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Pilot plant study for effective heat transfer area of coiled flow inverter

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ABSTRACT

Three new coiled flow inverter (CFI) heat exchangers with heat transfer area (A_t) of 0.88 m^2 (4-banks), 0.44 m^2 (2-banks) and 0.22 m^2 (1-bank) were designed, fabricated and commissioned to develop a more compact heat exchanger. More than 800 experiments were carried-out in counter-flow configuration. The hot and cold fluids were used in the tube and shell side of CFI heat exchanger, respectively. Tube side flow rates were varied from 50–300 kg/h for water and 30–100 kg/h for compressed air, respectively. The shell side flow rates were varied from 100–2000 kg/h for water and 400–750 kg/h for air, respectively. The overall heat transfer coefficients of present CFI heat exchangers were found in good agreement with the results reported for the CFI heat exchangers of A_t = 1.76 m^2. The proposed CFI heat exchanger with A_t = 0.22 m^2 provides 2.2–4.5 and 2–3.6 times higher overall heat transfer coefficient as compared to SHE and PHE of A_t = 1.76 m^2, respectively. The present study offers a small footprint CFI heat exchanger to meet the same heat transfer duty as compared to previously reported study.

1. Introduction

Coiled tubes are widely used as a heat exchanger in the modern energy conversion and power utility systems, heating ventilating and air conditioning (HVAC) engineering, food, pharmaceutical, fertilizers, and chemical industries. Coiled tube heat exchangers (CHE) provides significantly higher heat transfer rate as compared to the conventional heat exchangers, due to secondary flow pattern and augmented interfacial mixing induced by the centrifugal force. The recent work on coiled tube as heat exchanger are reported in the literature [1–6].

Saxena and Nigam [7] reported a significant development on the coiled tube by realizing its importance for process intensification in different fields. The authors proposed an innovative device called coiled flow inverter (CFI), developed by introducing a 90° bend in between the helical coils of equal axil length. The performance of the CFI was close to plug flow reactor. The effectiveness of CFI can be assessed by the value of dimensionless time at which first element of tracer appears at the reactor outlet. The dimensionless time was as high as 0.85 for the negligible molecular diffusion condition and the value of dispersion number was as low as 0.0013 for the significant molecular diffusion condition even at a Dean number of 3.

The plug flow behavior of CFI recently prompted researchers to use it for different applications in the process industry. It has been reported that CFI has superior performance as compared to coiled tubes for many applications such as polymerization reactor [8–10], liquid–liquid reactions [11], micro reactor for metal extraction [12], inline mixer [13], pharma application in protein refolding [14], heat exchanger [15–17] and other heat and mass transfer applications [18–21].

Coiled flow inverter was introduced to achieve better mixing and narrower residence time distributions during polymerization reaction [9,10]. CFI provides significantly lower value of polydispersity index (PDI), 1.39 compared to 1.53 for coiled tube using linear and branched polymers of 2-(dimethylamino) ethyl methacrylate (PDMAEMA). CFI reactors with three 90° bends (L_t = 3 m) and seven 90° bends (L_t = 6 m) were considered for continuous-flow atom transfer radical polymerization of 2-(dimethylamino) ethyl methacrylate [9]. An increase in molecular weight and monomer conversion along with decrease in the PDI was observed in CFI as compared to the coiled tube for the same operating parameters. It was reported that the throughput augmented by ten times without significant increase in PDI for CFI reactor (d_t = 4083 μm and L_t = 3 m) as compared to coiled tube microreactor. A milli-scale CFI with tube diameter of 3.2 mm and length of 210 cm was used for phase separation in slug flow [12].

Abbreviations: B, blower; C-100, fresh air cpmpressor; CFI, coiled flow inverter; CT, cooling tower; E-101, feed preheater; FI, flow indicator; FIC, flow indicator and controller; LMTD, log mean temperature difference; NTU, number of heat transfer units; PHE, plate heat exchanger; PT, pressure transmitter; SHE, shell and tube heat exchanger; TE, thermocouples; TIC, temperature indicator and controller; V, storage vessel.

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Nomenclature

Symbols

A_t	Tube side area (m^2)
A_s	Shell side area (m^2)
$C_{p,t}$	Heat capacity of hot fluid (kcal/kg-K)
$C_{p,s}$	Heat capacity of cold fluid (kcal/kg-K)
C_r	Heat capacity ratio
D_c	Curvature diameter (mm)
De	Deans number ($=Re\sqrt{1/\lambda}$)
d_t	Inner diameter of tube (mm)
d_s	Inner shell diameter (mm)
K	Thermal conductivity (W/m-K)
L	Length (m)
m_t	Tube side flow rate (kg/h)
m_s	Shell side flow rate (kg/h)
N_b	Number of 90° bends
N_{bf}	Number of banks in CFI heat exchanger
Nu	Nusselt number (hd_t/K)
Pr	Prandtl number
P_t	Pitch (mm)
P_{ti}	Tube side pressure (kgf/cm^2)
P_{si}	Shell side pressure (kgf/cm^2)
q_w	Heat flux (W/m^2)
r	Tube radius (mm)
Re	Reynolds number ($\rho v d_t/\mu$)
t_i	Temperature of the hot streams at inlet (°C)
t_o	Temperature of the hot streams at outlet (°C)
T_i	Temperature of the cold streams at inlet (°C)
T_o	Temperature of the cold streams at outlet (°C)
U	Overall heat transfer coefficient (W/m^2 °C)

Greek

ρ	Density (kg/m^3)
μ	Viscosity (kg-m/s)
λ	Curvature ratio (D_c/d_t)
ε	Heat exchanger effectiveness
ΔT_{max}	Fluid inlet temperature difference.

