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On the fully-developed heat transfer enhancing flow field in sinusoidally, spirally corrugated tubes using computational fluid dynamics

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A B S T R A C T

A numerical study has been carried out to investigate heat transfer enhancing flow field in 28 geometrically different sinusoidally, spirally corrugated tubes. To vary the corrugation, the height of corrugation e/D and the length between two successive corrugated sections p/D are varied in the ranges 0–0.16 and 0–2.0 respectively. The 3D Unsteady Reynolds-averaged Navier–Stokes (URANS) equations combined with the transition SST turbulence model are solved using the finite volume method to obtain the fully-developed flow field in a repeatable section of the heat exchangers at a constant wall temperature and at $\text{Re} = 10,000$. By studying the wide range of geometrically different tubes, the flow conditions vary significantly.

At low corrugation heights, only a weak secondary flow centred in the corrugated section is present. At higher corrugations heights, the tangential velocity component increases and eventually exceeds the axial velocity component causing the highest pressure to be located at the centre of the corrugated section. At these high corrugation heights, a further increase in corrugation height will at best only result in a small increase in Nusselt number but at a significantly higher pressure loss. To assess the performance as a heat exchanger, the ratio of enhanced Nusselt number to enhanced friction factor $\eta = (\text{Nu}/\text{Nu}_s)/(f/f_s)^{1/3}$ compared to the non-corrugated tube is used. Using this parameter, the simulations show a decrease in performance at higher corrugation heights. To link the detailed flow fields to the performance as a heat exchanger, non-dimensional correlations for heat transfer, pressure loss, and performance parameter are given.

1. Introduction

Transferring heat through a straight tube is used in numerous applications. These applications include, but are not limited to, power generation, air-conditioning, petrochemical, and diary applications. Two distinct different techniques for enhancing heat transfer are commonly used; namely a passive or active, where the active requires additional power input whereas the passive does not. Therefore, the passive technique is commonly used where the geometry is altered in a more of less sophisticated manner deforming the thermal boundary layer, creating recirculating local flow structures, or larger secondary flow structures flowing tangentially to the main flow. All these phenomena affect both heat transfer and friction characteristics.

To enhance the forced convection inside a passive heat exchanger tube, two different methods are typically used. One method is to alter the flow by changing the inner geometry of the tube. Another method is to insert loose or fastened geometrical inserts filling the cross-section of the tube, thereby promoting mixing resulting in enhanced heat transfer. These techniques do in general increase the pressure loss as well, which results in the best geometry having an optimal combination of increased heat transfer at slightly higher pressure loss. As a result, numerous studies have already been carried out to investigate the effect of both spirally and transversely tube corrugation.

Ganeshan and Rao [1] investigated the effect of Prandtl number in seven different spirally corrugated tubes having different width and height of corrugation while suggesting the ratio between heat exchanger capacity to pumping power to be 100–150% more efficient for $\text{Pr} = 4.3$ than for $\text{Pr} = 109$. As a result, this study suggests the spirally corrugated tubes to be attractive especially for fairly viscous fluids with high Prandtl numbers.

Zimparov et al. [2] conducted experiments on 25 spirally corrugated tubes having pitch heights e/D in the range 0.017–0.046 and pitch length in the range 0.25–0.65. The study found heat transfer enhancement factors range from 1.77 to 2.73 while the friction factor was increased from 100 to 400%.

