Chemical Engineering Science 119 (2014) 88–98

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Single phase fluid-stator heat transfer in a rotor–stator spinning disc reactor

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HIGHLIGHTS

- Heat transfer coefficients for a rotor–stator spinning disc reactor are presented.
- Fluid-stator heat transfer coefficients increase by increasing rotational velocity.
- Heat transfer coefficients are found to increase up to a factor of 5 at 30 rad s^{-1}.
- Throughflow and rotation dominated heat transfer regimes are observed.
- Volumetric overall heat transfer is found to be more than factor five higher than tubular reactors.

ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form
31 July 2014
Accepted 6 August 2014
Available online 12 August 2014

Keywords:
Convective heat transfer
Confined rotating flow
Rotor–stator spinning disc reactor
Compact heat exchange

ABSTRACT

Single phase fluid-stator heat transfer coefficients for a multi-stage rotor–stator spinning disc reactor are presented. The overall heat transfer coefficient is obtained by fitting experimentally obtained steady state outlet temperatures to an engineering model for the fluid flow inside the rotor–stator cavities. Heat transfer measurements are done for gap ratios of $G=0.017$ and 0.03, rotational Reynolds numbers of $Re_\omega=0$ to 12×10^5 and superposed dimensionless throughflow rates of $C_w=211$–421. From the overall heat transfer coefficient values for the fluid-stator Nusselt number Nu_s are obtained. For all values of C_w and G, Nu_s increases more than a factor of 4 by increasing Re_ω from 0 to 1.3×10^5. A throughflow dominated regime occurs for $Re_\omega<0.2\times10^5$, where Nu_s increases with increasing C_w and decreasing G. For $Re_\omega>0.2\times10^5$, rotation dominates the heat transfer and no influence of C_w and G on Nu_s is observed. The thermal performance of the multi-stage rotor–stator spinning disc reactor, quantified in the volumetric overall heat transfer coefficient, increases from $U_{ov}AV_R^{-1}=0.46\pm0.2$ to 0.93 ± 0.16 MW m^{-3} K^{-1} by increasing Re_ω from 0 to 4.5×10^5. The volumetric overall heat transfer coefficient of the multi-stage rotor–stator spinning disc reactor is more than a factor of 5 higher than in conventional tubular reactors.

1. Introduction

The rotor–stator spinning disc reactor (SDR) is a novel type of reactor which aims for intensification of mass transfer limited processes. High rates of gas–liquid Meeuwse et al. (2010a,b), liquid–liquid (Visscher et al., 2012) and liquid–solid (Meeuwse et al., 2010c) mass transfer have been reported. Therefore the SDR can increase production rates per volume of reactor for many mass transfer limited reactions, including multiphase and heterogeneously catalysed reactions. However, when highly exo- or endothermic processes are involved, intensification of the heat transfer rates is equally necessary to accommodate the increased production rates. This especially holds for exothermic reactions, both single and multiphase, often encountered in the chemical industry (e.g. hydrogenations, halogenations, nitrations). Hot spots, thermal runaway and overheating of the reactor surface are major concerns when intensifying these reactions (Phillips et al., 1997; Anxionnaz et al., 2008). The ability of a reactor to withdraw the produced heat of reaction through its heat transfer surface is quantified by the volumetric overall heat transfer coefficient $U_{ov}AV_R^{-1}$. To assess the potential of the SDR as a tool to intensify industrially relevant reactions, it is thus of great interest to investigate its heat transfer characteristics. The aim of the current work is therefore to quantify the heat transfer rates in the SDR for a single liquid phase in the reactor.

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http://dx.doi.org/10.1016/j.ces.2014.08.008

The setup used in this work is a multi-stage rotor–stator spinning disc reactor (MSDR), for which Meeuwse et al. (2012) presented gas–liquid and liquid–solid mass transfer rates. De Beer et al. (2014) presented an engineering model based on residence time distribution measurements and rotor–stator hydrodynamics. A single stage of the MSDR consists of a rotating disc (rotor) enclosed by two stationary discs (stators) and a stationary cylindrical housing, see Fig. 1(a). The axial clearance between the rotor and stators is low, typically in the range of millimetres. A high velocity gradient is present between the rotor and the stators, causing a high shear force to act on the externally applied fluid flow through the cavity. The high shear force acting on the fluid results in a large interfacial area and increased turbulence intensity, resulting in the high mass transfer rates reported previously (Meeuwse et al. 2010a–c; Visscher et al., 2012). Due to the analogy between mass and heat transfer, it is expected that the transfer of heat between the fluid and the stator (where heat can be withdrawn or supplied externally) is increased by rotation as well.

Indeed, enhanced convective heat transfer in rotating systems has been reported extensively in the literature for many geometries and conditions (Owen and Rogers, 1989; Harmand et al., 2012). However, no information is available for fluid-stator heat transfer in an enclosed rotor–stator cavity with the low aspect ratio ($G<0.03$) and externally applied throughflow as encountered in the spinning disc reactor. Moreover, all experimental heat transfer data for rotor–stator systems is obtained using air as fluid, making the translation to liquid phase heat transfer less reliable. This originates from the fact that the principle drive for all research on rotor–stator heat transfer so far, is the cooling of turbomachinery (Owen and Rogers, 1989).

This paper presents single liquid phase fluid-stator heat transfer coefficients in an multi-stage rotor–stator spinning disc reactor as a function of rotational velocity, liquid flow rate and rotor–stator axial clearance. A comparison is made with the available literature and engineering correlations for heat transfer coefficients in rotor–stator systems.

