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Parameter estimation applied to the heat transfer characterisation of Scraped Surface Heat Exchangers for food applications

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ABSTRACT

A parameter estimation approach was applied to characterise the heat transfer of Scraped Surface Heat Exchangers (SSHEs) specifically designed for the food industry. It is difficult to apply the data available in the literature to SSHEs, due to the specificity of each product, thermal treatment and geometrical configuration, making the thermal design of these apparatuses critical. Therefore, it appears to be more useful to assess the methodology used to derive a proper heat transfer correlation than to assess the form of the heat transfer correlation itself, as the correlation often cannot be transferred to other heat exchangers, even those that belong to the same class.

This study enabled successful and robust estimation of the heat transfer correlation for the product side Nusselt number and the external side heat transfer coefficient; this approach differs from Wilson plot methods, as no assumption is made regarding the functional dependence of the external side heat transfer coefficient.

The procedure was validated through application to both synthetic data and experimental data acquired from a coaxial SSHE pilot plant for the treatment of highly viscous fluid foods.

The procedure was optimised with the aid of sensitivity and uncertainty analysis, which provided considerable insight into the problem.

The application to synthetic data demonstrated that under typical operating conditions, areas of insensitivity to certain parameters are present. The application to the experimental data acquired under both heating and cooling conditions confirmed that the measured values of the overall heat transfer coefficient can be used to estimate the secondary fluid heat transfer coefficient, as well as the power law dependence of the internal fluid Nusselt number on the rotational Reynolds number and the Prandtl number together with the multiplicative constant. The uncertainty analysis provided the confidence intervals associated with each estimated parameter, thereby enabling the quality and robustness of the resulting heat transfer correlations to be determined.

1. Introduction

Parameter estimation represents a powerful tool for many engineering applications such as the design of heat exchangers. In fact, this approach offers the ability to estimate unknown parameters, which are often crucial for the design and optimisation of the whole heat transfer apparatus. This strategy appears to be particularly useful in the design of heat exchangers that are customised for certain specific purpose, as often happens with Scraped Surface Heat Exchangers (SSHEs). SSHEs may provide a suitable solution to actively enhance the convective heat transfer mechanism in highly viscous or sticky fluids, i.e., in conditions that are generally critical due to the limited heat transfer coefficients that can be achieved given the low Reynolds number values that generally characterise the fluid flow, as shown by Bozzoli et al. (2010), Rainieri et al. (2011, 2012a, 2013), Datta (2002) and Rozzi et al. (2007).

In these heat exchangers, the product to be heated/cooled flows axially in an annular section between a stationary outer cylinder and a powered coaxial rotor. The inner wall of the outer cylinder is periodically scraped by blades attached to the rotor, while the heating or cooling fluid circulates into the external jacket, which is generally equipped with flow baffles.

There are generally between two and four blades, which can be arranged longitudinally on the rotor wall along the whole length of the heat exchanger. Alternatively, short blades can be arranged in couples and shifted by 180° with respect to the rotor axis, in the presence or absence of some degree of overlap. These two

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Nomenclature

A_i	heat transfer inner surface area, $A_i = \pi D_i L$ (m^2)
A_o	heat transfer outer surface area, $A_o = \pi D_o L$ (m^2)
C	multiplicative constant, Eq. (6)
$CI^{95\%}$	confidence interval, Eq. (14)
CV	coefficient of variation, Eq. (15)
D_i	exchanger tube inner diameter (m)
D_o	exchanger tube outer diameter (m)
D_r	rotor shaft diameter (m)
h	convective heat transfer coefficient (W/m^2 K)
j	fluid specific enthalpy (J/kg)
J^*	scaled sensitivity coefficient
$\mathbf{J}$	Jacobian operator
L	heat exchanger's length (m)
m	mass flow rate (kg/s)
n	number of blades
N	rotational velocity (r.p.s)
Nu	inner side Nusselt number, Eq. (5)
P_i	generic unknown parameter
Pr	Prandtl number
Q	heat transfer rate (W)
R_w	wall thermal resistance (K/W)
Re_r	rotational Reynolds number, Eq. (7)
S	target function
T	fluid temperature (K, °C)
U	overall heat transfer coefficient (W/m^2·K)
α	Reynolds number exponent, Eq. (6)
β	Prandtl number exponent, Eq. (6)
ΔT_{ml}	logarithmic mean temperature difference (K, °C)
η	fluid dynamic viscosity (Pa s)
λ	fluid thermal conductivity (W/m K)
λ_w	wall thermal conductivity (W/m K)
ρ	density (kg/m^3)
σ	standard error

Subscripts

i	inner-side
o	outer-side
in	inlet section
out	outlet section

configurations are named continuous and alternate blades, respectively (D'Addio et al., 2012).

