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INFLUENCE OF SOLUBLE POLYSACCHARIDE ON THE ADHERENCE OF PARTICULATE SOILS

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ABSTRACT

The removal of particulate soils from solid surfaces is the key process of cleaning many industrial devices, such as heat exchangers and spray dryers (food and pharmaceutical sector), and may be influenced by the presence of solutes, in particular of macromolecules. The present study deals with the influence of soluble polysaccharide on the adherence of particulate fouling of open surfaces and on subsequent cleaning. Model substrates differing by hydrophobicity (glass and polystyrene) were soiled with a suspension of quartz particles, taken as a model of hard hydrophilic soil. Dextran was chosen as a model of soluble polysaccharide. The substrates were soiled with or without previous conditioning with the polysaccharide solution (80mg/l). The quartz particles suspension was prepared in three ways: (i) suspension in a polysaccharide solution (80mg/l), (ii) same as (i) and subsequent washing three times, (iii) suspension in water. The substrates were soiled by spraying the suspension and dried for 30min before cleaning treatment with a water flow in a radial flow chamber. The aggregates observed after soiling differed considerably between glass and polystyrene, whether the substrate and/or the quartz particles were or were not conditioned with dextran. Conditioning polystyrene with dextran increased slightly the adherence of quartz particles, while the opposite was observed when conditioning glass with dextran, whatever the mode of quartz particles conditioning. The effect of conditioning quartz particles with dextran at the concentration used was not significant.

INTRODUCTION

Particulate soils are a concern in many cleaning processes of different industries: heat exchangers; spray dryers (food and pharmaceutical industry); laundry and dish washing (detergent industry); de-inking (recycling of papers) and microchips cleaning (semiconductor industry). The removal of those soils from solid surfaces is a daily problem in food industry, in catering industry or in medical applications where high hygienic levels must be maintained. In food and pharmaceutical industries, the cleaning efficiency influences the final quality of the products, absence of cross-contaminations and batch integrity (Stephan et al., 2004; List and Müller, 2005). The presence of adhering particles and microorganisms is also undesirable after cleaning and disinfection of open surfaces, where the ambient general level of hygiene is critical. Open surfaces are exposed to splashing and aerial contamination. The interactions between the substrate and particulate contaminants have to be well understood in order to reduce equipment fouling, to improve the efficiency of cleaning and disinfection or to develop easy-to-clean surfaces (Podczeck, 1999). The hydrodynamic effects are important for the cleaning efficiency due to the shear stress forces acting at the wall (Lelièvre et al., 2002; Jensen et al., 2005; Blel et al., 2007). However, the wall shear stress, mainly governed by the flow rate and the equipment design, alone cannot explain cleaning performance (Jensen et al., 2007; Detry et al., 2009a; Blel et al., 2010). The size and the density of particles are major parameters which control the interaction with substrates. According to Ziskind et al. (1995), 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 = $dp.V^*/v$, V^* is the friction velocity (($V^* = (\tau w/\rho m)^{½}$, τw, mean wall shear stress, ρm, fluid density) and v, 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. But, 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.

In the food and pharmaceutical industries, fouling leads to frequent interruptions of production process for cleaning. Polysaccharides, proteins, lipids and other biopolymers are the main components of food mixtures. These compounds contain a variety of different functional groups (carboxylic, phosphoric, amino, hydroxyl) that can individually interact with surfaces and mediate adhesion processes (Speranza et al., 2004). Proteins on the outer surface of the bacteria are known to play an important role in the initial attachment to solid surfaces (Flint et al., 1997; Caccavo, 1999; Lower et al., 2005). But the role of proteins and other biopolymers in the particulate soils adhesion remains unknown. According to Detry et al. (2011), the presence of soluble macromolecules (mainly polysaccharides with a small proportion of proteins) in the aqueous phase of starch suspensions plays a role in particle-substrate interactions. However, the role of each of these macromolecules in the adhesion mechanism according to the surface nature is not clearly defined.

Studying the influence of soluble macromolecules on fouling with a suspension of particles and on surface cleaning is important because: (i) it may give practical information on the influence of surface nature and particle surfaces properties (Jones et al., 2002); (ii) it may give an insight into the physico-chemical mechanisms involved (Tadros, 1980); (iii) in particular it may clarify the role of the soluble macromolecules involved in particles adherence; (iv) it opens the way to designing and evaluating easy-to-clean surfaces.

