Chemical Engineering Science 62 (2007) 2386–2396

Chemical Engineering Science

www.elsevier.com/locate/ces

Coiled flow inverter as a heat exchanger

Vimal Kumar, Monisha Mridha, A.K. Gupta, K.D.P. Nigam*

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

Received 25 August 2006; received in revised form 9 January 2007; accepted 14 January 2007
Available online 1 February 2007

Abstract

In the present work attempts are made to investigate the hydrodynamics and heat-transfer characteristics of a coiled flow inverter (CFI) as heat exchanger at the pilot plant scale. The experiments are carried out in counter-current mode operation with hot fluid in the tube side and cold fluid in the shell side. Experimental study is made over a range of Reynolds numbers from 1000 to 16,000 using water in the tube side of the heat exchanger. The shell side fluids used are either cooling water or ambient air. The coiled flow inverter is made up of coils and 90° bends and inserted in a closed shell. The shell side is fitted with three types of baffles to provide high turbulence and avoid channeling in the shell side. The bulk mean temperatures at various downstream positions are reported for different flow rate on tube side, as well as the heat transfer efficiency of the heat exchanger is also reported. Pressure drop and overall heat-transfer coefficient is calculated at various tube and shell side process conditions. The outer and inner heat-transfer coefficients are determined using Wilson plot technique. The results show that at low Reynolds numbers, heat-transfer is 25% higher as compared to coiled tubes. At high Reynolds numbers, the configuration has less influence on heat transfer. New empirical correlations are developed for hydrodynamic and heat-transfer predictions in the coiled flow inverter.

Keywords: Coiled flow inverter (CFI); Coiled tube; Bends; Heat transfer; Friction factor

1. Introduction

Heat transfer is an essential component of nearly all industrial processes, ranging from power production, chemical and food industries, electronics, environment engineering, waste heat recovery, manufacture industry, air-conditioning, refrigeration and space applications. Consequences of improper heat-transfer include non-reproducible processing conditions and lowered product quality, resulting in the need for more elaborate downstream process system and increased heat-transfer area. Despite its importance, however, heat-transfer performance is seldom characterized rigorously for industrial systems. Detailed characterization is important, particularly in laminar flows, which have a serious potential to lead to inhomogeneity and poorly mixed regions within the flow systems. In case of laminar flow condition, the heat-transfer is low as compared to turbulent flow conditions. In a turbulent or unstable flow, on the other hand, the heat transfer is higher due to transverse fluctuations in the fluid velocity. In the process industry the turbulence between the fluid elements is increased by using either inserts or internal grooves for enhancing the mixing and heat-transfer (Nauman et al., 2002, 2003). The inserts and internal also leads into higher wall shear stresses and pressure drop since they introduce an additional no-slip surface or roughness, which results into larger pumping costs. Therefore, it is advantageous to consider devices, which do not increase the pressure drop and also not affect the smoothness of the inner wall, but provide enhancement in the degree of fluid mixing.

Secondary flow in a plane normal to the principal flow direction is very effective to enhance fluid mixing and heat-transfer. In the coiled tubes, the modification of the flow is due to the centrifugal forces caused by the curvature of the tube, which produce a secondary flow field with a circulatory motion pushing the fluid particles toward the core region of the tube (Fig. 1a). Because of the stabilizing effects of this secondary flow, laminar flow persists too higher Reynolds number value in helical coils as compared to straight tubes. Consequently, the differences in heat and mass transfer performance between coils and straight tubes are particularly distinct in the laminar flow region. Dean (1927, 1928) was the first to investigate flow in

* Corresponding author. Tel./fax: +91 11 26591020.
E-mail address: nigamkdp@gmail.com (K.D.P. Nigam).

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doi:10.1016/j.ces.2007.01.032

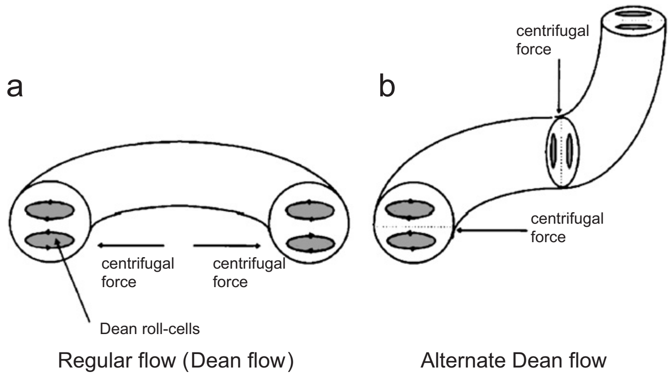

Fig. 1. Generation of spatially chaotic particle paths in coiled tube by inserting a 90° bend. (Source: Kumar and Nigam, 2005; Castelain et al., 2000)

