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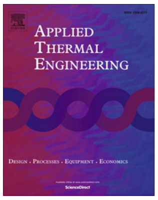

A brief review on frictional pressure drop reduction studies for laminar and turbulent flow in helically coiled tubes

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HIGHLIGHTS

- Review on pressure drop reduction studies in helically coiled tubes.
- Air bubbles, surfactant and polymer additives are effective in diminishing drag.
- Drag reduction is diminished in relation to straight tubes.
- Drag reduction is predominantly evident in turbulent flow.
- Drag reduction diminishes with higher coil curvatures and excessive *Re* numbers.

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ABSTRACT

This review, summarises the pertinent literature on drag reduction (DR) in laminar and turbulent flow in coiled tubes. Due to their compact design, ease of manufacture and superior fluid mixing properties, helically coiled tubes are widely used in numerous industries. However, flow through coiled tubes yields enhanced frictional pressure drops and thus, drag reduction is desirable as it can: decrease the system energy consumption, increase the flow rate and reduce the pipe and pump size. The main findings and correlations for the friction factor are summarised for drag reduction with the: injection of air bubbles and addition of surfactant and polymer additives. The purpose of this study is to provide researchers in academia and industry with a concise and practical summary of the relevant correlations and supporting theory for the calculation of the frictional pressure drop with drag reducing additives in coiled tubes. A significant scope for future research has also been identified in the fields of: air bubble and polymer drag reduction techniques.

1. Introduction

Due to their compact design, ease of manufacture and high efficiency in heat and mass transfer, helically coiled tubes are widely used in a number of industries and processes such as in the food, nuclear, aerospace and power generation industries and in heat recovery, refrigeration, space heating and air-conditioning processes. Due to the formation of a secondary flow, which inherently enhances the mixing of the fluid, helically coiled tube heat exchangers are known to yield improved heat transfer characteristics when compared to straight tube heat exchangers. The secondary flow, which finds its origins in the centrifugal force, is perpendicular to the axial fluid direction and reduces the thickness of the thermal boundary layer. However, for single and multiphase flows, the secondary flow yields a substantial increase in the frictional pressure drop, which often results in diminished system efficiencies (due to enhanced pumping power requirements). For air-water two-phase bubbly flow in helically coiled tubes, Akagawa et al. [2] reported frictional pressure drops in the range of 1.1–1.5 times greater than those in straight tubes, ceteris paribus, whilst, with the use of nanofluids, such a penalty could nullify the enhanced efficiencies gained with the dispersion of nanoparticles in the base fluid [7]. Moreover, due to the secondary flow, the flow characteristics are significantly different to those in straight tubes. Whereas in straight tubes the transition from laminar to turbulent flow occurs at Reynolds numbers in the region of 2500, the transition in curved tubes takes place at higher Reynolds numbers. The critical Reynolds number (Eq. (1)) is used to determine the transition of the flow from laminar to turbulent flow [23].

