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Single phase mixing in coiled tubes and coiled flow inverters in different flow regimes

Loveleen Sharma, K.D.P. Nigam, Shantanu Roy*

Department of Chemical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India

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ABSTRACT

The present study focuses on the measurement of residence time distribution (RTD) in coiled tubes and coiled flow inverters (CFI) over a wide range of Reynolds numbers (N_{Re}), in contrast to earlier studies that have reported the RTD over a very narrow range, mainly restricted to the laminar region. The analysis of our experimental data reveals the existence of three distinct flow regimes in coiled structures, *viz.* laminar flow with prominent Dean circulation, laminar flow with less contribution of Dean circulation, and fully developed turbulent flow. Even though the turbulent transition is known to be delayed in coiled geometries, good radial mixing brought in by Dean circulation results in a narrow RTD of the exiting fluid even when the flow is clearly laminar. For coiled flow inverters, the 90° inversion allows further enhanacement in overall mixing, albeit at the cost of extra pressure drop. The effect of different design parameters on the role of secondary flow for coiled geometries of varying number of inversions (n) and curvature ratios (λ) has been investigated. Finally, a master plot is developed between the dispersion number (D/Ud_t) and Reynolds number (N_{Re}) showing the marked improvements in cross-sectional mixing in coiled flow, over that in straight tubes. Based on this, a correlation is presented.

1. Introduction

Precise control on mixing is universally desired target in many process applications. Progressively stringent requirements of process efficiency and intensification are driving the need for having efficient mixing with minimal energy input. The commonly employed techniques for efficient mixing use turbulence produced by mechanical agitation, or by introduction of second phase, or by placing obstacles in the flow path. Any attempts to maintain a high degree of mixing is generally associated with rapid energy dissipation and temperature rise when done in a mixing vessel; or equivalently, high pressure drop and high and non-uniform shear when done in a tubular structure. Some of these methods, particularly those employing high shear and associated heating, are not acceptable when the material to be mixed is sensitive to temperature or shear, such as food/ polymeric materials or pharmaceutical products (Paul et al., 2004).

Coiled tubes have been reported to present a promising mechanism for achieving this by inducing transverse mixing even when the mean flow is at low velocity and clearly in the laminar region. This kind of flow behavior is based on a double vortex circulation pattern in the cross section. The phenomena of vortex formation is understood to be through the action of the centrifugal force experienced by the fluid elements flowing along a curved trajectory, as shown schematically in Fig. 1. Such a flow pattern was first described by Dean (1927, 1928), who presented a theoretical treatment to the problem by solving the incompressible Navier-Stokes equation under the limiting condition of very small Reynolds number, and obtained an expression for the circulating fluid velocity. Named after Dean (Dean, 1927, 1928), the flow through a curved channel is quantified by the dimensionless Dean number (N_{De}), which is analogous to Reynolds number (N_{Re}) in straight tubes. The former incorporates the effect of curvature in its definition ($N_{De} = N_{Re}/\sqrt{\lambda}$). Following the initial work of Dean (1927, 1928), coiled tubes were suggested as a central philosophy for reducing axial dispersion (Koutsky and Adler, 1964; Trivedi and Vasudeva, 1975; Saxena and Nigam, 1979, 1981; Singh and Nigam, 1981), and subsequently many researchers propagated their use as static mixers (Castelain et al., 2000; Kumar et al., 2006). Building on these early contributions, the novel design of coiled flow inverter (CFI) has been presented that uses the combined benefits of coiling and flow inversion to further enhance the performance of coiled geometries in mixing applications (Saxena and Nigam, 1984). The claimed advantages of the CFI as an inline mixer (Mridha and Nigam, 2008; Mandal and Nigam, 2011) are that even though the mixing performance is significantly high, it has no moving parts, no fixed inserts, and smaller footprint.

* Corresponding author.
E-mail address: roys@chemical.iitd.ac.in (S. Roy).

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Nomenclature

ADM	Axial dispersion model
CFI	Coiled flow inverter
C	Flow-averaged mean concentration (mol/m^3)
C_O	Maximum tracer concentration in step-response experiment (mol/m^3)
d_c	Diameter of coil (m)
d_t	Inside diameter of tube (m)
D	Axial dispersion coefficient (m^2/s)
F_c	Centrifugal force (N)
F	C/C_O (dimensionless)
h	Coil pitch (m)
L	Tube length (m)
n	Number of bends (dimensionless)
N_{Bo}	Bodenstein number (dimensionless)
N_{De}	Dean number (dimensionless)
N_{Re}	Reynolds number (dimensionless)
$N_{Re,c}$	Critical Reynolds number (dimensionless)
N_{Pe}	Peclet number (dimensionless)
N_{Sc}	Schmidt number (dimensionless)
r_c	radius of curvature (m)
RTD	Residence time distribution (1/s)
t	Time (s)
$\bar{t}$	Mean residence time (s)
U	Average velocity (m/s)

Greek symbols

θ	Dimensionless time (dimensionless)
σ^2	Variance (s^2)
σ_θ^2	Dimensionless variance (dimensionless)
ρ	Density (kg/m^3)
λ	Curvature ratio (=d_c/d_t) (dimensionless)