The extraction efficiency in CFI reactor was close to thermodynamic equilibrium for both the model systems of toluene–water–acetone and *n*–butyl acetate–water–acetone.

The hydrodynamics and heat transfer performance of CFI was investigated for constant and temperature dependent properties of the fluid [22,23]. The velocity and thermal profiles were obtained to demonstrate the basic difference between CFI and helical coil tube. The higher heat transfer coefficient was found for temperature-dependent viscosity as compared to the constant viscosity, while reverse phenomena was observed for friction factor. The heat transfer experiments were conducted at pilot plant scale in CFI of $A_t = 1.76\,m^2$, previously [15]. The tube side heat transfer coefficient in CFI heat exchanger was found 25% higher as compared to the helical coiled tube for lower values of Re (<10000). The heat transfer augmentation was up to 12% for $Re > 10000$. The Nusselt number correlations were developed for two different flow regimes.

$$Nu = 0.08825 Re^{0.7} Pr^{0.4} \lambda^{-0.1} Re < 10000, \quad (1)$$

$$Nu = 0.0271 Re^{0.85} Pr^{0.4} \lambda^{-0.1} Re < 10000 \quad (2)$$

The heat transfer characteristics of CFI were numerically and experimentally investigated for turbulent flow conditions [17,24]. CFI shows 4–13% enhancement in the heat transfer coefficients as compared to the coiled tube of same dimensions, even for higher values of Re. The relative increase in pressure drop was 2–9%. Experimentally obtained friction factor and Nusselt number for CFI, were also compared with the results of shell and tube (SHE) and plate type heat exchangers (PHE) reported in the previous study [17]. The number of transfer units (NTU) in CFI heat exchanger was found nearly 3.7–7.5 times higher as compared to SHE and 2–2.5 times higher to that of PHE. New correlation of Nusselt number was developed for compressed air flow in CFI heat exchanger under turbulent flow condition.

$$Nu = 0.123 De^{0.78} Pr^{0.4}, 3800 < Re < 14000 \quad (3)$$

In literature, the experimental data are reported only for single CFI heat exchanger of $A_t = 1.76\,m^2$ [15,17]. Intuitively, it may be argued on the basis of residence time distribution studies reported in the literature [7], that smaller heat transfer area may be required to meet the same heat transfer duty. Therefore, in the present work, attempt has been made to study the heat transfer performance of CFI by varying the heat transfer area. Three different CFI heat exchangers with different heat transfer areas of $A_t = 0.88\,m^2$ (4-banks), $A_t = 0.44\,m^2$ (2-banks) and $A_t = 0.22\,m^2$ (1-bank) were installed to experimentally optimize the heat transfer area. The effect of different process parameters such as tube and shell side flow rates, tube side inlet temperature and type of the fluid (water and air) were investigated over a wide range of Reynolds number. The pressure drop and heat-transfer data analysis for shell side of CFI heat exchanger was also carried out.

2. Experimental apparatus and method

2.1. Test section

Three new CFI heat exchangers with different heat transfer areas of $A_t = 0.88\,m^2$ (4-banks), $A_t = 0.44\,m^2$ (2-banks), and $A_t = 0.22\,m^2$ (1-bank) were installed in our pilot plant of CFI heat exchanger with $A_t = 1.76\,m^2$ [15,17]. The experiments were carried-out for different possible combination of tube and shell side fluids viz. hot water–cooling water, hot water–ambient air, hot air–cooling water and hot air–ambient air. A schematic diagram of the pilot plant of CFI heat exchanger test facility is shown in Fig. 1.

The experimental setup was made up of a primary hot loop and a secondary cold loop. The primary hot loop consists of the liquid and gas flow system for tube side of CFI heat exchanger. The liquid flow system consist of a liquid storage vessel (V-101, $V = 500$ l, SS-304), a reciprocating plunger type pump (P-101, flow rates capacity: 30–320 kg/h), a dampener (FI-101, $V = 10$ l, SS-316) was installed after pump (P-101) to minimize the flow fluctuations, an inline electric resistance preheater (E-101, $P = 5$ bar, $T = 40$–180 °C) to heat-up the feed liquid up to the desirable inlet temperature. The gas flow system consist of piston fresh air compressor (C-101), a single staged, water cooled, diaphragm type reciprocating recycle air compressor (C-102), and an air reservoir (V-102, $V = 300$ l). Three air filters (F-101) were installed after the air reservoir (V-102) to remove moisture and dust particles. Air flow rate in tube side of CFI heat exchanger was controlled through a pneumatic controller (FIC-101, flow rate capacity: 0.01–4 m^3/h). The signal from pneumatic controller (FIC-101) was transmitted to an electrical transmitter with electrical output in the range of 4–20 mA. A spill back loop was attached with the flow controller to reduce pressure drop across the feed section. An inline electric resistance preheater (E-102, $P = 40$ kgf/cm^2, $T = 40$–280 °C) was installed to heat-up the compressed air up to a desirable inlet