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Experimental study of the transitional flow regime in coiled tubes by the estimation of local convective heat transfer coefficient

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ABSTRACT

The present work is focused on studying the transition between the laminar and turbulent flow regime in coiled tubes. Wall curvature is a popular heat transfer enhancement technique since it gives origin to a secondary flow in the flowing fluid due to the non-uniformity of the centrifugal force over the cross section. This phenomenon, both in the laminar and the turbulent flow regime, promotes local maxima in the velocity distribution that locally increase the temperature gradient at the wall by enhancing the heat transfer and, at the same time, leading to a significant variation in the convective heat-transfer coefficient along the circumferential angular coordinate. However, this geometry delays the transition from laminar to turbulent regime, transition that, in the majority of the papers available in the scientific literature, has been investigated on the basis of pressure drop data behaviour. In the present work the estimation of the local convective heat transfer coefficient distribution, based on the solution of the inverse heat conduction problem in the tube's wall, is proposed as a complementary and detailed tool to investigate the transitional flow regime. Moreover, the present research, thanks to the application of the proposed approach to an experimental case, gives additional information on the phenomenon of transition in coiled tubes.

1. Introduction

Wall curvature is one of the most frequently used techniques to enhance convective heat transfer [1,2]: it causes the fluid to experience the centrifugal force, which depends on the local axial velocity of the fluid particles. Such centrifugal force, that in coiled pipes is not uniform over the cross section, promotes secondary flows in the fluid. The cause is the difference of the axial velocity between fluid particles flowing in the core of the tube and fluid particles flowing close to the tube wall. The fluid is pushed from the tube core region toward the outer wall where it bifurcates and drives the fluid near the wall toward the inner wall of the tube, thus forming a pair of recirculating counter-rotating vortices, usually named as Dean vortices [3]. This phenomenon induces local maxima in the velocity distribution that locally increase the temperature gradient at the wall by maximising the heat transfer [4–6]. This additional convective transport increases also the pressure drop with respect to the straight tube behaviour.

Dean [7–8] solved the simplified Navier–Stokes equations for a coiled pipe of small curvature showing that the flow is governed by the Dean number $De = Re \cdot \delta^{0.5}$, where Re is the Reynolds number and δ is the curvature ratio, defined as the ratio of the pipe diameter to the coiling diameter.

Both in the laminar and the turbulent flow regime, the curvature produces an irregular distribution of the velocity field over the cross-section of the tube which leads to a significant variation in the convective heat-transfer coefficient along the circumferential angular coordinate: it presents higher values at the outer bend side of the wall surface than at the inner bend side [6,9,10].

For what concerns the transitional regime in coiled tubes, to the present Authors' knowledge, there are neither experimental nor numerical data in terms of local heat transfer coefficient, although, in curved pipes, the process of transition to turbulence differs qualitatively from that in straight ones.

Almost the totality of the tests performed with the purpose of detecting the transition to turbulence in coiled tubes concerned the analysis of pressure drop characteristics. In the early studies on this topic, as reported by Berger et al. [11] in an extended literature review on fluid flow in curved pipes, the earlier departure from the linear pressure drop/flow rate behaviour observed in curved tubes with respect to straight pipes, was interpreted as an indication of the transition to turbulence. On the contrary, Dean [6,7] with his work demonstrated that this departure from the linearity in the relationship between the pressure drop and the

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Nomenclature

a	helix diameter [m]	T	temperature [K]
c_p	specific heat at constant pressure [J/kg·K]	Q	heat power [W]
D	tube diameter [m]	α	angular coordinate [rad]
f	Darcy friction factor	δ	curvature ratio $\delta = D/a$
h	convective heat-transfer coefficient [W/m^2·K]	Π	dimensionless torsion of the coil $\Pi = P/(\pi \cdot a)$
k	thermal conductivity [W/mK]	μ	dynamic viscosity [Pa·s]
p	pressure [Pa]	ρ	density [kg/m^3]
$\dot{m}$	mass flowrate [kg/s]		
q	convective heat flux per unit area [W/m^2]	*Subscripts, superscripts*	
r	radial coordinate [m]	b	bulk
w	mean axial velocity [m/s]	e	entrance
z	axial coordinate [m]	env	environment
De	Dean number	ext	external
Nu	Nusselt number	f	fluid
P	coil pitch [m]	int	internal
Re	Reynolds number $Re = \rho \cdot w \cdot D/\mu$		

flow rate wasn't the signal of an anticipated transition to turbulence but an indication that the flow in curved tubes is not self-similar.

