3D FLOW ANALYSIS OF HEAT TRANSFER IN A SCRAPED SURFACE HEAT EXCHANGER (SSHE)

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Abstract

This paper deals with numerical analysis of 3D model of an SSHE is developed in order to study the fluid flow and heat transfer with a steady state laminar, non-isothermal flow of pure glycerine, which can be treated as a Newtonian fluid. The variation of the local heat transfer coefficient based on the inner wall temperature and bulk fluid temperature as a function of the main process parameters, namely, rotational Reynolds number (Re_{rot}), axial Reynolds number (Re_{axi}) and number of scraper blades (2, 3 and 4), is obtained. The results have shown that viscous dissipation has a significant effect on the cooling of glycerine. The local heat transfer coefficient increases slightly when increasing the number of scraper blades. Larger increases of the same occurred with higher rotational Reynolds number and axial Reynolds number. A correlation of the average Nusselt number is obtained in terms of the rotational and axial Reynolds numbers. This is expected to be useful in the design of SSHEs handling highly viscous fluids.

Keywords— scraped surface heat exchanger; Newtonian fluid; inner wall temperature; Bulk fluid temperature; Local heat transfer coefficient

Introduction

SCRAPED SURFACE HEAT EXCHANGER (SSHE) is a device which consists of an annular gap with a cylindrical rotor and stator as shown in Fig 1.1. Scraping means removal of fluid from the boundary. This breaks the thermal and hydrodynamic boundary layers at the surface and there by enhances the heat transfer. Specifically SSHEs is used for the thermal treatment of high-viscous fluids. SSHE is widely used in food industry for sterilizing or cooling highly viscous fluids such as mayonnaise, cream cheese, peanut butter and ice cream. As the treated fluids in SSHE are highly viscous, fouling problems may occur and reduce significantly the thermal efficiency of SSHE. The presence of rotating blades in the annulus makes it possible to avoid the possible fouling problem on the heat exchanger surface, and improve the heat transfer treatment received by the product.

A short discussion of the previous studies of authors who attempted to focus on the heat transfer and basic flow patterns in SSHE is presented here. Trommelan et al. [1] was the first person to describe the fluid

flow and heat transfer mechanisms for the design and operating conditions of the SSHE. Penny and Bell [2] suggested that the clearance between the edge of the scraper blade and the stator wall is not constant, but it is dependent on the operating conditions of the SSHE. De Gode et al. [3] studied the freezing of water-ethanol slurries using an ice generator with a blade clearance of 3 mm and 1 mm, to examine the heat transfer coefficient on the exchanger surface. Toh and Murikami [4] studied the shape of two scraper blades, one curved and another, perpendicular to the wall. Bott and Ramero [5] numerically studied an SSHE to compare the overall heat transfer coefficient with different numbers of scraper blades like 2, 4 and 6. Yataghene et al. [6] conducted a numerical study of the fluid flow and heat transfer within a SSHE, using 130 µm clearance of the blade gap with pure glycerin fluid and examined the mixing time for the exit temperature of the SSHE.

The objective of the present work is to create a 3D model of an SSHE and study the fluid flow and heat transfer in steady state laminar non-isothermal flow of pure glycerine (newtonian fluid) with temperature dependent viscosity. The clearance between tip of the blade and the stator is taken as $\delta_{gap} = 130$ µm and varying the number of scraper blades are 2, 3 and 4. The relevant dimensionless numbers for the present study are the Rotational Reynolds numbers (Re_{rot}), axial Reynolds number (Re_{axi}) and number of scraper blades. The four rotational Reynolds numbers (Re_{rot}) investigated are 26.39, 79.17, 158.39, 237.61 and the axial Reynolds numbers (Re_{axi}) are 0.6, 1.21, 1.82, and 2.43. Parametric study is done by keeping the rotational Reynolds number constant and varying the axial Reynolds number (Re_{axi}), and repeating the same procedure as above for different (Re_{rot}). Thus for each scraper blade, 16 simulations are to be performed and for three different scraper blades, 48 simulations are to be carried out. The local heat transfer coefficient for the heat exchanger surface is based on the inner wall temperature and bulk fluid temperature for each cross section of the SSHE. The parameters for which thermally developed flow occurs are examined.
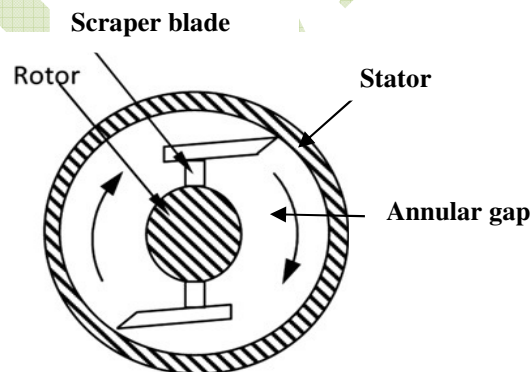