In any of the possible configurations, the heat transfer coefficient is augmented by the mixing of the fluid in the boundary layer, activated by the rotation of the shaft (Härröd, 1986) and by backmixing phenomena (D'Addio et al., 2013). The complex flow pattern established in SSHEs is often described by adopting the axial Reynolds number and the rotational Reynolds number (Härröd, 1986).

Increasing the rotational Reynolds number results in several different flow regimes (Härröd, 1986), and this complex flow is affected by many factors including the blade profile, the entry region effect, the possible non-Newtonian rheological behaviour and the thermally induced modification of the working fluid properties.

Although SSHEs are frequently used in industrial applications such as in the dairy and food industry where the fluid under treatment often undergoes phase changes and is often highly viscous and exhibits complex rheological behaviour, the scientific literature on this topic contains some gaps, including the thermal design of these apparatuses (Boccardi et al., 2010; Fayolle et al., 2013). Very few studies in the open scientific literature address the topic of SSHE design using a theoretical approach (Härröd, 1986), although the numerical approach has led to some critical results (Yataghene and Legrand, 2013; Rainieri et al., 2012b).

Most studies about SSHEs are based on experimental investigations of single-phase and two-phase heat transfer modalities. The mostly widely used correlations have been reviewed by Härröd (1986), Abichandani and Sarma (1987) and Skelland (1958).

The experimental data are treated by adopting the dimensional analysis approach, but due to the specificity of each plant and product treated, it is often difficult to extend the validity of the suggested heat transfer correlations that often hold for the particular geometry under investigation.

Generally, the experimental investigations reported in the literature aim to measure the average product Nusselt number for different conditions (different rotational or axial Reynolds number values, heating/cooling conditions) and different geometric configurations (number and/or profile of the blades). The product convective heat transfer coefficient is generally indirectly derived by measuring the overall heat transfer coefficient, which accounts for both the internal and external convection thermal resistances, and for the conductive thermal resistance of the tube wall. This procedure is sometimes performed by assuming that the external thermal resistance is much lower than the inner resistance (D'Addio et al., 2013). This simplified approach can lead to misleading conclusions for SSHEs because increasing the rotational velocity of the rotor makes the magnitude of the inner and outer thermal resistances comparable.

For the internal side heat transfer correlation, a monomial form is generally adopted by accounting for the dependence of the Nusselt number on the rotational Reynolds number and the Prandtl number, while the dependence on the axial Reynolds number is generally disregarded (Härröd, 1986).

One of the simplest methods used to account for the external side heat transfer coefficient is the well-known Wilson plot technique (Wilson, 1915), which was originally developed to estimate the inside heat transfer coefficient in a steam condenser by holding the shell side mass flow rate constant and assuming a known power law dependence of the internal heat transfer coefficient on the fluid velocity (Wilson, 1915). A simple linear curve fitting procedure was used to estimate both the sum of the wall and shell side resistances and the constant of the internal side heat transfer correlation. Briggs and Young (1969) suggested and validated a procedure for determining three unknowns rather than two, as the exponent expressing the power law dependence of the internal Nusselt number on the Reynolds number was also estimated. A more general approach based on a non-linear regression scheme was presented by Khartabil and Christensen (1992). A unified Wilson plot method based on non-linear regression was applied by Styrylska and Lechowska (2003). Some of these approaches assume that the external side heat transfer is constant, while others assume that it follows some specific correlation, the parameters of which have to be estimated.

A general review of the Wilson plot method and its modifications to determine convection coefficients in heat exchanger devices is presented by Rose (2004) and Fernández-Seara et al. (2007).

In our opinion, this approach appears to be unsuitable to accurately describe the performance of SSHEs. In fact, the convective heat transfer on the external side cannot often be analytically