$$Re_{crit} = 2E4\delta^{0.32} \tag{1}$$

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Nomenclature

C	concentration (ppm)
Cc	non-dimensional surfactant concentration (–)
Cst	empirical constant (–)
d	tube internal diameter (m)
dr	drag ratio (–)
D	helix diameter (m)
De	Dean number ($Re\delta^{1/2}$) (–)
De'	modified Dean number ($Re'\delta^{1/2}$) (–)
De''	modified Dean number ($Re_{gen}\delta^{1/2}$) (–)
DR	drag reduction (%)
f	friction factor (–)
FC	friction coefficient (–)
Gz	Graetz number ($RePr/z$) (–)
Gz'	modified Graetz number ($Re'Pr'/z$) (–)
H	pitch (m)
K	rheometric and technical consistency index (Pa s^n)
L	length (m)
ME	mean error (%)
n	power law model flow behaviour index (–)
N	number of turns (–)
N_{De}	Deborah number (–)
N_{De}'	modified Deborah number (–)
P	pressure (Pa)
Pr	Prandtl number (–)
Pr'	modified Prandtl number (–)
Q	volume flow rate (m^3/s)
Re	Reynolds number (–)
Re'	modified Reynolds number as proposed by Metzner and Reed [31] $\left[8^{1-n}\left(\frac{3n+1}{4n}\right)\left(\frac{V^{2-n}d_t^n\rho}{K}\right)\right]$ (–)
Re_{crit}	critical Reynolds number ($2E4\delta^{0.32}$) (–)
Re_{gen}	generalised Reynolds number $\left(\frac{V^{2-n}d_t^n\rho}{8^{n-1}K}\right)$ (–)
SD	standard deviation (%)
T	temperature (°C)
Tc	non-dimensional surfactant solution temperature (–)
TRD	turbulence reduction: drag (–)
V	flow velocity (m/s)
VC	volume concentration (%)
VF	volumetric void fraction (–)
We	Weber number (–)
Wi	Weissenberg number (σ_{el}/σ_v) (–)
WC	weight concentration (%)
x	axial distance of coiled pipe (m)
z	dimensionless axial distance (x/d_t) (–)

Greek

β	reduced friction factor (–)
δ	curvature ratio (–)
ε	coil eccentricity (–)
θ	angle from inlet of curved pipe (°)
λ	relaxation time (s)
μ	viscosity (cP)
μ_o	zero shear rate viscosity (cP)
v	average fluid velocity (ft/s)
ρ	density (kg/m^3)
σ	stress (N/m^2)
Γ	quality (%)

Subscripts

a	ambient temp
b	bubble
bf	base fluid
c	coil
$crit$	critical
DRF	drag reducing fluid
eff	effective
el	elastic
eit	external diameter of inner tubing
gen	generalised
iot	internal diameter of outer tubing
l	liquid
lm	laminar
m	mean
nd	non-dimensional
o	zero
p	polymer solution
s	solvent
st	straight tube
t	tube
tb	turbulent
tp	two-phase
T	elevated temperature
v	viscous

where δ is the curvature ratio defined through Eq. (2).

$$\delta = \frac{d_t}{D_c} \tag{2}$$

For $\delta^{-1} < 8.6E2$ whilst for $\delta^{-1} > 8.6E2$, Re_{crit} for a curved tube is equal to that for a straight pipe.

Another dimensionless number, unique to coiled tubes, is the Dean number, given in Eq. (3). It is used to characterise the flow in curved tubes and quantifies the magnitude of the secondary flow due to the centrifugal force [32].

$$De = Re\sqrt{\delta} \tag{3}$$

The performance of coiled tubes is a complex function of the coil design parameters (Fig. 1) as well as the resultant pressure drop. Therefore, drag reduction (DR) techniques could be particularly beneficial for systems with curved tubes. Intriguingly, whilst numerous investigations have been reported on DR in straight channels and pipelines with the: injection of air bubbles [37,16], dispersion of surfactants [18] and polymers [54,3], there is a pau-

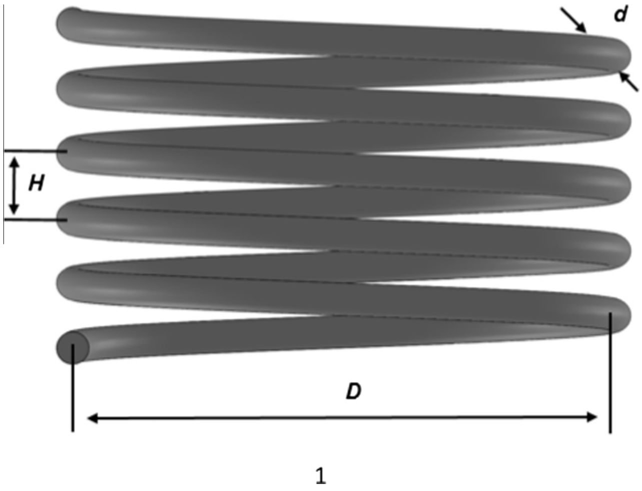

Fig. 1. Schematic representation of helical pipe characteristics.