The aim of the present study was to assess the influence of soluble polysaccharide on particulate soils adhesion on open surface and to improve the understanding of mechanisms affecting soiling and cleanability. Model substrates differing by hydrophobicity (glass and polystyrene) were soiled with a suspension of quartz particles and cleaned using a radial-flow cell. These particles were taken as a simplified particulate soil model. Dextran was chosen as a model of soluble polysaccharide because of its high solubility and because it was possible to select a defined molecular size from dextrans having a variety of molecular weights. In contrast with more highly branched polysaccharides such as dextrin, dextran contains more than 95% of only one type of glucose linkage. The substrates and the quartz particles were involved with or without previous conditioning with the polysaccharide solution. Untreated substrates and quartz are the blanks. Conditioned substrates simulate surfaces on which polysaccharides may be adsorbed for any reason (poor previous cleanin, several cycles of use without cleaning…). Conditioned particles represent a model complex mixture containing polysaccharides. Furthermore using washed and non washed quartz particles offers a comparison between the effects of polysaccharides just adsorbed or deposited by drying.

EXPERIMENTAL

Material

Glass slides (75mm×25mm×1mm, 50mm×50mm×1mm and 16mmx37mmx1mm) were purchased from Menzel-Gläser (Germany). Polystyrene sheets (300mm×300mm ×0.25mm) were purchased from Goodfellow (United Kingdom) and cut to the desired dimensions (75mm ×25mm×0.25mm and 16mm×37mm×0.). MilliQ water was produced by a MilliQ-50 system from Millipore (France). The chemical products used were ethanol 96%, Sulfuric acid (98%), Hydrogen peroxide solution (30%) purchased from Sigma-Aldrich (Wisconsin, USA) and RBS 50 cleaning agent (Chemical Products R. Borghgraef, Belgium). A solution of dextran from *Leuconostoc mesenteroides,* (20% (w/w), mol wt 500 000) was purchased from Sigma-Aldrich (Wisconsin, USA). Ground quartz particles (M400) were provided by Sibelco Benelux (Belgium).

Substrate pretreatment

Before soiling, the glass samples were immersed for 10min at 50°C in an alkaline detergent medium, 2% (v/v) RBS 50 aqueous solution (pH = 11.9) and sonicated for 10min in ultrasonic cleaner (Branson 3200, USA) to remove dust particles from test surface. The samples were then rinsed with MilliQ water and cleaned by immersion in a piranha mixture (sulfuric acid/hydrogen peroxide 2:1 (v/v)) at room temperature for 10min and rinsed thoroughly with MilliQ water. Polystyrene samples were first cleaned with ethanol, dried with Kimtech Science paper (Kimberly–Clark, United Kingdom) and immersed for 30min in ethanol. These samples were then rinsed thoroughly with MilliQ water. Both glass and polystyrene samples were dried with a gentle flow of nitrogen and wrapped in aluminum foil. The glass and polystyrene samples so pretreated were divided in two groups. The first group was conditioned for 1h in an 80mg/l dextran solution at room temperature, flushed with nitrogen for removing the liquid film and wrapped in aluminum foil until examination. The second group was not conditioned (called bare surface).

Soil preparation and treatment

Quartz particles with a size about 10 to 30µm were isolated from initial batch (particle size distribution 1.1 to 60.3µm) by repeated sedimentation. According to Stokes law, the rate of sedimentation of an isolated particle (V_p), considered as a sphere, is defined by Eq. (1) (Maciborski et al., 2003; Andre et al., 2011):

$$V_p = gd^2 \frac{\left(\rho_p - \rho_m\right)}{18\mu} \tag{1}$$

where d is the particle diameter, (ρ_p−ρ_m) is the density difference between the particle and the fluid of known viscosity μ and g is the gravitational constant. Knowing the settling velocity V_p, the time t needed to traverse a height D can be determined as t=D/V_p. The particle size distribution of the isolated particles (Mastersizer 2000, Malvern Instruments, United Kingdom) of the isolated fraction used here was unimodal, ranging from 7.6 to 32.7µm diameter (D10%=10.6µm; D50%=17.1µm; D90%=27.1µm).

