Corrugation Profile Effect on Heat Transfer enhancement of laminar flow Region

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Abstract**—**Corrugations for Enhancement of heat transfer surface are used in many engineering applications such as heat exchanger, air conditioning and refrigeration systems. Many techniques have been investigated on the enhancement of heat transfer rate in order to reduce the size and cost of the required equipment especially in the design of heat exchangers. One of the most important methods used is a passive heat transfer technique. This method when employed in the heat exchanger showed that the overall thermal performance improved significantly. Computational Fluid Dynamics (CFD) simulation of heat transfer and fluid flow analysis in a laminar flow regime in spirally corrugated tubes with horizontal orientation are presented in this paper. Constant wall heat flux condition was applied with water as a working fluid. At Reynolds number range of 100-1300, spirally corrugated tubes were examined and the results are compared to the standard smooth tube. Results shows that heat transfer enhancement in the range of (18.4-36.3) % have been achieved

Keywords**—**Corrugation, Heat Transfer Enhancement, Laminar Flow, Spiral, Profile

I. Introduction

There are basically two concepts to increase the rate of heat transfer, one is the active method and the other is the passive method. The active method requires external sources and the passive method requires certain surface geometries or fluid additives. The benefits of heat transfer enhancement have been demonstrated in many experimental and numerical studies.

The motivation behind this activity is the desire to obtain a more efficient heat exchangers and thermal transport devices for other industrial applications, with the main objective being to provide energy, material, and economic saving for users of heat transfer enhancement technology.

Corrugated tubes are widely used in modern heat exchangers, because they are very effective in heat transfer enhancement. Spirally corrugations are considered as turbulators; as it is considered as an integral surface of the wall. There are few studies concerned with spirally corrugated tube, a helically corrugated tubes was experimentally investigated by [1]. They studied the effects of pitch-to-diameter ratio and rib-height to diameter ratio on heat transfer enhancement. Isothermal friction and thermal performance factor in a concentric tube heat exchanger were also examined. Their results show that the heat transfer and thermal performance of the corrugated tube was considerably increased compared to those of the smooth tube depending on the rib height/pitch ratios and Reynolds number. Also, the pressure loss result reveals that the average friction factor of the corrugated tube is in a range between 1.46 and 1.93 times more than that of the smooth tube. Heat transfer and isothermal friction pressure drop for two tubes of three-start spirally corrugated combined with five twisted tape inserts was tested by [2]. The results show a higher friction factor and inside internal heat-transfer coefficients than those of the smooth tube under the same operating conditions.

Correlation equations developed by [3], [4]. Based on the heat-momentum transfer analogy for the heat transfer and pressure drop in tubes having simple and multiple helical internal ridging. Heat transfer enhancement of up to 2:5 to 3 times was reported.

Other studies on pressure drop and heat transfer coefficient for flow inside doubly-corrugated tubes were achieved by [5]. Twelve different geometries have been analyzed and the results showed that only some of them yield an improved performance, expressed by the authors in terms of heat exchanger volume reduction. Spirally enhanced tubes Performance in terms of a single non dimensional geometric parameter, which the severity, was expressed by [6]. It was shown that for severity values between 0.001 and 0.01, the heat transfer enhancement is accompanied by relatively low friction factor increase, thus confirming the efficiency of this kind of geometries.

The fluid flow in annuli has been investigated by [7]. Spirally fluted, indented and ribbed tubes were placed inside a smooth outer tube. Detailed temperature profile measurements and flow visualization tests were performed for the laminar, transitional and turbulent flow in order to better understands the development of the swirl in the bulk flow. It was found that the fluted inner tubes are the most efficient in promoting the secondary flow and hence in enhancing the convective heat transfer.

Reference [8] investigated the experimental friction factor and Nusselt number data for laminar flow through a circular duct having integral helical corrugations and fitted with a helical screw-tape insert. Predictive friction factor and Nusselt number

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correlations are were also presented, and the thermo hydraulic performance was also evaluated.

A numerical simulation was performed [9] to examine the turbulent flow and temperature fields in helical tubes cooperating with spiral corrugation. The effects of the spiral corrugation parameters and Reynolds number on the flow and heat transfer were evaluated. The results show that the spiral corrugation can further enhance heat transfer of the smooth helical tube. Decrease of the pitch of spiral corrugation can enhance heat transfer in the tube. Within the research scope, helical tubes cooperating with spiral corrugation show 50-80% increase of heat transfer while the flow resistance is 50-300% larger than that in the smooth helical tube.

