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Towards a better understanding of 2D thermal-flow processes in a scraped surface heat exchanger

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ABSTRACT

To optimise and to improve heat transfer in heat exchangers, a special construction with rotational blades, called scraped surface heat exchanger (SSHE), can be applied. Despite SSHE are widely used, thermal-flow processes in these devices are still not well understood. The paper presents and describes a method allowing for precise determination of heat transfer coefficient value in case of periodic heat transfer with mechanical removal of thermal boundary layer. In order to get a better insight into these phenomena, we present numerical study on laminar forced convection in a two-dimensional SSHE model. Transport equations of mass, momentum and energy are solved in a non-inertial coordinate system using finite volume method framework. Numerical model was compared both with available analytical models based on the penetration theory and experimental data available in literature. The main goal is to investigate impact of a wide range of non-dimensional parameters on heat transfer rate. Rotational Reynolds and Prandtl numbers and a non-dimensional gap varied in range 10–1000, 0.71–56.00 and 0.005–0.15, respectively. It was found that the heat transfer rate increases with increasing both Reynolds and Prandtl numbers, and decreases with increasing the non-dimensional gap. The major conclusion resulting from numerical calculations is that the non-dimensional gap plays an important role in the laminar flow regime.

1. Introduction

In numerous solid–fluid thermal interactions occurring in technology, the natural heat transfer speed is not satisfactory and requires some more or less sophisticated enhancement. Heat transfer enhancement techniques may be generally divided into passive and active ones [1]. Passive techniques (rough surfaces, extended surfaces, swirl-flow devices, etc.) do not require external energy in contrast to the active ones (mechanical aid, surface vibration, electric field acting, etc.) and they are easier to apply. However, if high value of heat transfer coefficient is desired, passive techniques are insufficient and active techniques are usually applied.

One of the active techniques is a scraping method based on mechanical removal of the thermal boundary layer. In spite of increasing number of papers concerning this technique, there is still lack of knowledge on the thermal boundary layer scraping technique. The goal of this paper is a better understanding of 2D thermal flow processes during scraping heat transfer enhancement.

With the use of thermal boundary layer scraping technique, heat transfer increases due to mechanical removal of fluid near the wall directly participating in the heat transfer. Thermal boundary layer developed near the wall is the main thermal resistance. If this layer is mechanically removed, it decreases thermal resistance and higher heat flux can be obtained. The layer is scraped off by blades called scrapers. Although additional mechanical energy to move the scrapers is required, this technique is very attractive, because in comparison to other methods higher heat transfer coefficients can be reached. Generally, aforementioned method is used for very viscous liquids characterised by high Prandtl number (mayonnaises, creams, ice-creams, etc.) but it is also possible to achieve high heat transfer enhancement for fluids with low value of Prandtl number such as gases. Hagge and Yunkhan [2] reported, that ten times heat transfer rate increase was observed with air used as a working fluid.

The thermal boundary layer scraping technique is commonly applied in the scraped surface heat exchangers (Fig. 1). Generally, these devices consist of a stationary cylinder called a stator, a rotating shaft (rotor) and blades (scrapers) mounted on the shaft.

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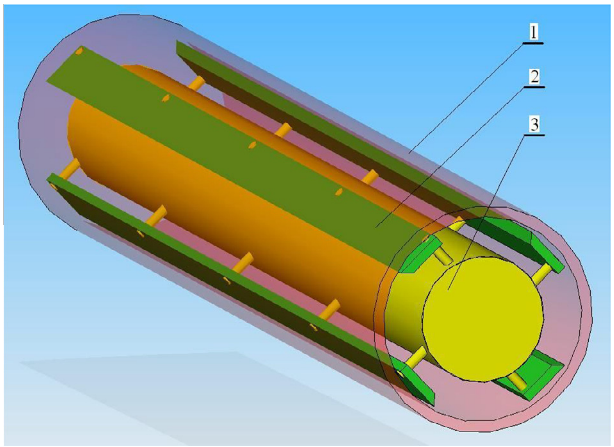

Fig. 1. Schematic draw of scraped surface heat exchanger (SSHE): (1) stator, (2) blade (scraper), (3) rotor.

The working fluid is slowly pumped through an annular space between a cooled (heated) external cylinder and a rotating shaft. Scrapers continuously scrape the inner cylinder surface and remove the fluid. This intensifies heat transfer rate and promotes better mixing.