helically coiled circular tubes, and found that a pair of symmetric vortices was formed on the cross-sectional plane due to centrifugal force. The strength of secondary flow is characterized by Dean number

$$N_{De} = \frac{N_{Re}}{\sqrt{\lambda}}, \tag{1}$$

where λ is the curvature ratio and is defined as the ratio of coil diameter to tube diameter i.e., $\lambda = D/d$. Extensive reviews on flow fields in curved ducts were reported by Berger et al. (1983), Shah and Joshi (1987), Nandakumar and Masliyah (1986) and Saxena and Nigam (1986).

1.1. Chaotic configuration (combination of coils and bends)

There is global heat-transfer enhancement in the helical coiled tube; still the isotherms of temperature for different fluids contain segregated cold and hot regions. The Dean roll cells divide the cross-section into two zones in each of which the isotherm forms the closed curves. Fluid particles inside the Dean roll cells are prevented from approaching the hot walls; thus mixing is poor, giving rise to a heterogeneous temperature field. Therefore in the coiled tubes, heat and mass transfer can be further enhanced by inserting some perturbation in the geometry.

Techniques commonly used to enhance mixing often involve the generation of turbulent flow. In some cases, however, fluids with long molecular chains can be damaged by high shear stresses, and also energy is lost by turbulent agitation. In the regular laminar regime, mixing is induced mainly by molecular diffusion. The idea of generating a spatial (Lagrangian) chaotic behaviour from a deterministic flow by simple geometrical perturbations has attracted much attention in recent years. Saxena and Nigam (1984, 1986) proposed a new technique, "bending of helical coils," to cause multiple flow inversion at low flow rates. For the case of fully developed secondary flow, a 90° bend induces a flow inversion, which narrows the RTD for equal arm lengths before and after the bend (Fig. 1b). They assessed their device by the fact that even at a Dean number of 3 the value of the dispersion number as low as 0.0013 was obtained under the condition of significant molecular diffusion and in the case of negligible molecular diffusion the value of dimensionless time at which the first element of tracer appeared at outlet was as high as 0.85.

Jones et al. (1989), Acharya et al. (1992, 1994a,b), Duchene et al. (1995) and Peerhossaini and Le Guer (1992) presented an alternative regime in laminar flow that has dispersive properties close to a turbulent regime using the phenomenon of chaotic advection. In chaotic advection, the fluid–particle trajectories are chaotic and enhance mixing, consequently increasing heat transfer. Such tools were addressed in Mokrani et al. (1997). The details of the chaotic and temporal flows are discussed by Acharya et al. (1992) and Chagny et al. (2000).

In the present work, chaotic flow is generated by the phenomenon of flow inversion by inserting 90° bends between regular coil tubes. The axis of each coil is rotated by 90° with respect to the neighbouring coil; this makes the generation of roll-cells in a plane perpendicular to the previous one, due to the reorientation of the centrifugal forces. This geometrical perturbation is the main cause of flow inversion phenomenon.

The aim of the present work is to characterize the performance of a coiled flow inverter (CFI) as heat exchanger for a water–water or water–air (tube side fluid–shell side fluid) counter-current flow system experimentally on the pilot plant scale. The effect of the fluid flow rate on the heat transfer and hydrodynamics were studied in the tube as well as in the shell side of the heat exchanger. In the present work bent coils were considered as tube side which is inserted into a cylindrical shell. The shell of the heat exchanger is comprised of three types of baffles. These features along with the pilot plant scale study are being reported first time, which is not considered in the previous literature. The most important information in the design of the heat exchanger is the pressure drop and the heat-transfer coefficient. Based on the fitting of experimental data, new correlations of the heat-transfer coefficient and friction factor for the CFI are proposed for practical applications.

2. Experimental study

The purpose of the study is to determine experimentally the hydrodynamics and fully developed heat-transfer variations with flow rates in the CFI as heat exchanger. Experiments on the heat exchanger were carried out in order to obtain a measure of their relative performance in terms of heat transfer and pressure drop and the results obtained were compared with the data reported in the literature for coiled tube. Since the experiments were carried out over a range of Reynolds numbers, therefore the comparison was made based on the inner heat-transfer coefficient as well as the pressure drop in this range. The pressure drops and heat-transfer experimental data analysis were also carried out in shell side of the heat exchanger.

2.1. Experimental apparatus

A schematic diagram of the heat exchanger test facility is shown in Fig. 2. The test facility was composed of a primary hot