Numerical investigation requires less time and cost and many tube shapes and geometries can be modeled and processed. Therefore, the main objective of this study is to investigate the heat transfer enhancement numerically of three tubes of different spiral corrugation profiles and determine which corrugation has the best thermal performance under the certain boundary conditions.

II. Geometrical Configuration

Heat transfer enhancement through spirally corrugated tubes is an interesting technique for obtaining more efficient heat exchangers at minimum cost [11]. So, three different spirally corrugated tubes *circular*, *waved*, and *curved* profiles have been simulated numerically, each has outside diameter (envelope diameter) D_n of 22 mm, inner diameter (bore diameter) D_b of 20 mm, as shown in Fig. 1, 2, and 3 respectively. All of them have the same characteristic parameters of spiral rib height to diameter, e/d of 0.05 and spiral rib pitch to diameter, p/d of 12.5, the geometry configurations were achieved by using SolidWorks 2012×64 premium edition software, The fluid medium is water and the flow velocity is relative low and steady, so the flow problem can be considered as incompressible steady flow problem, in assumption that water behave as a Newtonian fluid.

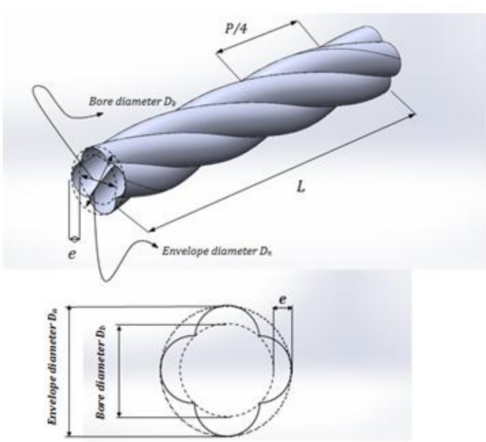

Fig. 1 Circular Corrugation Profile

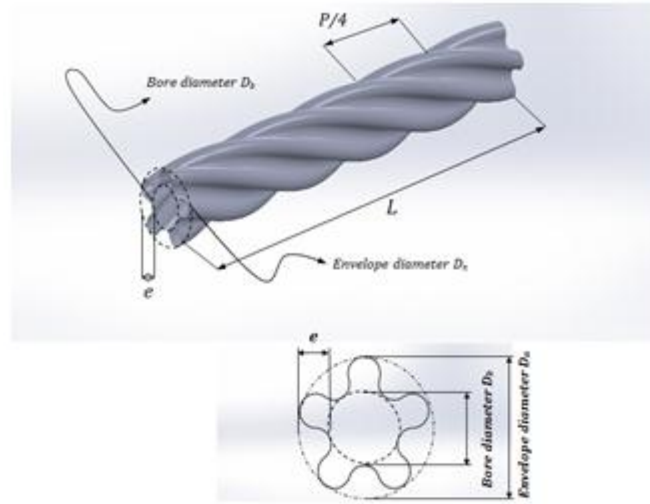

Fig. 2 Waved Corrugation Profile

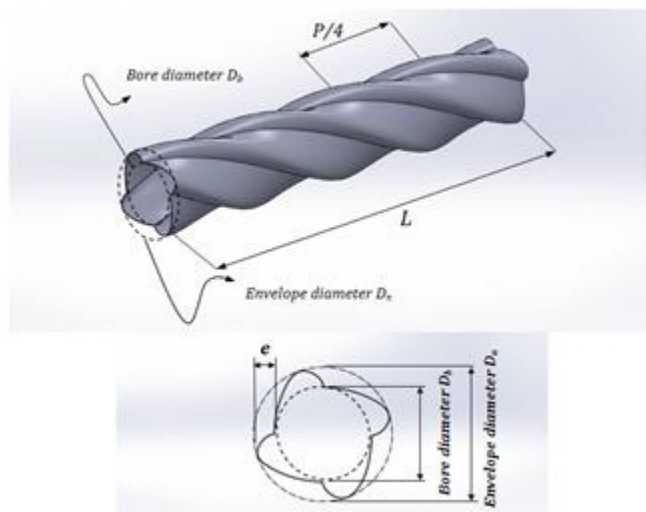

Fig. 2 Curved Corrugation Profile

III. Govern Equations

The governing equation of the flow problem in the Cartesian coordinates system as follows

Conservation of mass:

$$\nabla \cdot \rho \vec{V} = 0 \tag{1}$$

Momentum equation:

$$\nabla \cdot \left(\rho \vec{V} \vec{V} \right) = -\nabla P + \nabla \cdot \left(\mu \nabla^2 \vec{V} \right) \tag{2}$$

