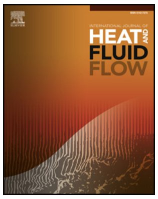
International Journal of Heat and Fluid Flow 71 (2018) 68–79

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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



Numerical investigation of the interaction between local flow structures and particulate fouling on structured heat transfer surfaces

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ARTICLE INFO

Keywords:
Particulate fouling
Dispersed two-phase flow
Eulerian–Lagrangian LES
Dimples
Vortex structures
Heat transfer
Pressure loss

ABSTRACT

The paper is addressed to the application of Eulerian–Lagrangian Large Eddy Simulations (LES) for the investigation of the interaction between turbulent flow structures, heat transfer and particulate fouling in aqueous suspension on structured surfaces, which is an important research field in context of particle-laden two-phase flows. An efficient Lagrangian-Particle-Tracking algorithm is used to predict the trajectory of each suspended foulant particle (dispersed phase), suitable for dilute and dense dispersed two-phase flows by taking the fluid-particle (two-way coupling) as well as inter-particle interactions (four-way coupling) into account. The complex turbulent carrier flow (continuous phase) is calculated by eddy-resolving LES. Calculations have been performed for fully developed turbulent channel flows at moderate Reynolds numbers in combination with a sharp-edged spherical dimple considering a dimple depth/diameter ratio of $t/D = 0.26$ and a rectangular cavity with an equal cavity depth/side length ratio for comparative purposes. In order to get a detailed insight into fundamental fouling processes and to verify the numerical results high-precision experimental investigations of particulate fouling of different dimpled surfaces have been carried out. The fouling investigations are conducted using a relatively low mass loading of up to 0.2% and particle diameters of 3 μm and 20 μm for the simulations, whereas a particle diameter of 3 μm is used for the experiments. The simulated fouling layer distribution for the spherical dimple within a smooth, narrow channel is compared with these experimental measurements and exhibits a satisfying agreement. Additionally, the arising local flow structures and thermo-hydraulic performances of the selected surfaces are numerically investigated in absence and presence of particulate fouling.

1. Introduction

Structured surfaces such as ribs, pin fins, dimples and protrusions are extensively used as heat transfer enhancement techniques, especially in compact heat exchangers, which reduce the thermal resistance of the sublayer adjacent to solid walls. This is achieved by generating secondary flows, which interfere the boundary layer growth, as well as flow recirculation and shear-layer reattachment, promoting mixing and an increase of the turbulence intensity (Ebrahimi and Naranjani, 2016). Various types of structured heat transfer surfaces have been thoroughly investigated with the objective to promote the heat transfer with a minimum hydraulic pressure loss. The application of dimpled surfaces is an efficient way to increase the thermo-hydraulic performance, defined as ratio between heat exchange and flow resistance, revealing a significant heat transfer augmentation at low pressure drop penalty. Afanasyev et al. (1993) investigated the pressure drop and heat transfer on a plate with dimples in the turbulent regime. A maximum heat transfer augmentation of about 40% accompanied by a low increase of hydraulic losses was observed. Other astonishing results are documented by Chyu et al. (1997), who evaluated the hydraulic losses and heat transfer enhancement for a surfaces with an array of hemisphere and tear-drop shaped cavities in the range of Reynolds number $10,000 \leq \mathrm{Re}_{D_h} \leq 50,000$ based on the hydraulic diameter. The results showed that both kind of concavity configurations induce a heat transfer enhancement up to 2.5 in contrast to the opposite smooth wall whereas the flow resistance was half as that for rib tabulators. The effect of the channel height and dimple depth on heat transfer within the turbulent flow regime has been studied by Mahmood et al. (2001) and Ligrani et al. (2001, 2003). Due to the steadily growing computational resources, structured surfaces have been investigated numerically within the last years. A comprehensive numerical study of the flow physics inside a single dimple has been conducted by Isaev et al. (2010),

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https://doi.org/10.1016/j.ijheatfluidflow.2018.03.002
Received 5 December 2017; Received in revised form 31 January 2018; Accepted 4 March 2018

