The Re range stated includes the value at which flow is considered turbulent in pipe flow (Re = 2300), and the value of Re = 20000 just as a value with which the range will end. The primary flowing liquid inside the heat exchanger of a CANDU steam generator is heavy water. Heavy water or D_2O contains a deuterium atom in place of a hydrogen atom. This deuterium contains an exta neutron making the water heavier. This fluid acts as the moderator and coolant and flows through the heat transport system. The D_2O used will have the following properties. (ρ = 1100kg/m^3, μ = 0.00125 Ns/m^2, α = 1.27x10^{-7} m^2/s) which will return a Pr value of Pr = 8.95. To simplify the calculations, an assumption will be made that the D_2O is incompressable, the viscosity remains constant, and the flow is along a streamline. To show directly how the Nu value changes as a function of only the Re number, the geometry of each tape has been kept constant. Four different ratios are present when observing the expression for the Nu value as seen in table 2. These
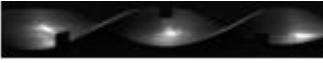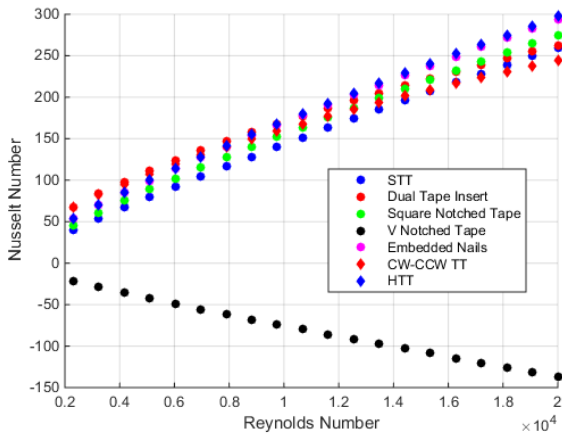
Fig 5 – Twist, depth, width, and pitch ratios have been set to 1.5 instead of 1.

Table I – Nusselt Number and Visual aid Comparisons for each of the Twisted Tape Inserts

Method and Visual Aid	Nusselt Number Correlation	Reference
STT (Fig 1)	$Nu = 0.027Re^{0.862}Pr^{0.33}(Y)^{-0.215}$	3
Dual Tape Insert **Fig 6.a**	$Nu = 0.238Re^{0.627}Pr^{0.3}(Y)^{0.346}$	4
'Square' Notched Tape **Fig 6.b**	$Nu = 0.041Re^{0.826}Pr^{0.33}(Y)^{-0.228}$	3
'V' Notched Tape **Fig 6.c**	$Nu = 0.0296Re^{0.853}Pr^{0.33}(Y)^{-0.222}(1+(d/W))^{1.148}(1+(w/W))^{-0.751}$	5
TT w/ embedded nails **Fig 6.d**	$Nu = 0.0638Re^{0.789}Pr^{0.33}(Y)^{-0.257}$	6
CW and CCW TT **Fig 6.e**	$Nu = 0.31Re^{0.6}Pr^{0.4}(Y)^{-0.36}(1 + sin\theta)^{0.44}$	8
HTT **Fig 6.f**	$Nu = 0.053Re^{0.796}Pr^{0.4}(Y)^{-0.127}((p/D))^{-0.188}$	9

Y is defined as the twist ratio and is the number of twists within one period.

(d/W) is the depth ratio. It is the ratio between the depth of the notch to the width of the notch

(w/W) is the width ratio. This is the ratio between the width of the notch to the length of the period

(p/D) is the pitch ratio. This is the ratio between the distance between to minimum or maximum points and the diameter of the pipe

different ratios are twist ratio, depth ratio, pitch ratio, and width ratio. All of these have been defined below table 2. To maintain that only the Nu value is dependant on Re value, all ratios above have been defined as 1 for fig 4 and 1.5 for fig 5.

Choosing the values of 1 or 1.5 has no significance pertaining to the comparison itself and has been done for simplicity.

III. DISCUSSION

Nu number increased for all but one TT insert based on how Re changes. Fig 4 and fig 5 were created by iterating each Nu formula through the Re range. For the first testing case where twist, pitch, width, and depth ratios were set to 1, the HTT performed the greatest returning a Nu value of 337.78 at Re = 20000. The closest tape insert to this level of performance was the embedded nails tape with Nu = 325.41.

Similarly in the case with the ratios being 1.5, the HTT performed the best with Nu = 297.27 and the embedded nails tape insert very close in performance with Nu = 293.21. The lower Re range (Re = 8000) shows that the CW-CCW tape, Nu = 162.3, performs the best of the tapes. The 'V' notched tape shows a major decrease in Nu value.

This particular tape insert requires that the geometry be in

the proper ratios. If the depth ratio[5] is 0.43, width ratio[5] is 0.34 and the twist ratio[5] is 2. With these dimensions, at a Re value of 11000, the Nu number would be 120[5]. This would make this form of TT comparable in performance to the other TT at this Re number.

As previously mentioned, the increase of the turbulence will increase the friction factor inside the pipe as a consequence to this the head loss of the system will increase.

IV. CONCLUSION

Optimization is a difficult challenge when designing nuclear reactors. Most choices that benefit one aspect will harm the performance of another. In the case of the CANDU reactor, the heat transport system can be improved with the addition of twisted tape (TT) inserts into the heat exchanger tubes. Of the compared TT inserts, all but one of the twisted tapes showed a positive increase in the Nusselt (Nu) value, which caused a heat transfer coefficient to also rise improving heat transfer inside the steam generator.

The Reynolds number is important to consider as it impacts which tape insert is more effective within that flow regime.. For lower Re values Re = 2300 to 10000, the dual tape insert and the clockwise/counter-clockwise tape performed the greatest Nu = 162.3. In the higher Re range Re = 10000 to 20000, the helical twisted tape is desired with Nu = 337.78. The goal of inserting a TT into a heat exchanger is that heat transfer will be improved, the HTT will allow for more heat transfer at the larger Re values.

With all of these tape inserts it is important to observe the effect they will have on the friction factor as well. If the friction factor becomes too large, the head loss in the system will be more than the primary pump can overcome. These tape inserts can be implemented to increase the heat transfer in a CANDU reactor.

Notes and References

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