Energy equation:

$$\nabla \cdot \left(\rho \vec{V} C_p T \right) = \nabla \cdot \left(k \nabla T \right) \tag{3}$$

IV. Numerical Procedure

The commercial CFD code FLUENT (*FLUENT*, *14.0*) was used to analyze the model flow characteristics of smooth and corrugated tubes, mesh generation are performed in *Gambit 2.4.6* environment. The length of the aluminum tubes are 2 (m), and the number of starts is 4 and the water temperature was set at 300 (K), the water properties are not constant for all solution steps, its variable with temperature, i.e. μ, cp, $\kappa=f(T)$. The applied heat flux q″ is 2000 (W/m^2) which applied around the whole tube length. At the inlet, the water velocity can be set for different value according to the required Reynolds number. Flow was simulated at five Reynolds number values which are 100, 400, 700, 1000, and 1300.

To find optimal number of grids, five different numbers indicated by seven mesh spacing were tested for the heat flux. As the mesh spacing increases, the error compared the results with that from the finest tested mesh spacing, eventually, the 0.2 mesh space was chose as an optimum one. The governing equations are discretized by the finite volume method and solved by the steady-state implicit format. The SIMPLE algorithm is used to couple the velocity and pressure fields. The first-order upwind scheme is applied after testifying that it can get similar results for the terms of the governing equation to those by the second-order upwind scheme. The convergence criterion for continuity residual was 1.1×10^{-4}, energy residual was 1.3×10^{-7}, x-velocity residual was 4.7×10^{-7}, y-velocity residual was 4.6×10^{-7}, and z-velocity residual was 8.7×10^{-6}.

V. Results And Discussion

The primary assessment criteria of convective heat transfer performance indicated by Nusselt number Nu, and to validate the numerical smooth tube results with previous studies, the following (4) of local Nusselt number was used [12].

$$Nu_X = \left\{4.364\left[1+\left(\frac{Gz}{29.6}\right)^2\right]^{1/6}\right\} \left\{1+\left[\frac{Gz/19.04}{\left[1+\left(\mathrm{Pr}/0.0207\right)^{2/3}\right]^{1/2}\left[1+\left(Gz/29.6\right)^2\right]^{1/3}}\right]^{2/3}\right\}^{1/3} \tag{4}$$

where

$$Nu_X = \frac{q''D_h}{k[T_w(X)-T_B(X)]} \tag{5}$$

The Graetz number is useful in determining the thermally developing flow entrance length in ducts. A Graetz number of approximately 1000 or less is the point at which flow would be considered thermally fully developed. It as follow

$$Gz = \frac{\pi}{4}\frac{\mathrm{Re}\, d_h\, \mathrm{Pr}}{X/D_h} \tag{6}$$

The local heat transfer coefficient can be calculated as follow

$$q''(X) = h[T_w(X)-T_B(X)] \tag{7}$$

Where q'' represents the heat flux, Tw(x) and Tb(x) are the local wall and bulk temperatures, respectively, The local Nusselt number for the corrugated wall is defined as:

$$Nu = \frac{hD_h}{k} \tag{8}$$

where D_h is the hydraulic diameter

The effects of the roughness parameters such as height, width and length of roughness of corrugated tubes on the thermal and flow fields are recently interested because its appreciable advantages, so, it's important to know which type of corrugation has better heat enhancement performance, The dimensionless roughness parameters: the corrugation pitch-to-tube diameter ratio p/d of 12.5 and the corrugation height-to-tube diameter ratio e/d of 0.05 were fixed to ensure that all tubes subjected to the same conditions of Reynolds number, heat flux, inlet temperature, mesh spacing and also the iteration run.

The numerical results were compared with (4) for validation as shown in fig. 4, it found that the deviation is less than 2 %, hence, it's acceptable and the numerical procedure and simulation is also acceptable.

Spirally corrugation increase heat transfer enhancement, these forms causes increase their surface for a given distance and increase the convection on both sides these plates [13].

It can be seen from the fig. 5 that there is no sufficient enhancement in heat transfer due to low Re of 100 and the flow become fully developed at a distance of 0.7 (m) from the inlet for the same previous reason.

Fig. 6 shows better results, it can be clearly seen that the curved spiral corrugation has the better enhancement than the others, whereas the flow become fully developed at distance of 1.1 (m) the reason behind this is that the corrugation makes gigging swirls at the secondary flow which delay the flow to be fully development.