Figure 1.1: Transversal cross-section of SSHE [6]

MATHEMATICAL FORMULATION
The physical model and coordinate system

A 3D model of SSHE is created in Gambit (Ver. 2.4.16). In view of the geometry, the Cartesian co-ordinate system is chosen to describe the geometry, where X, Y and Z axis are taken in the horizontal, vertical and axial directions of the SSHE respectively. The model is shown in Fig. 2.1.
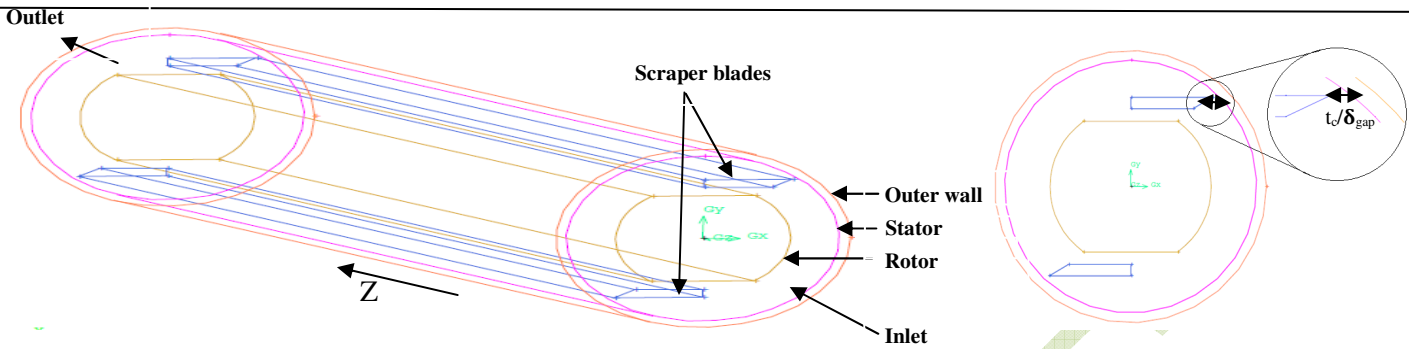
Figure 2.1: 3D model of SSHE with 2 scraper blades of 130 µm clearance

The SSHE consists of a rotor stator surface represents the wall heat exchanger, where a constant wall temperature is applied to the outer wall. In this study the three different scraper blades are 2, 3 and 4 with a constant tip clearance of δ_{gap}=130 µm. The 3D model of SSHE with 3 scraper blades is as shown in Fig 2. Other dimensions of the SSHE device are: stator diameter (Ds) =0.065m, rotor diameter (Dr) =0.040m, stator length (Ls) =0.6m, number of blades (n) =2, 3, and 4, area of cross section =2.945e-3 m², and tip clearance (δ_{gap}) =130 µm.

GRID INDEPENDENCE STUDY

A commercially available meshing tool is used to generate good quality hexagonal grids. A structured mesh overlaying the hexahedral elements is generated with the Gambit (Ver. 2.4.16) software meshing tool. The mesh density is increased near the wall and especially in the clearance region to ensure accuracy there, as greater temperature changes in the fluid are expected to occur in these regions. The mesh is highly concentrated at the tip of the blades and ensured there were at least 4 mesh points across the tip of the clearance. This was done by performing a number of simulations with different mesh sizes, starting from a coarse mesh and refining it until physical results were no more dependent on the mesh size. The hexahedral cells were retained to have good discretization accuracy. Four mesh refinements of 863600, 1031600, 1279200 and 1448000 cells were tested and compared with a physical parameter of bulk temperature of the fluid for each cross section of SSHE with 2 scraper blades. For good accuracy of the results, the case with 1279200 cells can be employed as this gives no significant difference compared to that with 1448000 cells. A fine mesh of 1279200 cells is chosen for further analysis as shown in Fig. 3.1.
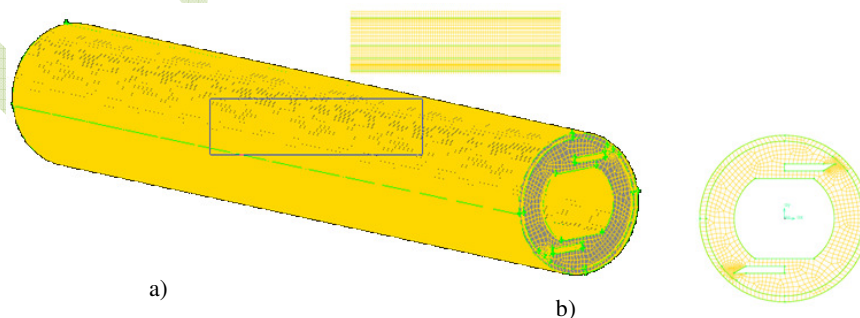

a)

b)

Figure 3.1: a) Computational of physical domain of a SSHE and used grid, all physical domains was meshed with hexahedral cells of (1279200) b) SSHE Transverse cross section of the mesh topology of physical

GOVERNING EQUATIONS

In this section the governing equations are stated for the heat transfer and fluid flow including viscous dissipation in the SSHE. Steady state, non-isothermal, incompressible flows have been considered.