Nomenclature

a	thermal diffusivity
B	width
D	diameter
c_p	specific heat capacity
C_D	drag coefficient
C_f	Fanning friction factor
E	energy
f	Darcy friction factor; frequency
$\mathbf{F}$	force vector
h	convective heat transfer coefficient
H	height
I	moment of inertia
$\mathbf{J}$	heat flux vector
k	turbulence kinetic energy; thermal conductivity
L	length
m	mass
$\dot{m}$	mass flow rate
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Re	Reynolds number
$\mathbf{S}$	strain rate tensor; source term
t	dimple depth; time
T	temperature
$\mathbf{T}$	torque vector
u, v, w	velocity components
V	volume
x, y, z	Cartesian coordinates
x_f	fouling layer thickness

Greek symbols

α	fouling phase fraction
β	mass loading
ζ	random vector
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	standard deviation
τ	stress
ϕ	volume fraction
$\boldsymbol{\omega}$	angular velocity vector

Subscripts

0	based on centerline velocity; based on smooth channel
b	bulk
c	cell
Ch	based on hydraulic diameter of the channel
D	based on dimple print diameter
D_h	based on hydraulic diameter
f	fluid
p	particle
p, 50	mean particle value
rms	root mean square
sgs	subgrid-scale
t	turbulent
w	wall

Superscripts

$\ldots^+$	dimensionless
$\overline{\ldots}$	filtered
$\ldots'$	fluctuation
$\langle\ldots\rangle$	time averaged

Abbreviations

EFD	Experimental Fluid Dynamics
FNU	Formazin Nephelometric Unit
LDA	Laser Doppler Anemometry
LES	Large Eddy Simulation
LPT	Lagrangian-Particle-Tracking
URANS	Unsteady Reynolds-averaged Navier–Stokes Equations

who investigated the influence of the Reynolds number and dimple depth on the turbulent heat transfer and hydraulic loss in a narrow channel by solving the unsteady Reynolds-averaged Navier–Stokes (URANS) equations. LES conducted by Turnow et al. (2011) for a Reynolds number range (based on dimple print diameter) of $20,000 \leq \mathrm{Re}_D \leq 40,000$ revealed coherent vortex structures, which change their orientation in time. Moreover, a three-dimensional proper orthogonal decomposition (POD) analysis on the pressure and velocity fields showed tornado-like spatial POD structures. Additional studies of the thermo-hydraulic efficiency of dimple packages have been performed by Elyyan et al. (2008), Lienhart et al. (2008) and Turnow et al. (2012).

With the structuring of the surface the undesired deposition of crystals, microorganism or particles from the fluid may be enhanced. Fouling on heat exchanging surfaces reduces the efficiency of heat exchangers and increases flow resistance leading to a decrease of the thermo-hydraulic efficiency. That potentially results in higher technical and economical effort like higher costs in energy or maintenance (Bohnet, 1987; Schönitz et al., 2015). Besides crystallization fouling particulate fouling is one of the main reasons for efficiency problems. The suspended particles in the heat exchanging fluid are for instance corrosion products, sand or mud (Müller-Steinhagen, 2010; Krause, 1986).

The formation of deposits consists of the transport of particles to the surface and the adhesion on the wall. The mechanism of transport and adhesion is comparable to a reaction of first order. Literature surveys for different models describing fouling mechanism are given by Bott (1995), Suitor et al. (1977) and Epstein (1978). The base of most models for the transport mechanisms of particulate fouling is the well-known model from Kern and Seaton, in which the deposition of mass is considered next to the removal of mass (Kern and Seaton, 1959). The particle transport can either be mainly affected by drag force and gravity which is the case for large particles ($D_p > 20$ µm) or influenced by drag forces and Brownian motion for small particles ($D_p < 1$ µm) (Beal, 1970). After the transport to the wall the adhesion forces determine the appearance of fouling layers. Among the various forces of adhesion the van der Waals forces and the electrostatic forces are the dominant ones for particles. Both are considered in the DLVO model introduced by Derjaguin, Landau, Verwey and Overbeek (Oliveira, 1997; Hoek and Agarwal, 2006). The deposition is formed, if the adhesion forces are higher than the removal forces exerting by the fluid's shear stress. Otherwise the particles are removed from the surface back to the fluid. This fluid dynamic correlation is described by Cleaver and Yates with their ”burst-model”. The difference of deposition rate and removal rate is the time depending mass flow for the deposition (Cleaver and Yates, 1973).

The objective of this investigation is to clarify the role of turbulent flow structures generated by dimpled surfaces with respect to mass transport and particulate fouling using large-scale resolving Eulerian–Lagrangian LES and high-precision fouling measurements.