The increasing of Re, fig. 7 gives good impression about the effect of spiral corrugation, the maximum Nusselt number Nu_x achieved at the tubes inlet (*entrance region*)because of the maximum temperature difference at this region and also the flow is not fully development yet.

From fig. 8, and 9, we can easily differentiate between each type of corrugations, from their results, each one start to shows its advantages and characteristics. The curved corrugation profile has the better performance because it offers smoothly successive corrugation to the flow, and the fluid layers in contact with tube wall along the passage. Whereas, the other corrugation have many swirls at the notches and trough bottom which preventing the direct contact between fluid and the wall, in spite of this kind of swirl transfer heat by convection, but, it also acts like a resistance between the wall and fluid layers.

Fig. 10 shows the average Nusselt number against Reynolds number for all corrugation profiles. Waved corrugation has better thermal performance than for the rest corrugation because of the large smooth corrugation surface which increases the convective area between tube wall and working fluid, which leads to higher heat transfer enhancement among corrugation types.

It found that the Heat transfer enhancement of circular corrugation tube when compared to the smooth tube is in range of (13.8-22.17) %, for waved corrugation (15.7-30.5) %, and for curved corrugation (18.4-36.3) %.

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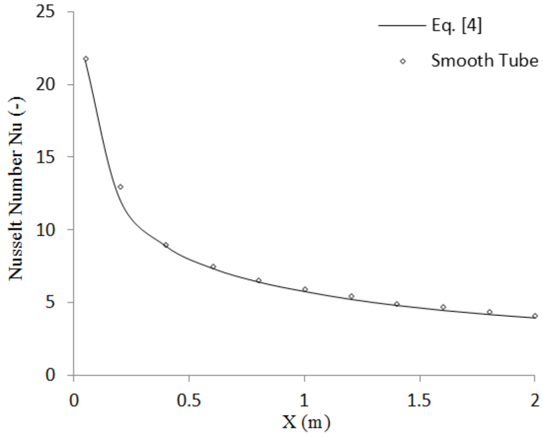

Fig. 4 Results Validation for Nusselt Number of (6) With Numerical Results of Smooth Tube

