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Cleanability study of complex geometries: Interaction between *B. cereus* spores and the different flow eddies scales

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ABSTRACT

Wall shear stress measurements and the distribution size of turbulent structures at the confined zone near the wall were used in order to investigate the cleanability of a part of a dairy processing line consisting in a manometer and a two-way valve. Geometry of equipment was discerned as an important factor governing the flow behavior and thereafter the initial contamination and the cleanability of the installation. Interactions between suspended spores and coherent turbulent structures of different sizes were used to explain the eventual re-adhesion of spores in confined zones of the loop. These interactions also helped to explain the role of the bursting phenomenon in the increase of the wall shear stress which induces spores detachment.

1. Introduction

Adhesion of microorganisms on a food processing line surfaces is a cause of concern in many food industries, given that deposition and attachment of bacterial cells are the first steps in microbial colonization of surfaces. In many studies, the cleaning efficiency is related to various parameters such as the surface roughness of equipment and the physico-chemical properties of the cleaning solution [1–3]. The hydrodynamic effects are also considered as important in the definition of the cleaning efficiency due to the shear stress forces acting at the wall [4–6]. This factor is mainly governed by the flow rate and the equipment design which affect the magnitude and the repartition of the hydrodynamic forces exerted on the wall [7]. On the other hand, different works on cleaning-in-place (CIP) processes have emphasized the contribution of the fluctuating shear rate in addition to the mean value of wall shear stress to the removal of bacteria [4–6] and confirmed the necessity to operate under turbulent flow regimes. Recent investigations of the hydrodynamic effects on bacterial removal from the surface equipment are mainly focused on the mean and the fluctuating shear stress at the wall [3–5]. However, detachment mechanisms of an individual spore or particle and the different involved forces remain weakly investigated. The present work aims to analyze this approach using literature data and experimental analysis made on a part of a dairy processing line.

Bacterial removal phenomenon due to shear stress forces occurs in the confined near wall zones. These zones are characterized by the production of a major part of the turbulent kinetic energy and high numbers of eddies of various sizes, each characterized by a given amount of rotational kinetic energy. These eddies result from the action of dissipative forces, governed by the viscosity of the fluid, on the structures generated by the increase in rotational kinetic energy.

Several papers have dealt with both experimental and modeling aspects of the particle motion in a turbulent flow [8–11]. The typical characteristics of this flow and the relevant length and time scales are used to explain the particle deposition and detachment. The same approach is used in this work in order to analyze bacterial contamination and cleanability of a part of a dairy industry equipment. The different scales lengths are determined using signal processing applied on the instantaneous variation of the fluctuating component of the wall shear stress.

The increase of the wall shear stress values up to the adhesion forces may induce particle detachment from the surface. However, experimental measurements showed that particle removal form a surface is not instantaneous and takes place over a period of mechanical forces application [9]. Thus, the removal processes from the wall have a statistical origin closely related to the turbulent behavior of the flow. Cleaver and Yates [12] have proposed the concept of coherent boundary layer structures, or “bursts”, in

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Nomenclature

d_p^*	dimensionless diameter of the particle
d_p	diameter of the particle (m)
dt	travel time (s)
D_{max}	diameter of large turbulent structures (m)
$E(k)$	spectral energy of the velocity
FRS	shear rate fluctuation (%)
f	spectral frequency (Hz)
k	wave number
Ra	average roughness (μm)
Re	Reynolds number (dimensionless)
R_{ss}	Lagrangian autocorrelation function
$Sh(t)$	Sherwood number (dimensionless)
$S_{x_{lev}}(t)$	wall shear stress using the "Levêque solution" (s^{-1})
$S_{x_{sob}}(t)$	wall shear stress using Sobolik et al. [24] method (s^{-1})
$\bar{S}_x, s_x(t)$	average value and fluctuating velocity gradients (s^{-1})
V_c	mean velocity of the flow ($m\,s^{-1}$)
V^*	friction velocity ($m\,s^{-1}$)
W_{ss}	power spectral density (PSD) (s^{-1})
x	axial direction