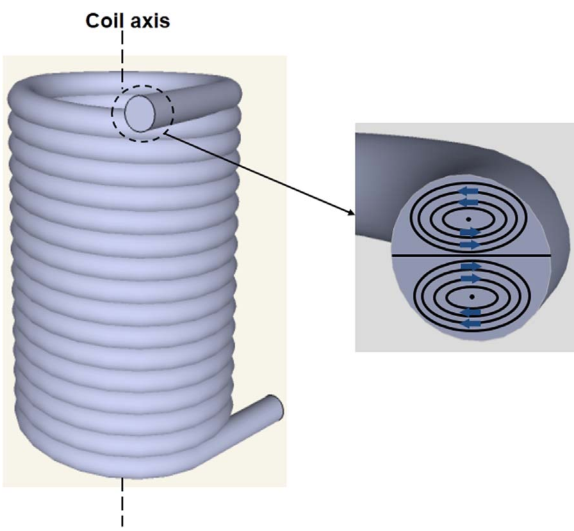

Fig. 1. Vortices or Dean vortices formation in a coiled tube.

Various recent reports demonstrate the use of CFI in multiphase flows (Vashisth and Nigam, 2007, 2008a, 2008b, 2009), reactor for continuous protein refolding (Sharma et al., 2016), microreactor for polymerization (Parida et al., 2014a, 2014b), heat exchanger (Kumar et al., 2007; Kurt et al., 2015; US Pat. No. US007337835B2), and extractor (Gürsel et al., 2016; Kurt et al., 2016). However, merely one publication by Saxena and Nigam (1984) actually focusses on the actual assessment of fluid dispersion in CFI, and that too over the limited range of Reynolds number of $10 \le N_{Re} \le 200$. Further, that work does not elucidate on the relative roles played by coiling in the geometry and flow inversion for a wide range of flows. In addition to these, the role of varying geometric parameters on the performance of CFI for different flow regimes was not considered in that work, since the primary aim of their study was to develop a device whose performance is closer to Plug Flow Reactor (PFR). Thus, Saxena and Nigam (1984) was more a "proof-of-concept" paper rather than comprehensive exploration of radial mixing behavior.

Furthermore, the fluid dispersion behavior in coiled geometries is dependent on the combined action of centrifugal and Coriolis forces induced by the curvature and pitch (or torsion) respectively, with their relative contributions thought to be changing with variation in mean flow velocity (Wang, 1981; Liou, 1992; Saxena and Nigam, 1983). Our analysis has resulted in capturing variation of axial dispersion coefficient (quantified as Peclet number (N_{Pe})) over a wider flow range ($68 \le N_{Re} \le 11146$), and in the process a consolidated "master curve" for axial dispersion in coiled geometries has been obtained.

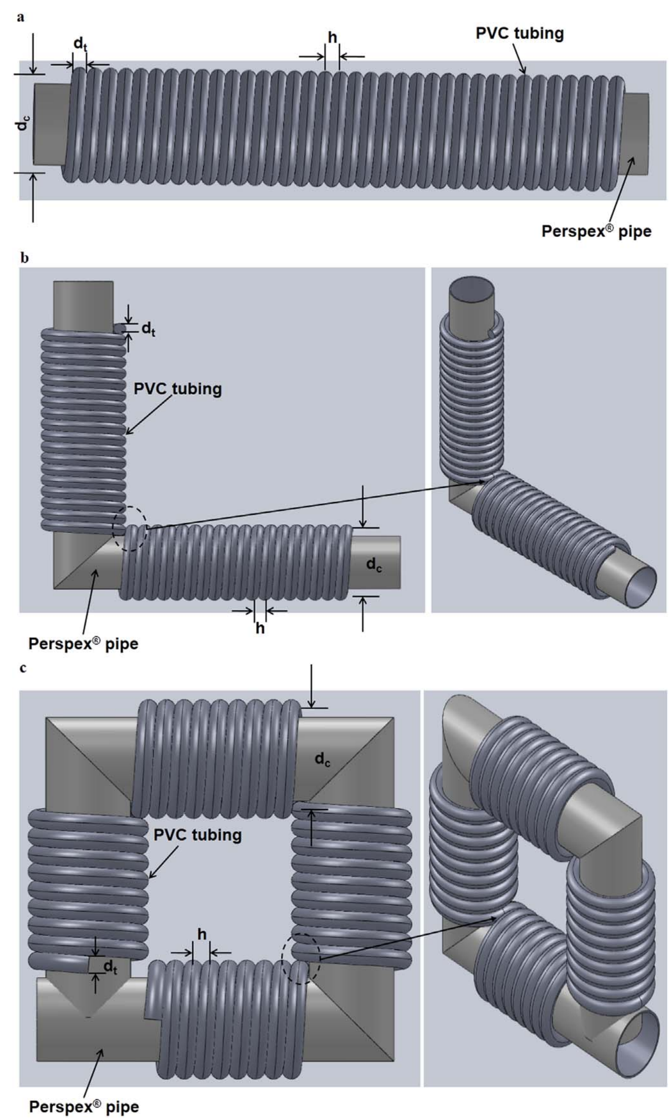

Fig. 2. Schematics for (a) straight helical coil (no inversion), n=0; (b) helical coil with

2. Experimental setup and methodology

Fig. 2**a-c** show the different coiled geometries and their geometrical parameters, where an *equal* length of PVC tubing was wound tightly on