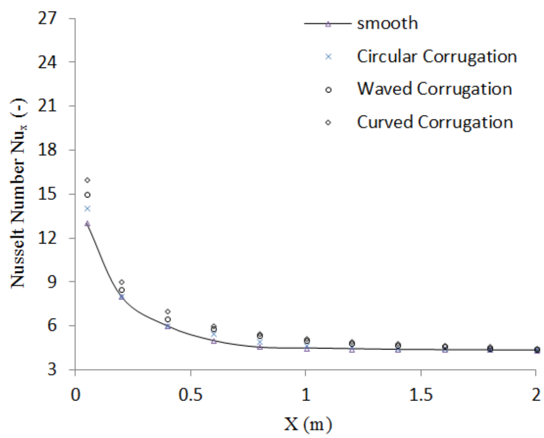

Fig. 5 Nusselt number of different tube geometries vs. axial distance at Re=100

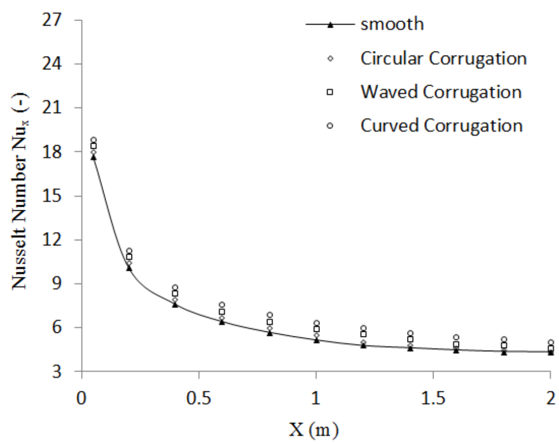

Fig. 6 Nusselt number of different tube geometries vs. axial distance at Re=400

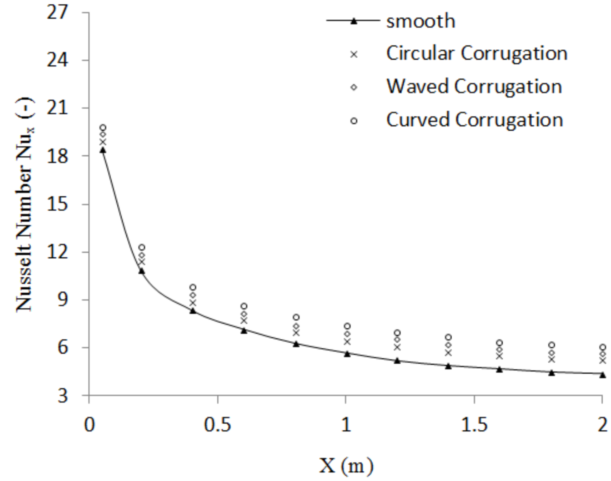

Fig. 7 Nusselt number of different tube geometries vs. axial distance at Re=700

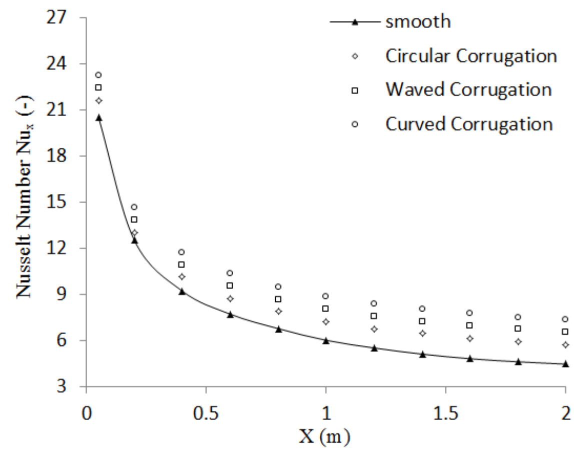

Fig. 8 Nusselt number of different tube geometries vs. axial distance at Re=1000

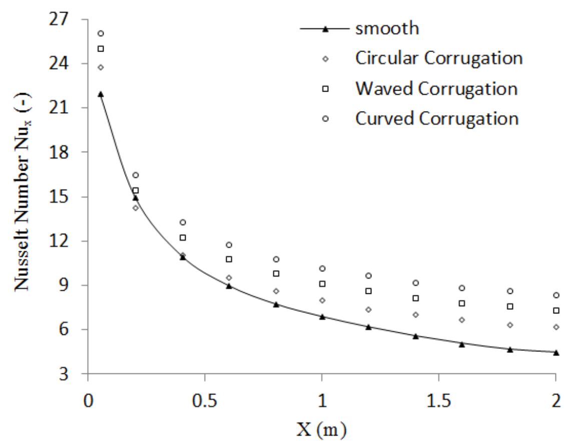

Fig. 9 Nusselt number of different tube geometries vs. axial distance at Re=1300

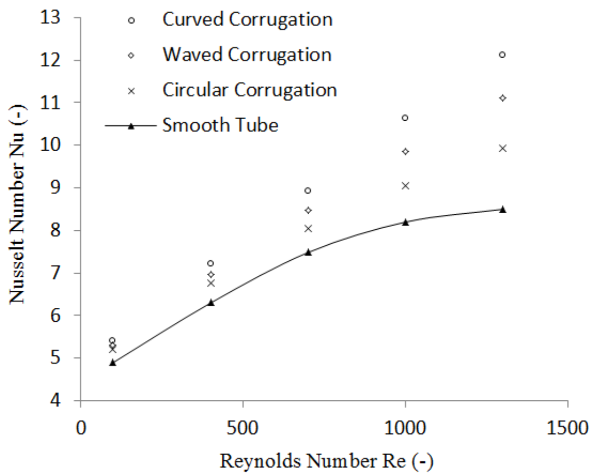

Fig. 10 Average Nusselt number vs. Reynolds number

VI. Conclusion

In this study, three different spiral corrugation profiles have been examined to determine which geometry has the best heat transfer enhancement, from the obtained results, it was found that the whole three geometries have poor heat transfer performance at low Re, and good at high Re, whereas, the curved corrugation tube has the best thermal performance among the other corrugation types, it has enhancement of (18.4-36.3) % for Re=100 –1300. While the circular corrugation tube has the lowest heat transfer enhancement and the waved corrugation tube is in between.

