International Journal of Heat and Mass Transfer 118 (2018) 75–87

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental study of heat transfer to non-Newtonian fluids inside a scraped surface heat exchanger using a generalization method

D. Crespí-Llorens [a,*], P. Vicente [a], A. Viedma [b]

[a] Dep. Ing. Mecánica y Energía, Universidad Miguel Hernández, Av. Universidad, s/n, 03202 Elche, Spain
[b] Dep. Ing. Térmica y de Fluidos, Universidad Politécnica de Cartagena, Dr. Fleming, s/n, 30202 Cartagena, Spain

ARTICLE INFO

Article history:
Received 23 June 2017
Received in revised form 8 September 2017
Accepted 27 October 2017
Available online 22 November 2017

Keywords:
Heat transfer
Non-Newtonian
Power Law
Experimental
Enhanced heat exchanger

ABSTRACT

The heat transfer process to a non-Newtonian pseudoplastic fluid inside a scraped surface heat exchanger has been experimentally analysed. The scraping device consists of a rod with semicircular pieces mounted on it, which are in contact with the inner surface of the pipe. The whole moves axially and thus, the pieces scrape the inner surface of the pipe, in order to avoid fouling formation and enhance heat transfer.

Pressure drop, heat transfer and power consumption measurements, using non-Newtonian pseudoplastic fluids, have been carried out in static and dynamic conditions of the scraper. Four flow regions have been identified: attached laminar, detached laminar, transitional and turbulent flow regions. A generalization method for the fluid viscosity that includes the effects of the non-Newtonian behaviour has been used. Friction factor and Nusselt number have been successfully correlated by employing the generalized viscosity on pressure drop and heat transfer results, both in static and dynamic conditions, for three of the four identified flow regions (it was not possible to get correlations in the transition to turbulent flow region). The study shows that, despite the high power consumption of the scraping movement, the device is suitable for an industrial process using non-Newtonian fluids, since it prevents fouling, increases heat transfer, provides flexibility and enhances the final product quality. Furthermore, the obtained correlations are a valuable tool in the design of heat exchangers.

1. Introduction

Heat exchangers in the food and chemical industries usually have low efficiency when working with non-Newtonian fluids. These fluids have high apparent viscosities and therefore, laminar flow at high Prandtl numbers usually occurs. Moreover, the fouling problem in these heat exchangers has a significant impact on heat transfer inefficiencies and on cleaning downtime [4,5]. Besides, high temperature gradients in heated fluids are common, which decreases the quality of the process and sometimes of the fluid itself.

Moving insert devices that scrape the heat exchanger surfaces can be the best option, since they solve some of the problems that may occur when smooth pipes are employed on high viscous fluids. When the heat transfer surface is scraped, the heat exchanger is not required to be oversized to take into account the heat transfer decrease due to fouling. Moving scrapers permit us to work in food or chemical processes without the need of stops that affect plant productivity. Heating a fluid which is highly mixed, produces a uniform temperature field in the fluid that improves its quality, which is of the utmost importance in the food industry.

Many investigations have focused on scraped surface heat exchangers (SSHE), studying their flow pattern characteristics [26], their thermo-hydraulic performance [10] or their scraping efficiency [25].

A series of works studied the performance of Newtonian and non-Newtonian flows inside scraped surface heat exchangers (SSHE) with rotating blades. Mabit et al. [19] used an electrodiffusion technique in order to investigate the shear rate on such devices, observing maximum shear rate at the scraping surface and on the leading edge of the blades. Yataghene et al. [31] undertook a numerical investigation to characterize the shear rates for Newtonian and Non-Newtonian fluids. Later, they [29] studied the effect of index and consistency behaviour of shear thinning fluid using power-law rheological behaviour on the viscous dissipation through a numerical model. Finally, they [30] performed an experimental analysis using Newtonian and non-Newtonian fluids where they studied flow patterns inside a scraped surface heat exchanger (SSHE) with a rotating blade under isothermal

* Corresponding author.
E-mail address: dcrespi@umh.es (D. Crespí-Llorens).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.115
0017-9310/

Nomenclature

$a_i, \ldots, e_i$	correlation constants
D, R	inner diameter and radius of the pipe (Fig. 1)
d, R_s	diameter and radius of the insert device rod (Fig. 1)
D_h	hydraulic diameter, $D_h = D - d$
h_i	film coefficient inside the pipe
h	constant in function Δ
k	thermal conductivity
L_p	pressure ports separation length
m	flow consistency index (rheological property)
N	number of experimental measurements
Q	flow rate
P	distance from one scraper to the next one at the same angular position
Δp	pressure drop
r	radial position
t	scraper length (see Fig. 1)
T	temperature
U	uncertainty for a confidence level of 95%
u	fluid velocity
u_b	bulk velocity
v_s	velocity of the scraper (positive in co-current direction)