Thermal boundary layer scraping phenomenon was studied by many researchers both analytically and numerically. The most common analytical model in the literature is based on the penetration theory, which was formulated independently by Kool [3], Latinen [4] and Harriott [5] (K–L–H model). According to this model, fluid layer adjacent to the wall is considered stagnant. It is assumed that heat transfer mechanism between two consecutive scrapers passes takes place only by transient heat conduction in the layer, analogously as in semi-infinite body. In this model convection term is neglected and, after the scraper passes, the fluid is ideally mixed with the bulk fluid. Fourier solution for the average heat transfer coefficient h is given as [3–5]

$$h = \frac{2}{\sqrt{\pi}}\sqrt{k\rho c_p n n_B} \tag{1}$$

where $k,\ \rho$ and c_p are the thermal conductivity, density and specific heat of fluid respectively. Rotational velocity is denoted by n, and n_B is the number of scrapers. In the non-dimensional form, Nusselt number can be written as

$$Nu = \frac{2}{\sqrt{\pi}}\sqrt{n_B Re Pr} \tag{2}$$

In Eq. (2) Re is Reynolds number for mixing processes and is defined as

$$Re = \frac{nD^2\rho}{\eta} \tag{3}$$

where D is a stator diameter and η is dynamic viscosity of a fluid.

On account of assumptions, the K–L–H model has major drawbacks. The first one is that when the scraper passes, energy is mainly transferred by convection but not conduction. Moreover, the model does not take into account two important factors, namely the scraper-to-wall gap and fluid dynamic viscosity. Harriott [5] has found that heat transfer coefficients from Eq. (1) is in good agreement with the experimental values obtained for low-Prandtl number, but in the case of pasty materials they are overestimated. Ramdas et al. [6] conducted experimental studies on a scraped surface heat exchanger in laminar flow regime with two petroleum lube fractions and corn syrup working fluids. The researchers compared experimental results with penetration theory and asserted that this model gives highly over-predicted values of heat transfer coefficient for viscous fluids they used. Similar conclusions have been made by Abichandani and Sarma [7]. Their studies involved experimental determining Nusselt number in a scraped surface heat exchanger in the turbulent regime. Materials used during experiments: water, ethanediol, paraffin liquid and glycerol. Even for water (low viscous fluid), the differences in Nusselt number values, expected from the penetration theory and observed in the experiment, were up to 90%. The authors concluded that the penetration theory model gives erroneous results due to the assumption that heat transfer is independent of viscosity, what is ambiguous, especially in the turbulent regime.

Penney and Bell [8] proposed an improved model, nevertheless it did not become as famous as the K–L–H model and it is little known in the literature. The model is a combination of a stagnant film theory and the penetration theory. It assumes that the scraper does not clean the wall perfectly and a thin, stagnant fluid layer always occurs on the surface of the wall. This is caused by hydrodynamic forces, which repel the scraper from the wall. The layer between the scraper and the wall highly influences heat transfer and it has to be taken into consideration. The stagnant film-penetration model (P–B model) assumes that the layer can be treated as a solid layer on the wall surface and the heat transfer coefficient h can be expressed as

$$h = \frac{1}{\frac{\delta}{k} + \frac{1}{\sqrt{8c_p\rho k n/\pi}}} \tag{4}$$

where δ is the scraper-to-wall gap. Its non-dimensional form can be written as follows

$$Nu = \frac{1}{\frac{\delta}{D} + \frac{1}{\sqrt{8RePr/\pi}}} \tag{5}$$

In case of large gaps, experimental results were in good agreement with theoretical ones. However, when the value of the gap was set to zero, the model gave about 100% over-predicted values of the heat transfer coefficient. The authors stated that it was only a qualitative check. In the literature, a few other models also exist (e.g. [9,10]). However, these models include axial flow effects and they are out of scope in the present work and are not considered in the paper.

Researchers analysed the heat transfer and fluid flow in scraped surface heat exchangers also numerically. Due to low axial velocities two-dimensional assumption was usually made. De Goede and De Jong [9] conducted experimental and numerical studies on heat transfer and fluid flow in a scraped surface heat exchanger in the turbulent regime. Their numerical model covered only an isothermal flow. It was shown that scrapers contribute to vortices formation. The induced vortices caused more intensive and efficient surface renewal and increase in heat transfer rate was observed.

Wang, Houlton and McCarthy [11,12] developed two-dimensional analytical and numerical models for power law fluids. The authors verified the models via an experimental technique – Magnetic Resonance Imaging. However research involved only isothermal conditions and focused on mixing processes in SSHE.

Stranzinger et al. [13] have also considered isothermal flow in a two-dimensional narrow annular gap reactor. The authors examined an influence of a scraper blade angle and rotor velocity on flow conditions, both for Newtonian and shear-thinning fluids. Calculations have been done for a constant gap in the laminar regime. Numerical results were compared with experimental ones, obtained with the use of digital-particle image velocimetry (D-PIV) technique. It was found that flow field strongly depends on rotor velocity in the studied regime.