In the rotating reference frame, the continuity equation in steady state for the relative velocity is written as:

$$\nabla\left(\vec{v}_r\right) = 0 \qquad (1)$$

The momentum equation is written as:

$$\nabla\left(\vec{v}_r\, \vec{v}_r\right) + \left(2\,\vec{\omega}\times\vec{v}_r\right) + \left(\vec{\omega}\times\vec{\omega}\times\vec{r}\right) = -\nabla p + \nabla\vec{\tau}_r \qquad (2)$$

Where, $\left(2\,\vec{\omega}\times\vec{v}_r\right)$ is coriolis acceleration and $\left(\vec{\omega}\times\vec{\omega}\times\vec{r}\right)$ is centripetal acceleration

Energy equation for the fluid in steady state for rotating frame is expressed as:

$$\underbrace{\nabla\left(\vec{v}_r . H_r\right)}_{\text{Forced heat convection}} = \underbrace{\nabla\left(k\nabla T\right)}_{\text{Heat conduction}} + \underbrace{\nabla\left(\vec{\tau}_r\, \vec{v}_r\right)}_{\text{Viscous heating}} \qquad (3)$$

Energy equation for solid:

$$\nabla.\left(\rho_{steel} C_{psteel}\left(-\omega\times r\right)T\right) = \nabla\left(k_{steel}\nabla T\right) \qquad (4)$$

The system of non-dimensionalisation is:

$$\mathrm{Re}_{axi} = \frac{W_{axi} d_{equ}\rho}{\eta} \quad \mathrm{Re}_{rot} = \frac{\omega . r_s d_{equ}\rho}{\eta} \quad \mathrm{Pr} = \frac{\eta c_p}{k}$$

BOUNDARY CONDITIONS

We have examined in this work the fluid cooling process occurring in an SSHE. For the fluid flow, the momentum equation (Eq. 3) boundary conditions are specified as follows: On the stator: $v = \omega\times r$. At the rotor and scraper blade: $v = 0$. Flow at inlet: v_{in} m/s. Outflow: zero velocity gradient $\partial v/\partial n = 0$. The fluid (glycerin) is introduced at the SSHE inlet with the temperature of T_{inlet}=288K, and was cooled with the constant outer wall temperature T_w=278K. The temperature difference between the wall heat exchanger and fluid inlet was ΔT=10K. Adiabatic conditions were assumed for the rotor and scraper blade. Zero temperature gradient is assumed at the outlet.

Ansys Fluent code uses the finite volume method for descritization. The governing steady-state equations for mass and momentum conservation are solved with a segregated approach. In this approach, the equations are

sequentially solved with implicit linearization. Volume-faces advective fluxes were approximated using a second- order upwind interpolation scheme. Because of the effect of the viscosity variation due to heat transfer, a coupling between velocity and temperature fields must be considered. The pressure-velocity coupling is implemented using iterative correction procedure (SIMPLEC algorithm). For the energy equation too, a second-order upwind interpolation scheme is used.

RESULTS and DISCUSSION

In order to obtain the performance characteristics of 3D model of SSHE for the fluid flow and heat transfer, a parametric study is carried out by varying number of scraper blades (2, 3 and 4), by keeping tip clearance as 130 µm, the angular velocity of the rotor and the axial velocity of the fluid entering the SSHE. Graphs are plotted to show the variation of inner wall temperature, bulk temperature and the local heat transfer coefficient. The local heat transfer coefficient is calculated with Eq. (5) with respect to the axial distance. Correlations are obtained for the average Nusselt number based on the average heat transfer coefficient in terms of the process parameters.