Greek symbols

γ	shear rate
μ_g	generalized viscosity of the flow, $\mu_g = m\,\phi(n)\left(\frac{u_b}{D_h}\right)^{n-1}$
ρ	fluid density
τ	shear stress

Dimensionless numbers

β	blockage parameter, $\beta = 1 - v_s/u_b$
Δ	relationship between axial velocity gradients at the heated wall, for a power law fluid and for a Newtonian fluid
f	Fanning friction factor, $f = \Delta p D_h / 2 L_p \rho u_b^2$
n	flow behaviour index (rheological property)
Nu	Nusselt number
Pr_g	generalized Prandtl number, $Pr_g = c_p \mu_g / k$
$Pr_{g,ref}$	reference Prandtl number for one set of experiments
$\phi(n)$	generalization function
Re_g	generalized Reynolds number, $Re_g = \rho u_b D_h / \mu_g$
ω	non-dimensional scraping velocity, $\omega = v_s/u_b = 1 - \beta$

Subscripts

a	the device under study (scraper)
av	section average value
g	non-dimensional number based on the generalized viscosity
sp	smooth pipe
dy, st	dynamic or static scraper respectively
w	value at the inner pipe wall

and continuous flow conditions. However, few studies have focused on the analysis of processes using non-Newtonian fluids within scraped surface heat exchangers (SSHE) with reciprocating scrapers, where the scraping device moves axially.

According to Chhabra and Richardson [7], pseudoplasticity is the most common non-Newtonian behaviour in the process industry. Pseudoplastic fluids are characterized by an apparent viscosity which decreases with increasing shear rate within a certain range of shear rates, and the Power Law model is widely used to represent this behaviour [13,6]. For such fluids, the friction factor depends on the Reynolds number and the pseudoplasticity of the fluid, represented in this model by the flow behaviour index n. Metzner and Reed [22] developed a generalization method for smooth pipes which defines a generalized fluid viscosity so that the friction factor depends only on the Reynolds number defined with such viscosity. Afterwards Kozicki et al. [18] and Delplace and Leuliet [11] extended its use to ducts with uniform cross section.

Recently, the authors [8] defined a generalized viscosity for geometries with non-uniform cross section in static conditions of the scraper and also studied the flow pattern in static and dynamic conditions [9]. In this research, the generalization method of the former work has been applied to the moving scraper. Experimental results will show the possibilities of applying this non-dimensional methodology, that simplifies and generalizes the study of the mechanical and thermal problems.

This work presents an experimental study of the heat transfer process to a pseudoplastic non-Newtonian fluid in a tubular SSHE. The scraper is shown in Fig. 1 and consists of semicircular shaped devices mounted on a moving rod. A hydraulic cylinder impels the whole alternatively along the axial direction and the device scrape the internal wall of the tube. The movement can be done sporadically to remove fouling, in that case, the study of the device in static conditions (static scraper) will be enough to evaluate its performance. In other cases, it will be better to actuate the scraper continuously at different velocities in order to increase heat transfer. In these situations, the power consumption of the movement has to be considered in the energy balance.

The research has two objectives. The first is to evaluate the performance of the device under study, which works with non-Newtonian fluids. For that, pressure drop, heat transfer and power consumption have been measured as functions of the involved variables: Reynolds number, Prandtl number and scraping velocity. The second objective is to evaluate the applicability of a generalization method for the viscosity of a power law fluid to the case of a moving scraping device.

Friction factor and Nusselt number have been correlated by employing the generalized viscosity on pressure drop and heat transfer results, both in static and dynamic conditions. Finally a performance evaluation of the heat transfer enhancement has been calculated to determine the negative effect of the power consumption for the scraping movement.

2. Experimental setup

The experimental set-up shown in Fig. 2(a) has been used to measure pressure drop, heat transfer and the moving rod power consumption for different flow regimes and scraping velocities.

2.1. Experimental set-up description

The experimental facility consists of two circuits:

- *The primary loop*, containing the test section (8) and the viscometer (12) in parallel.
- *The cooling loop*, which controls the temperature of the test fluid in the main tank(1).