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Nomenclature

A	cross-sectional area
C_p	pressure coefficient
D	pipe diameter
e	corrugation height
f	Darcy–Weisbach friction factor
h	convective heat transfer coefficient
k	thermal conductivity
L	length of pipe section
p	pressure
p	corrugation length
Pr	Prandtl number
Re	Reynolds number
T	temperature
u	fluid velocity
y^+	dimensionless wall distance
Greek letters	
η	thermal performance parameter
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	wall shear stress
ϕ	axial flow parameter
ψ	swirling flow parameter
Subscripts	
b	bulk values
s	non-corrugated reference pipe
w	wall values
z	local coordinate along pipe length
Acronyms	
CFD	computational fluid dynamics
GCI	grid convergence index
SST	shear-stress transport
URANS	Unsteady Reynolds-averaged Navier–Stokes

While most studies focus on the region unaffected by entrance effects, Rainieri and Pagliarini [3] investigated entrance for highly viscous fluids with Reynolds number ($90 < \text{Re} < 800$) using experiments and found that even a high swirl component does not always result in enhanced heat transfer for $200 < \text{Re} < 800$.

The number of studies on corrugated tubes of different shapes are increasing in literature. They range from twisted square ducts (Bhadouriya et al. [4]), twisted oval tubes (Tan et al. [5]), sinusoidal transversely corrugated tubes (Zheng et al. [6]), to more commonly reported corrugated tubes of different shapes. Ağra et al. [7] does a numerical study on two corrugated and two helically finned tubes and while concluding that the helically finned tubes generally have better heat transfer and higher pressure loss, more studies should be carried out on a wider range of geometrical parameters to investigate the detailed flow. Han et al. [8] investigated convex corrugated tubes using 2D axisymmetric CFD simulations. The study concluded that asymmetric corrugated tubes exhibit an increased heat transfer performance of 8–18% compared to symmetric corrugated tubes. Mohammed et al. [9] reported integral values of heat transfer and pressure loss for tubes categorised by pitch height, rib height and rib width. The study concluded that of the geometries investigated, the highest Nusselt number was obtained for the highest height and width and lowest pitch. Han et al. [10] investigated opposite flow directions in the same corrugated tubes and found that the larger corrugation radius should be located in the upstream direction for corrugations described by two corrugation radii.

The more recent study by Vicente et al. [11] presents a systematic investigation where both the Reynolds and Prandtl numbers are varied from 2000 to 90,000 and 2.9 to 92 respectively for ten different corrugated tubes. Furthermore, the study gives an overview of different correlations presented in literature and concludes that for the same corrugation type, the published results deviate by a factor of 1.3–3 in friction factor augmentation and between 1.2 and 2 for Nusselt number augmentation. Likewise, the literature overview by Kareem et al. [12] gives a great overview of all the studies published in the period 1977–2015. The study clearly shows that the number of publications on passive heat transfer enhancement has increased in recent years, which is attributed an increased awareness of energy savings. Furthermore, the study concludes that even though quite a number of studies already have been published, more parameters should be investigated to cover larger design spaces.

While a large number of experimental studies on different spirally corrugated tubes have been carried out, more detailed studies on the flow field in various corrugations are limited. This study presents a systematic approach where geometrical changes are made to the sinusoidally, corrugated tube by varying the corrugation height and length. Furthermore, the effects of changing the geometry are quantified by comparing to non-dimensional maps for heat transfer and pressure loss.

2. Geometry and parameters of interest

2.1. Terminology and representation of the geometry

The geometry in this study is fully described by two parameters; a corrugation height and a corrugation length. Depending on the type of corrugated tube, different sets of dimensionless numbers are typically used to describe the geometry. For sinusoidally corrugated tube investigated in this study, the geometry is fully described by two numbers; a corrugation height and length defined as:

1. Corrugation length p: the corrugation length being the streamwise distance between two successive points where the geometry repeats itself.
2. Corrugation height e: the corrugation height being the constant distance between the surface of corrugated tube and the non-corrugated tube with same diameter.

While including a lot of parameters defining the corrugations, numerous studies have shown that two main parameters are required to describe the performance; namely corrugation height and length. The purpose of this study is therefore to vary these parameters widely. To make the results applicable to any size of corrugated tube, the rest of the study reports corrugation heights and lengths made non-dimensional with the tube diameter, forming Π_1 and Π_2:

$$\Pi_1 = p/D \quad (1)$$

$$\Pi_2 = e/D \quad (2)$$