$$h = \frac{q_w}{T_{in,w} - T_{bulk}} \qquad (5)$$

Axial variations of temperature difference and local heat transfer coefficient

The local heat transfer coefficient based on inner wall temperature and bulk fluid temperature calculated using Eq. (5) along the axial distance of SSHE is shown in Figs. 6.1 (a, b,) for different Reynolds numbers and also for different scraper blades. The general variation of local heat transfer coefficient reveals that it is of high value near the inlet section of the exchanger because of the thickness of the boundary layer is very small. It decreases continuously due to the increasing thermal boundary layer thickness. When increasing the number of scraper blades (i.e., 4 and 3 as against 2 scraper blades), better local heat transfer coefficient is achieved and improvement in the performance of the SSHE is obtained by achieving thermally fully developed flow of fluid occur.
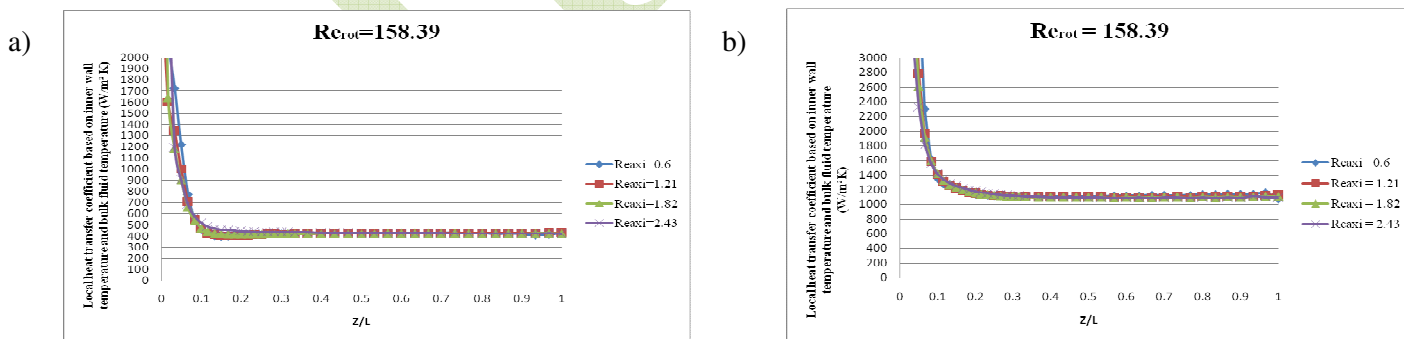
a)

b)

Fig 6.1 (a, b) Local heat transfer coefficient based on inner wall temperature and bulk fluid temperature of 2 and 4 scraper blades with Re_{rot}=158.39 and Re_{axi}=0.6, 1.28, 1.82 and 2.43 respectively.

Correlations for average Nusselt number

The correlation obtained using multiple regression analysis is:

$$Nu = a\, \mathrm{Re}_{rot}^{b}\, \mathrm{Re}_{axi}^{c} \qquad\qquad (6)$$

where a, b and c are the constants of the correlation. In order to determine the constants a, b and c of the model several numerical simulations were carried out. Figs. 6.2 (a, b) show the parity plots between computed and correlated Nusselt number in which 16 data points pertaining to one dimensionless clearance are shown for each plot. Although not presented, similar plot is also obtained for the remaining clearance. The correlation constants are given in Table 1:
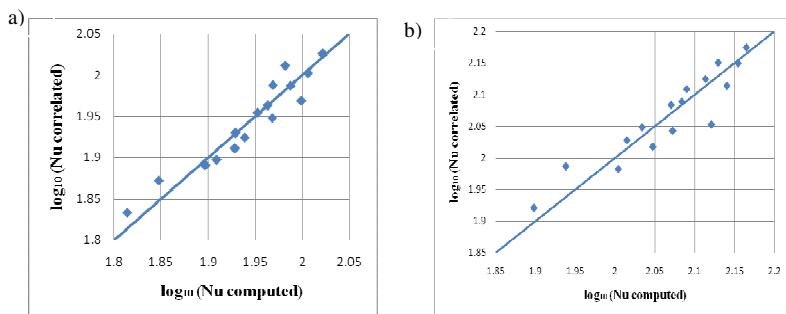

Table 1: Correlation constants

Correlation constants	2 scraper blades	3 scraper blades	4 scraper blades
a	51.62	58.40	59.95
b	0.08	0.13	0.13
c	0.18	0.19	0.20
R^2	0.95	0.93	0.92

Fig. 6.2 Parity plots between computed and correlated values of Nusselt number for a) 2 scraper blades b) 4 scraper blades

CONCLUSIONS

A 3D numerical model is employed to examine the thermal performance of an industrial scraped surface heat exchanger device. A parametric study is done and the following conclusions are reached:

1) The flow and temperature distribution increases with increasing the rotational Reynolds number because of viscous dissipation of the fluid.
2) The difference between inner wall temperature and bulk fluid temperature increases due to viscous dissipation of the fluid.
3) The local heat transfer coefficient based on inner wall temperature and bulk fluid temperature increases along the length of the SSHE in the axial direction with increasing the number of scraper blades.
4) A heat transfer correlation is obtained for the average Nusselt number in terms of the rotational and axial Reynolds numbers, which are the process parameters.

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