Nomenclatures

Symbol	Quantity	Units
C_p	Heat capacity	$[Kjkg^{-1}K^{-1}]$
D	Tube diameter	[m]
E	Error	
e	Roughness height	[m]
F_s	Safety factor	
f	Friction factor	
GCI	Grid independence index	
Gz	Graetz number	
h	Heat transfer coefficient	$[Wm^{-2}K^{-1}]$
k	Thermal conductivity	$[Wm^{-1}k^{-1}]$
L	Tube length	[m]
Nu	Nusselt number	
P	Pressure	$[Nm^{-2}]$
p	Pitch of corrugation	[m]
Pr	Prandtl number	
q″	Heat Flux per Unit Aea	$[Wm^{-2}]$
r	Refinement ratio	
Re	Reynolds number	
T	Temperature	[K]
u	Fluid velocity	$[ms^{-1}]$
X	Axial distance	[m]
Greek Symbols		
ν	Kinematic viscosity of the fluid	$[m^2s^{-1}]$
ρ	Density of fluid	$[Kgm^{-3}]$
μ	Dynamic viscosity	$[Nsm^{-2}]$
Subscripts		
B	Bulk	
b	Bore	
e	Envelope	
h	Hydraulic	
in	Inlet	
X	Local	
*	Dimensionless	

References

[1] S. Pethkool, S. Eiamsa-ard, S. Kwankaomeng, and P. Promvonge, "Turbulent heat transfer enhancement in a heat exchanger using helically corrugated tube," *International Communications in Heat and Mass Transfer*, vol. 38, pp. 340–347, March 2011. http://dx.doi.org/10.1016/j.icheatmasstransfer.2010.11.014

[2] V. Zimparov, "Enhancement of heat transfer by a combination of three-start spirally corrugated tubes with a twisted tape," *International Journal of Heat and Mass Transfer*, vol. 44, pp. 551–574, Feb. 2001. http://dx.doi.org/10.1016/S0017-9310(00)00126-5

[3] J. G. Withers, "Tube-side heat transfer and pressure drop for tubes having helical internal ridging with turbulent/transitional flow of single-phase fluid. Part 1. single-helix ridging," *Heat Transfer Engineering*, vol. 2, pp. 48–58, jul–sept. 1980. http://dx.doi.org/10.1080/01457638008962750

[4] J. G. Withers, "Tube-side heat transfer and pressure drop for tubes having helical internal ridging with turbulent/transitional flow of single-phase fluid. Part 2. single-helix ridging," *Heat Transfer Engineering*, vol. 2, pp. 43–50, Oct–Dec. 1980. http://dx.doi.org/10.1080/01457638008962755

[5] D. E. Richards, M. M. Grant, and R. N. Christensen, "Turbulent flow and heat transfer inside doubly-fluted tubes," *ASHRAE Transactions*, vol. 93, pp. 2011–2026, 1987.

[6] S. Garimella, V. Chandrachood, R. N. Christensen, and D. E. Richards, "Investigation of heat transfer and pressure drop enhancement for turbulent flow in spirally enhanced tubes," *ASHRAE Transactions*, vol. 94, pp. 1119–1131, 1988.

[7] S. Garimella, and R. N. Christensen, "Experimental investigation of fluid flow mechanisms in annuli with spirally fluted inner tube," *ASHRAE Transactions*, vol. 99, pp. 1205–1216, 1993.

[8] S. K. Saha, "Thermohydraulics of laminar flow through a circular tube having integral helical corrugations and fitted with helical screw-tape insert," *Chemical Engineering Communications*, vol. 200, pp. 418–436, Nov. 2013.
http://dx.doi.org/10.1080/00986445.2012.712579

[9] Y. Li, J. Wu, H. Wang, L. Kou, and X. Tian, "Fluid flow and heat transfer characteristics in helical tubes cooperating with spiral corrugation," *Energy Procedia*, vol. 17, pp. 791–800. Apr. 2012.
http://dx.doi.org/10.1016/j.egypro.2012.02.172

[10] R. K. Shah and D. P. Sekulic, *Fundamentals of Heat Exchanger Design*, Hoboken, NJ: John Wiley & Sons, Inc., 2003, pp. 503.
http://dx.doi.org/10.1002/9780470172605

[11] P. G. Vicente, A. Garcia, and A. Viedma, "Mixed convection heat transfer and isothermal pressure drop in corrugated tubes for laminar and transition flow," *International Communications in Heat and Mass Transfer*, vol. 31, pp. 651–662, Jul. 2004.
http://dx.doi.org/10.1016/S0735-1933(04)00052-1

[12] A. Bejan and A. D. Kraus, *Heat Transfer Handbook*, Hoboken, NJ: John Wiley & Sons, Inc., 2003, pp. 413.

[13] A. Z. Dellil, "Numerical simulation of a spiral wall," *Mechanika*, vol. 20, pp. 42–48, Jan–Feb. 2014.
http://dx.doi.org/10.5755/j01.mech.20.1.6589