A brief review of heat transfer studies in rotor–stator systems is presented in Section 2, followed by a description of the steady state heat transfer model in Section 3. The experimental setup, heat transfer measurements and contributions to the overall enthalpy balance are treated in Section 4. In Section 5 the fluid-stator heat transfer coefficients of rotor–stator spinning disc reactor are presented and compared to literature data.

2. Heat transfer in rotor–stator cavities

Fluid-stator heat transfer in an enclosed rotor–stator cavity with a low aspect ratio ($G<0.03$) and externally applied throughflow has not been investigated before. Only information on heat transfer in an enclosed cavity with no throughflow, Fig. 2(a), and in open cavities with throughflow, Fig. 2(b), has been presented.

Nikitenko (1963) and Shchukin and Olimpiev (1975) present heat transfer data for an enclosed cavity without externally applied throughflow. Nikitenko presents correlations for both the Nusselt number on the rotor Nu_r (Fig. 3, red dashed line) and the stator[1] Nu_s (Fig. 3, red solid line) as a function of the rotational Reynolds number Re_ω, independent of gap ratio G for $0.018 \le G \le 0.085$. The presented values of Nu_s are 12% lower than the well-established values for a rotating disc in quiescent air (the free disc) in the turbulent regime (Dorfman, 1963) (Fig. 3, black

[1] In the current work the Nusselt number on the rotor is defined as $Nu_r = h_r r_{r,o} k_f^{-1}$, and the Nusselt number on the stator is defined as $Nu_s = h_s r_{r,o} k_f^{-1}$. In the literature relevant to the current work the rotor radius is most widely applied as relevant dimension for Nu; this convention is followed here.

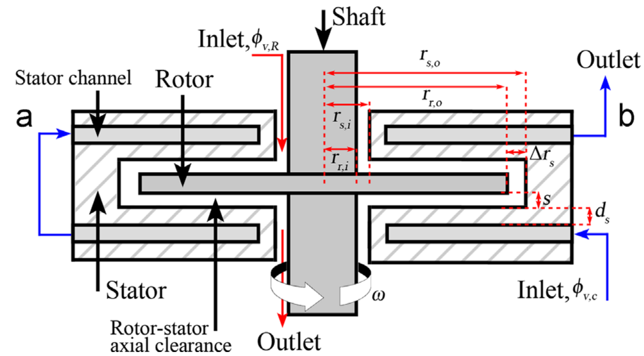

Fig. 1. Schematic representation of a single rotor–stator cavity of the multi-stage rotor–stator spinning disc reactor. It consists of a rotating disc (rotor) enclosed by a cylindrical housing (stator), as shown in (a). Within the stators cooling channels provide means for indirect heat exchange with the rotor–stator cavity (see Fig. 9). Nomenclature of the relevant dimensions used in this work is shown in (b).

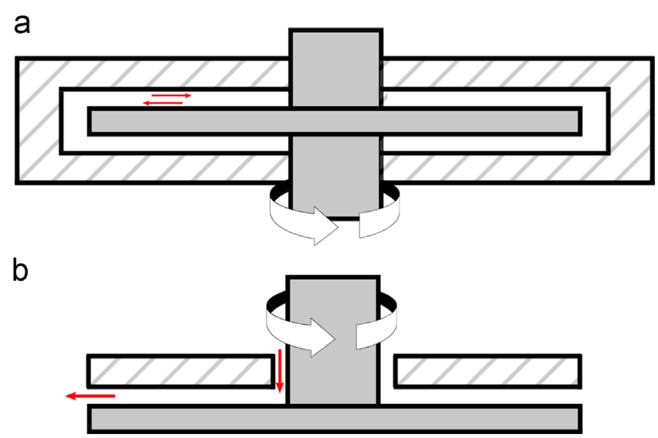

Fig. 2. Schematic representation of (a) an enclosed cavity with no throughflow and (b) an open cavity with throughflow. The case of centrifugal throughflow is indicated in (b), for centripetal throughflow the fluid stream is in the reversed direction.

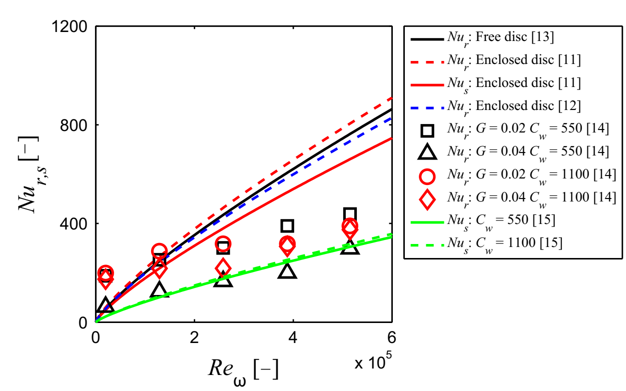

Fig. 3. Literature values of rotor Nu_r and stator Nu_s Nusselt numbers. The correlation for turbulent heat transfer from a free disc (Dorfman, 1963) is shown as a reference (solid black line). For an enclosed cavity without throughflow correlations obtained for Nu_r (Nikitenko, 1963; Shchukin and Olimpiev, 1975) (red dashed line and blue dashed line, respectively) and Nu_s (Nikitenko, 1963) (red solid line) are shown. For an open cavity Nu_r values for centrifugal throughflow, low G (≤ 0.04) and low C_w (≤ 1100) (Pellé and Harmand, 2009) are shown, as well as the empirical Nu_s correlation presented by Poncet and Schiestel (2007) for centripetal throughflow and two values of C_w (green lines). Note that these correlations and values for $Nu_{r,s}$ are valid for air as a fluid, no correction with Pr for water as fluid has been applied here. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)