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Axial dispersion in single and multiphase flows in coiled geometries: Radioactive particle tracking experiments

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HIGHLIGHTS

- Liquid phase Residence Time Distributions (RTD) are measured non-invasively.
- Experiments are performed for single and two-phase (gas–liquid) flows through coiled geometry.
- Quantified the axial dispersion and hence overall mixing over different flow regimes.

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ABSTRACT

Liquid phase residence time distributions (RTD) are reported by employing a novel experimental method of tracking a radioactive tracer particle during single phase and two-phase (gas–liquid) flows through a horizontal helical coil. Liquid and gas phase Reynolds numbers ($N_{Re,\ L}$ and $N_{Re,\ G}$) were varied in the ranges from 1061 to 23, 150 and 130 to 100,000 respectively. As part of this work, we tracked the entry and exit of the tracer particle in the coiled flow structure using an array of strategically placed scintillation detectors. From these experiments, it became possible to extract the residence time distribution (RTD) by enumeration of the trajectories of the tracer particle through the flow system. The investigations have resulted in explaining mixing performance for gas–liquid (two-phase) flow in coiled geometry, based on the trends in liquid phase Peclet number (N_{Pe}), over varying liquid and gas phase velocities.

1. Introduction

Fluid flow through coiled geometries is known to develop secondary flow patterns. Formation of such secondary flow patterns have been primarily attributed to centrifugal forces arising due to curved trajectories in such geometries. This kind of flow behaviour subsequently progresses into a double vortex circulation pattern in the cross-sectional plane perpendicular to the principal direction of flow at that point (as shown schematically in Fig. 1). These cross-circulating flow was first predicted from theoretical considerations by Dean (1927, 1928), and is hence referred to as Dean flow or Dean circulation. Such patterns are of great importance from hydrodynamics point of view, as they cause significant modification of the boundary layer structure and turbulent transition, and hence inspire the use of coiled tubes as laminar mixers or mixer-reactor (Vanka et al., 2004; Jiang et al., 2004; Kumar et al., 2006; Vashisth et al., 2008; Mridha and Nigam, 2008). Therefore, the examination of its performance across various flow regimes is in order.

An extensive literature on flow through helical coils shows that coiled tubes are very effective in reducing that axial dispersion in single phase flow (Koutsky and Adler, 1964; Saxena and Nigam, 1979, 1981; Singh and Nigam, 1981; Saxena, 1983a, 1983b; Trivedi and Vasudeva, 1975; Castelain et al., 1997). However, application of coiled geometries are not restricted to single phase flows only; rather there are many reported applications in the process industry involving multiple phases wherein good radial mixing is desired within each phase. In all such cases, coiled tubes and modifications thereof are suitable candidates. Past studies on two-phase coiled flows by Banerjee et al. (1969), Mujawar and Rao (1981), Saxena et al. (1990), Awwad et al. (1995), and Murai. et al., (2006) have focused on characterizing the holdup, pressure drop and visual observations (photography) of the flow pattern for coiled geometries. The measurements reported are based on gross estimates, such a holdup by collecting the total liquid held in the tubes, or overall pressure drop. Needless to say, there is interest and need to characterize multiphase flow properties by measuring local velocity or mixing characteristics, beyond mere visualization based observations. This is because owing to the complexity of multiphase flows, it is often argued that the gross flow measurements do not provide the much required deeper insights into the

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Nomenclature

d_c	Diameter of coil (m)
d_t	Inside diameter of tube (m)
D	Effective dispersion coefficient (m^2 /s)
h	Pitch (m)
Ku	Kurtosis (dimensionless)
L	Tube length (m)
l	Helical coil length (m)
$N_{Re,\ L}$	Liquid phase Reynolds number (dimensionless)
$N_{Re,\ G}$	Gas phase Reynolds number (dimensionless)
N_{Pe}	Peclet number (dimensionless)
RTD	Residence time distribution
Sk	Skewness (dimensionless)
t	Time (s)
$\bar{t}$	Mean residence time (s)
$\bar{t}_L$	Liquid mean residence time, for two-phase flow (s)
U	Liquid superficial velocity (m/s)
V_L	Volume of liquid collected (m^3)
V_C	Volume of coil (m^3)
Q_L	Volumetric flow rate of liquid (m^3/s)

Greek symbols

σ^2	Variance (s^2)
σ_θ^2	Dimensionless variance (dimensionless)
μ_3	Third moment about the mean (s^3)
μ_4	Fourth moment about the mean (s^4)
λ	Curvature ratio ($=d_c/d_t$, (dimensionless))
α_L	Liquid holdup (dimensionless)

