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Flow pattern assessment in tubes of reciprocating scraped surface heat exchangers

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ABSTRACT

Flow pattern in the tubes of an innovative scraped surface heat exchanger with reciprocating scrapers has been experimentally investigated. The scraper consists of a concentric rod inserted in each tube of the heat exchanger, mounting an array of semicircular plugs that fit the inner tube wall. A hydraulic piston provides the scraper with constant-velocity reciprocating motion. Phase-averaged velocity fields have been obtained with PIV technique for both scraping semi-cycles, with special emphasis on the effect of the scraping velocity (velocity ratio) and Reynolds number. Visualization results have been contrasted with experimental data on Fanning friction factor, obtaining a clear relation between flow patterns, pressure drop augmentation and turbulence promotion. CFD simulations for quasi-steady laminar flow provide a further insight into the relation of the flow structures with wall shear stress, and the contribution of pressure forces to global head losses, for each scraping semi-cycle.

1. Introduction

Scraped surface heat exchangers (SSHE) are commonly employed for heat transfer and crystallization processes in the food, chemical and pharmaceutical industries. These mechanically assisted devices are specially suited for products that are viscous, sticky or that contain particulate matter. During operation, the product is brought in contact with a heat transfer surface that is continuously scraped, thereby exposing the surface to the passage of untreated product [1].

High heat transfer coefficients are achieved because the boundary layer is continuously replaced by fresh material, while heat transfer surfaces remain clean. In addition to maintain high and uniform heat exchange, the scraper blades also provide simultaneous mixing and agitation, of utmost importance for laminar flow heat transfer enhancement [2]. Most commercial designs have a rotating shaft in the center with the product being pumped through the annular gap between the shaft and the outer cylindrical heat transfer tube. Flow and shearing profiles have been widely studied since the first works of Trommelen and Beek [3]. Influence of rotational speed and presence of blades has been analyzed in the remarkable works of Stranzinger et al. [4] and Dumont et al. [5], clarifying three different regimes characterized by pure shear flow, steady toroidal vortices and unstable, wavy vortices. Extensive reviews covering design aspects, heat transfer characteristics and power consumption of SSHE's can be found in Harrod [6] and Rao and Hartel [1].

This work presents an innovative concept of scraped surface heat exchanger. Within each tube is a concentric reciprocating rod, mounting an array of semi-circular elements with a pitch $P = 5D$ (see Fig. 1). These elements fit the internal diameter of the tubes. During the reciprocating motion, they scrape the inner tube wall. Additionally, the movement of the insert device generates macroscopic displacements of the flow, that continuously mix core regions with peripheral flow. As a result of the mentioned features, the reciprocating scraped surface heat exchanger (RSSHE) provides high overall heat transfer coefficients, and prevents down time for cleaning operations. Depending on the severity of the fouling phenomenon, the scraper can be either activated intermittently, or move continuously with adjustable scraping frequencies.

Commercially available versions of this RSSHE are manufactured by HRS-Spiratube S.L. under the brand UNICUS Dynamic Heat Exchanger, and by Alfa Laval Inc, with the brand Viscoline Dynamic Unit. Along with the industrial evidence of fouling reduction, the manufacturers claim for its higher heat transfer area, smaller number of shutdowns, lower induced shear stress in the product, and particle integrity in food applications, compared to rotating scraped surface heat exchangers. RSSHE's are progressively being introduced in the food industry, wastewater treatment processes, production of second-generation biofuels, etc.

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Nomenclature

A	annular cross-section (m^2)
D	tube inner diameter (m)
D_h	hydraulic diameter (m)
d	rod diameter (m)
F	force over a scraper pitch (N)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
P	pitch of the insert devices (m)
Δp	pressure drop across the test section (Pa)
S	scraping amplitude (m)
T	temperature (K)
v	velocity ($m\,s^{-1}$)

Dimensionless groups

f_h	fanning friction factor
Re_h	Reynolds number
ω	velocity ratio, v_p/v_f
c_F	force coefficient, $F/\frac{1}{2}\rho v_{f^2}A$
C_f	skin friction coefficient, $\tau_w/\frac{1}{2}\rho v_{f^2}$