Greek symbols

Λ	integral length (mm)
μ	dynamic viscosity of the fluid (Pa s)
η	Kolmogorov microscale (μm)
$\bar{\varepsilon}$	dissipation rate of the kinetic energy
ρ_f	fluid density ($kg\,m^{-3}$)
ρ_f	spore density ($kg\,m^{-3}$)
τ_0	time (s)
τ_w	mean wall shear stress (Pa)
υ	kinematic viscosity ($m^2\,s^{-1}$)

order to explain the removal of a particle from a surface. Flow visualization was used to describe the spatio-temporal distribution of the bursts. Shirolkar et al. [10] showed that the vortex stretching process induced the breaking of the large-scale structures to smaller ones structures according to the turbulence decay mechanism and can be explained by the effects of viscous forces. The size of the particle with respect to the eddy size is an important parameter determining the particle-eddy interaction. Indeed, small particles are carried by turbulent eddies under a rotational kinetic energy through the flow field [13]. Braaten et al. [14] have developed a model of particle detachment based on the hypothesis of the existing relation between coherent structures and particles resuspension. They have shown that the bursting phenomenon induces a high wall shear stress value which leads to particles removal. The concept of the fluctuating lift force was used by Reeks et al. [15]. They have developed a model based on the energy balance. When a particle is exposed to a turbulent flow field, a transfer of turbulent energy to the particle occurs. Detachment from the surface takes place when the particle accumulates enough energy to overcome the adhesion forces [9].

According to Ziskind et al. [9], the accumulated energy results from the hydrodynamic forces which can be considered as the combination of the mean shear stress and the fluctuating shear rate occurring at the boundary layer.

However, despite the number of studies dealing with turbulence generation and transport near the wall, few authors have been interested in the adhesion and the detachment mechanisms of bacterial cells in the confined near wall zone. Braaten et al. [16] have studied the detachment of *Lycopodium* spores under a turbulent flow regime. A monodisperse size distribution of spores with an average diameter of 28 μm was used.

Generally, the size and the density of particles are major parameters which control the kind of interaction with coherent structures. According to Ziskind et al. [9], large particles with size reaching the external region of the boundary layer ($1.8 < d_p^* < 70$ where d_p^* is the dimensionless diameter of the particle $= d_p \cdot V^*/\upsilon$, V^* is the friction velocity ($V^* = \sqrt{\tau_w/\rho}$) and υ, the kinematic viscosity) are subjected to the effect of the large scale motions in the external region. On the other hand, small particles for which the dimensionless diameter d_p^* is less than 1 are located deeper in the viscous sublayer, where the instantaneous velocity distribution is linear. In this zone the effect of the large scale motions on particles resuspension are excluded. But Corino and Brodkey [17] showed that ejections and sweeps of coherent structures contribute in the increase of the wall shear stress. Ziskind et al. [9] reported that horseshoe or hairpin vortices are the most important flow patterns which induce detachment of small particles from the wall due to their contribution in the generated shear stress forces. Thus, whatever the size of the particles, eddies generated near the wall induce mean and fluctuating shear forces. When these hydrodynamic forces are greater than the adhesion ones, resuspension occurs.

Shirolkar et al. [10] have studied the dispersion of rigid spheres in an homogeneous and isotropic turbulent flow, they showed that the size of particles play a fundamental role. These authors have classified particles in two categories with respect to the scale of dissipative motion or Kolmogorov microscale (η):

- a particle is referred as small if its diameter is smaller than the Kolmogorov microscale,
- a particle is referred as medium if its diameter lies between the Kolmogorov microscale and the integral length scale.

Thus, when a small particle, presenting a lower size than the smallest eddy, is introduced in a turbulent flow, it remains trapped inside an eddy for a certain duration before it undergoes the influence of another eddy. This particle presents velocity close to that of the flow. The maximum time during which the particle can remain under the influence of a given eddy is the lifetime of that eddy. However, if the particle is denser than the fluid, the inertial force at the fluid-particle interface induces fluctuations dampening its velocity compared to the fluctuations of the fluid velocity. When the interaction occurs between a medium-sized particle and an eddy presenting the same or a smaller size, particle can totally dissipate the eddy or change its structure. If the velocity of the particle is lower than that of the fluid, adhesion can occur [10].

Small inert particles adhered at a surface are held by very strong surface forces which result from a combination of physical attractions, chemical bonds and mechanical stresses. This combination is usually referred to as the adhesion forces [9]. The mechanism of particle adhesion at a surface takes place in several steps [8]. The most important one corresponds to mass transport which can occur under sedimentation, convection or diffusion processes. In turbulent flow conditions, the transport process of particles is mainly governed by convection and diffusion. However, viscous forces near the wall are high enough, thus the transport mechanism is mainly carried out by diffusion throughout the boundary layer. The adhesion process occurs due to attraction forces (van der Walls and electrostatic forces) between particles and the wall.

For bacterial spores, adhesion forces are complex due to their surface properties. In addition to the hydrophobicity and the relative charge of the surface which induce high attraction forces, *Bacillus cereus* spores are surrounded by an *exosporium* and long appendages, both inducing a strong adhesion to stainless steel