It is currently accepted that coil curvature suppresses turbulent fluctuations arising in the flowing fluid, smoothing the emergence of turbulence and increasing the value of the Reynolds number required to attain a fully turbulent flow, with respect to a straight pipe [3,12].

White [13] in his experimental work, analysed pipes with different curvature ratio δ and described the existence of a critical Reynolds number that defines the emergence of turbulence.

Many other studies [14–17] were carried out on the same topic and they all pointed out that the flow in curved pipes remains laminar up to Reynolds numbers higher at least by a factor of two than in straight pipes.

Ito [16] conducted a wide set of experimental tests for an ample range of curvature ratio and Reynolds number values investigating the transition to turbulence. The experimental results were reduced in order to find the following equation for the critical Reynolds number value:

$$Re_{cr} = 2000 \cdot (1 + 13.2 \cdot \delta^{0.6}), \tag{1}$$

valid in the range $5 \cdot 10^{-4} < \delta < 0.2$.

Also the paper of Srinivasan et al. [17] showed that the effect of curvature is to delay transition to turbulence with respect to straight pipes finding a similar correlation for the critical Reynolds number in curved tubes.

Cioncolini and Santini [3] carried out an experimental analysis of the friction factor in helical pipes in a wide range of curvature ratio and of Reynolds number. For values of curvature ratio higher than 0.0416 the transition to turbulence was more gradual than in straight pipes and it was indicated only by a change in slope of the curve of the friction factor as a function of Reynolds number. The critical Reynolds number value was approximated by the following equation:

$$Re_{cr} = 3 \cdot 10^4 \cdot \delta^{0.47}, \tag{2}$$

in the range $0.0416 < \delta < 0.143$.

Moreover, they found that the transition exhibits a more complex behaviour for lower curvature ratio values ($2.7 \cdot 10^{-3} < \delta < 0.0416$). The friction factor presents a first inflection point in correspondence of:

$$Re_{cr,I} = 12{,}500 \cdot \delta^{0.31}. \tag{3}$$

Beyond this point, the friction factor profile exhibits a local minimum followed by a local maximum; this second change in behaviour was individuated by the following equation:

$$Re_{cr,II} = 120{,}000 \cdot \delta^{0.57}. \tag{4}$$

After this second inflection point, the slope of the friction factor presented a constant profile marking in this way the end of the turbulence emergence process [3].

For what concern the heat transfer analysis some interesting works, also focused on the local behaviour, were performed by Abraham et al. [18] and by Taler et al. [19,20] but only concerning the straight pipes; to the present authors knowledge, there are not any works that investigate the transition between laminar and turbulent flow regimes in coiled tubes purposely throughout the study of neither the average nor the local heat transfer coefficient.

Nevertheless, many authors investigated either the laminar or the turbulent regimes in terms of average Nusselt number finding various correlations that, even if they don't focus on the specific study of the transition, remark a distinction between the two regimes. A wide review on helically coiled tubes and other curved pipes was conducted by Naphon and Wongwises [4].

Rainieri et al. [21] studied experimentally the forced convective heat transfer in helically coiled tubes with different curvature ratio values in the Reynolds and Dean number ranges 70–1200 and 12–290 respectively, by adopting ethylene glycol as working fluid. The experimental data were correlated by considering a dependence of the Nusselt number on the curvature ratio, Reynolds and Prandtl numbers for the helically coiled tubes. Also Xin and Ebadian [22] investigated experimentally the heat transfer and the fluid motion inside helically coiled pipes both in the laminar and turbulent regimes. The study was carried out adopting different fluids (air, water and ethylene glycol) on five uniformly heated helical pipes with different geometrical parameters (pipe diameter and pitch to coil diameter ratio).

The behaviour of the helically coiled tubes in turbulent regime was analysed also by Yildiz et al. [23] and the effect of placing spring-shaped wires inside that tubes was considered.

Both the average Nusselt number and the local Nusselt number have been never adopted in literature as an instrument to analyse the transition between laminar and turbulent flow regimes.

In the present work the local convective heat transfer coefficient distribution analysis is proposed as a complementary and detailed tool to investigate the transitional regime.

The estimation procedure presented in [24], is hereby applied to estimate the local convective heat-transfer coefficient at the fluid-