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Magnetic actuation of catalytic microparticles for the enhancement of mass transfer rate in a flow reactor

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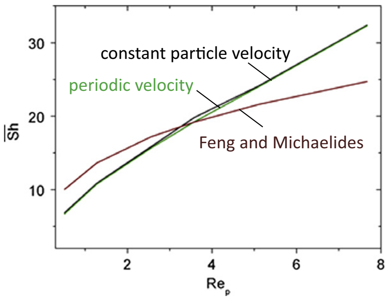
HIGHLIGHTS

- The mass transfer rate can be described by the Feng and Michaelides correlation.
- Three motion modes have been observed: below 0.4 Hz, between 0.4 and 0.6 Hz and above 0.6 Hz.
- Under variable velocity motion, the mass transfer rate decreases by 7.6%.
- The highest mass transfer rate is achieved at the frequency of 0.6 Hz.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of periodic changes in particle velocity on mass transfer to the reacting surface of a magnetic particle with a diameter 225 μm in laminar flow has been investigated in a microfluidic reactor. The periodic particle motion in a fluid was investigated under a sinusoidal magnetic field generated by a quadrupole arrangement of electromagnets around the reactor. The effect of operating frequency of the rotating magnetic field, intensity of the magnetic field, and phase shift between the two sets of magnets on particle dynamics has been studied. Three particle motion modes have been observed depending on the frequency of the applied field. The mass transfer rate was estimated under steady velocity and variable velocity of the particle using a mass transfer correlation by Feng and Michaelides (2001). The validity of this correlation for the case of variable particle velocity has been confirmed with a 2D numerical model, describing actual hydrodynamics and mass transfer towards the particle surface. The mass transfer coefficient depends both on the mean particle velocity and the deviation of velocity from the mean value. The periodic movement with variable particle velocity reduces the mass transfer coefficient by 7.6% as compared to steady state motion with the same mean velocity.

1. Introduction

Boundary layer flow around a moving surface represents an important type of flow occurring in a number of engineering processes. The applications of moving surfaces include cooling of metal plates on a conveyor belt in a vessel with a cooling fluid,

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Nomenclature

a_1	sensitivity coefficient for mass transfer rate with respect to normalised standard deviation from the average velocity
a_2	sensitivity coefficient for mass transfer rate with respect to average velocity
a_p	particle surface area per unit volume
b	difference between the maximum and average particle velocity
∇B	magnetic flux density
C_A	concentration of benzaldehyde aryl methyl acetal (species A)
C_o	initial concentration of benzaldehyde aryl methyl acetal
D_A	molecular diffusivity of benzaldehyde aryl methyl acetal
d_p	particle diameter
F	rotation frequency of external magnetic field
$k_{f\theta}$	local mass transfer coefficient
k_f	average mass transfer coefficient
k_r	reaction rate constant
n	number of measurement points
p	pressure
r	radius (in polar coordinates)
R	reaction rate
Re_p	Reynolds number
S	surface area in the direction of the flux of species A
Sc	Schmidt number
$Sh_{\theta,t}$	local Sherwood number
Sh_t	space-averaged Sherwood number for the whole particle surface
Sh	time-averaged Sherwood number for a single period of velocity oscillation
t	time
t_D	period of velocity oscillation
v	particle velocity
v_x	x component of the particle velocity
v_y	y component of the particle velocity
V	voltage on the coils
V_0	maximum voltage on the coils
V_p	particle volume
$\bar{v}$	average particle velocity
$\tilde{v}$	normalised average particle velocity
$v_{\max}$	maximum particle velocity

Greek letters

δ	boundary layer thickness
θ	angle (in polar coordinates)
μ	fluid viscosity
μ_0	vacuum permeability
ν	kinematic fluid viscosity
ρ	fluid density
$\Delta\chi$	difference in magnetic susceptibility between the particle and the fluid
$\bar{\sigma}_v$	standard deviation from average velocity
$\sigma_{v,\max}$	maximum standard deviation
$\tilde{\sigma}_v$	normalised standard deviation from the average velocity
ϕ	phase shift of external magnetic field
ω	angular frequency of external magnetic field, $\omega = 2\pi F$

extrusion of polymer plates from a die and heat treatment of materials traveling between a feed roll and wind up roll. The problem has been extensively studied over the last 50 years since the pioneering work of Sakiadis [1,2] who pointed out the differences in boundary conditions between a moving surface of finite length and a continuous surface. The essential difference between flow with a constant reference velocity and a variable velocity flow is that the particle velocity and thickness of the boundary layer change with time. While various aspects of boundary layer problems with constant reference velocity have been studied [3–5], the effect of non-steady motion of a surface has been explored to a much lesser extent [6–8].

In recent years, hydromagnetic flows and mass transfer have attracted increased research interest due to the exploitation of various magnetic micro and nanostructures. In microfluidics, core-shell catalyst particles can be synthesized consisting of a magnetic core and a catalytic shell. These magnetically controlled particles have been used for cell manipulation, microscopic drug delivery and in microsensor applications [9–11]. Antibody coated magnetic microparticles have also been used in the capture of target species flowing in a 75 μm wide micro channel [12]. Motion of these magnetic particles can be controlled using alternating magnetic fields where the particle velocity depends on the product of the absolute value and gradient of magnetic field. As a result, the particle velocity is not expected to be uniform or constant. Control of particle velocity and trajectory can be adjusted with a feedback control based on video monitoring of the particle location with each time and then correcting the motion by adjustments into the actuation protocol [13,14]. This procedure is rather complex and it requires the use of transparent reactor materials which are not always compatible with the chemical environment.

In numerous applications in the fine chemical and pharmaceutical industries [15–18], the properties of the final product depends greatly on mass transfer to the catalyst particle surface [19]. Due to the laminar flow conditions prevalent in microchannels, the transport of reactants to the catalyst surface is often limited by diffusion due to the formation of thick hydrodynamic and mass transfer boundary layers around catalytic particles [20]. Application of an external magnetic field by a quadrupole arrangement of electromagnets allows for the controlled manipulation of magnetic particles orthogonal to the direction of flow thus enhancing the mass transfer rates. This, in turn, allows for the use of reactants of higher concentration which leads to process intensification [21].

A quadrupole arrangement of electromagnets is the most common system used for magnetic particle motion control as it allows for a smooth rotational control of the magnetic particles by applying sinusoidal electric signals to two pairs of coils [22] or an oscillating motion by switching two electromagnets on and off [23]. Remote magnetic actuation provides advantages over other methods of energy input in its ability to apply relatively large forces at a distance. It can penetrate through most media, including biological material which is particularly useful for potential applications in microfluidics [24].

Particles move with a variable velocity in a sinusoidal magnetic field due to the magnetic forces at play. For example, when a particle (or an array of individual separated particles) approaches a magnetic pole at maximum field, the magnetic force increases due to the increasing magnetic field gradients and as a result the particle accelerates. As the magnetic field reduces the field gradients reduce and the particle decelerates due to the resistant drag force in the liquid ($F_d = -6\pi\mu RV$). Thus the Re number changes with time typically in the range between 1 and 50 which in turn