Greek symbols

β	blockage parameter, $(v_f - v_p)/v_f$ (−)
Γ	numerical surface
κ	radii ratio, d/D (−)
μ	dynamic viscosity (Pa s)
Ω	numerical volume
ρ	fluid density ($kg\,m^{-3}$)
τ	wall shear stress ($N\,m^{-2}$)

Subscripts

cc	counter-current
eq	co-current
f	fluid
in	tube inlet
med	average
out	tube outlet
p	scraper
s	smooth tube
w	tube wall
z	axial direction

The present work is devoted to the analysis of the flow pattern and the friction characteristics in tubes of reciprocating scraped surface heat exchangers. Particle Image Velocimetry (PIV) technique is employed for obtaining the two-dimensional velocity field in the symmetry plane of the tube in laminar regime. The separate performance of the device in the two scraping semi-cycles is considered in the analysis, thus defining counter-current and co-current stages. Flow patterns existing for different velocity ratios ω are identified, establishing as reference condition the performance of the still scraper. The influence of Reynolds number on the flow features is assessed.

Experimental results of Fanning friction factor for a wide range of Reynolds numbers and velocity ratios are contrasted with the visualization data, for both scraping semi-cycles. The contribution of the flow structures to the local shear stress is briefly analyzed with the numerical simulation tool Fluent, complementing the experimental data and providing further information towards the holistic understanding of the physical flow nature.

2. Experimental program

2.1. Visualization facility

The facility depicted in Fig. 2 was built in order to study the flow pattern induced by a wide variety of insert devices in round tubes [7]. The main section consists of a 32 mm diameter acrylic tube installed between two reservoir tanks, that stabilize the flow. The flow temperature is regulated by an electric heater and a thermostat placed in the upper reservoir tank. The flow is impelled from the lower calm deposit to the upper one by a gear pump, which is adjusted by a frequency converter. By using mixtures of water and propylene-glycol at temperatures from 20 °C to 60 °C, Reynolds numbers between 100 and 20,000 can be obtained. The tests presented in this work were carried out employing a mixture of 90% propylene-glycol and 10% water, at temperatures from 25 °C to 50 °C, yielding Reynolds numbers in the range from 36 to 378.

The test section has been placed five scraper pitches downstream (25D), this ensuring periodic flow conditions. To improve optical access in this section, a flat-sided acrylic box was placed around. The box was filled with the same test fluid that flows through the test section. Particle Image Velocimetry (PIV) has been employed for flow visualization.

PIV is a well-known technique to obtain global velocity information, instantaneously and with high accuracy [8]. In these experiments, planar slices of the flow field containing the symmetry plane of the inserted device were illuminated. The flow was seeded with polyamide particles of 57 μm mean diameter. The camera viewed the illuminated plane from an orthogonal direction and recorded particle images at two successive instants in time in order to extract the velocity over the planar two-dimensional domain. 2D velocity fields along a scraper pitch were assembled to provide an overall insight of the flow structure.

The spatial resolution of the measurement is 110 μm/pixel. A 1 mm thick light sheet is created by a pulsating diode laser of 808 nm wavelength. A computer synchronizes the camera shutter opening and the laser shot at sampling frequencies between 250 and 500 Hz, most appropriate for the test

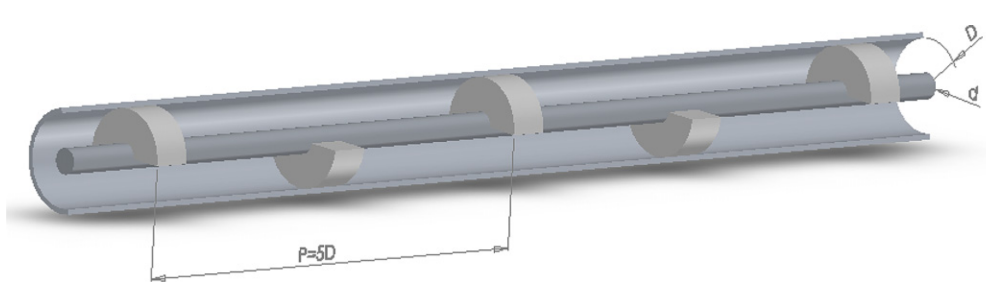

Fig. 1. Detail of the scraper geometry inserted in the tube. Typical designs cover the total length of the tube for full cleaning.