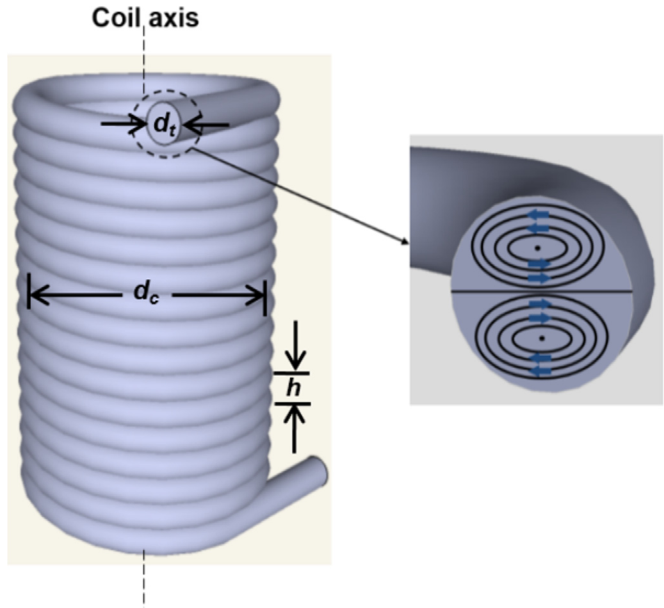

Fig. 1. Vortices or Dean vortices formation in a coiled tube.

flow. Flow visualization (photography), which has thus far been an important tool for characterization of two-phase flows in straight and coiled tubes, only provides a picture of the flow at the wall. Since phase segregation is known to be a common phenomenon even in straight tubes, and arguably in coiled tubes as well, clearly direct photography lead often to erroneous conclusions, biased largely by visual observations made at the wall. The curvature of the wall adds further challenges to clear visualization in the case of coiled tubes. Tomography would allay such concerns, but thus far nothing has been reported on tomographic investigations of two-phase flows in coiled tubes.

Furthermore, the problem of two-phase residence time distribution (RTD) measurements in two-phase flow in coiled tubes have also not attracted much attention. Performing classical tracer studies to get RTD are difficult in two phase systems since it is not very easy to clean “mixing cup” measurements, and online measurements are usually very noisy owing to the obstruction of the online probe by presence of the other phase. The only reported studies are by Rippel et al. (1966) and Saxena et al. (1996), which have been performed using classical tracer concentration measurement techniques in a limited set of air–water two-phase flow conditions. Rippel et al. (1966) compared the dispersion for two-phase, and single phase flow through coiled geometry over a range of liquid Reynolds number ($N_{Re,\ L}$) of 10–10,000. However, the gas flow conditions are not reported in that work. They reported the existence of three different dispersion patterns for two-phase flows. Furthermore, Saxena et al. (1996) investigated the two-phase RTD using upward and downward arrangements of coiled geometries, in which the curvature ratio (λ) was used as a parameter over liquid and gas Reynolds numbers ($N_{Re,\ L}$ and $N_{Re,\ G}$) in the range of 620–3200 and 1500–3000, respectively. The analysis from the two reported studies are not in complete agreement for two-phase flow in helical coils and also point towards discrepancy over their conclusions about flow regimes due to the limitation of flow range covered. Both studies suffer as well the typical problems faced by classical tracer injection techniques at high holdups of the dispersed gas phase. Also, the reported experimental work on helical configurations is only for smaller dimensions (order of 0.01 m or a few millimetres). One expects the flow behaviour and flow regime information to be markedly different on larger scales wherein surface tension is supposedly going to play a progressively lesser role, as compared to small of micro-channel helical coils.

In view of these lacunae in the literature, the main objective of this study is to investigate the liquid phase RTD in single and two-phase flows through a scaled-up helical coil (d_t=0.05 m), over a wide range of liquid and gas Reynolds number (N_{Re}). Further, these investigations have been done by tracking a single radioactive tracer particle (rendered neutrally buoyant with respect to the liquid phase), in line with the procedure outlined by Roy et al. (2001). Choice of this technique allowed us to probe the dispersion behaviour non-invasively without being constrained in any way to the flow regime and the corresponding gas holdup in the coiled tube. The highly penetrating gamma ray allowed us “optical access” into the coil (whose walls were opaque, being made of steel), and without any loss of accuracy due to two-phase interfaces. Details of this effort are reported in the flowing sections.

2. Experimental

The present method of RTD measurement was inspired by previous studies by Roy et al. (2001) and Bhusarapu et al. (2004), for estimating the solid circulation rate in the closed loop system. The method proposed by these authors has been modified appropriately for measuring the residence time distribution (RTD) of a reasonably large diameter helical coil with a periodic tracer circulation scheme. Fabrication of the experimental setup was