The quartz particles suspension (15% w/v) was pretreated in three ways: (i) suspension in a polysaccharide solution (80mg/l), (ii) same as (i) and subsequent washing three times after keeping at 4°C for 72h, (iii) suspension in water. For preparing suspension (i), 7.5g samples of quartz were first mixed with 25ml of distilled water and stired for 30min at room temperature. Then, 25ml of a dextran solution in distilled water (160mg/l) were added and the entire mixture was stired for 1h. Afterward, the suspensions were kept at 4°C (dextran storage temperature) for 72h (to leave time for possible dextran adsorption).The choice of dextran concentration in the suspension was based on the studies of Ma and Pawlik (2005).

Soiling procedure

The surfaces were soiled with the above mentioned quartz particles suspensions. The suspension was brought 30min at room temperature and soiling was performed by manual aspersion using a thin layer chromatography (TLC) sprayer located 40 cm from the substrate. The surfaces were dried for 30min in a dark cupboard at room temperature to have always the uniform environment conditions. The relative moisture content and temperature of the drying place, recorded with a Testo 175-H2 logger (Testo, Germany) every hour during periods of three weeks, were 39±3% and 20.6±1.9°C, respectively.

Cleanability assessment

Radial flow cell. The radial-flow cell (Fig. 1) was adapted from the design of Décavé (Décavé, 2002) and made of stainless steel (Detry et al., 2007). It consisted of an upper disk with a 2mm diameter central inlet and a lower disk in which the soiled square sample (A) was fitted. A trench was made along the perimeter of the square recess in the lower disk to avoid any perturbation generated by deformations of the sample near the cut edges. The distance (*h*) between the upper disk and both the sample and the lower disk was set by three adjustable micrometric screws and controlled to be 1.00±0.02mm with calibrated steel spacers. The fluid entering the cell was pumped from a 10 liter tank (C) by a peristaltic pump (D) (Watson Marlow 323SciQ, pumphead 314, 4 rollers). Before entering the cell (B), the fluid passed through a 1 liter glass container (E) (filled to a volume of 750 ml) to suppress the pulses from the pump. A complete description of the device and of its hydrodynamics can be found elsewhere (Detry et al., 2007; 2009a; 2009b).

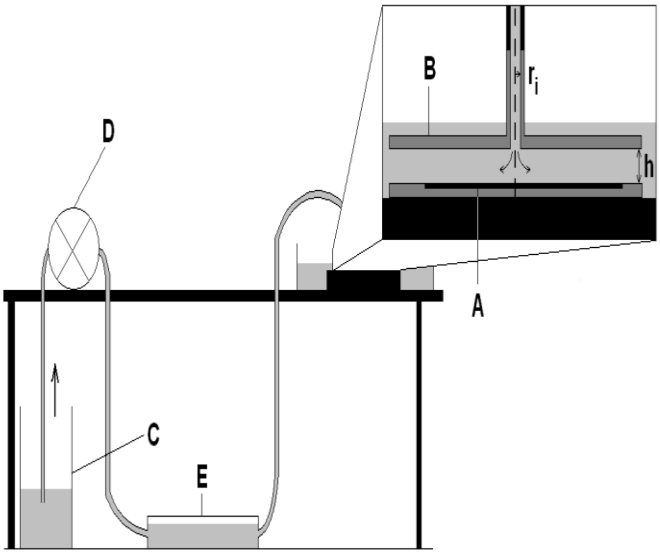


Fig. 1 Scheme of the radial-flow cell installation, (A)Sample; (B) radial-flow cell; (C) cleaning fluid tank; (D) pump; (E) glass container; (*ri*) inlet radius; (*h*) disk spacing (Detry et al., 2007).

Procedure. The cleaning fluid used was distilled water and cleaning was performed at 20°C at two flow rates (190 and 390ml/min) for 5min. The soiled sample was immersed in the flow cell container. Then, the upper disk of the RFC was placed and the sample was immediately exposed to a flow at the desired flow rate. After 5min, the upper disk of the RFC was gently removed from the flow cell. The sample was removed and dried at room temperature.

Quantification. Pictures of the substrate were taken before and after cleaning, using an epifluorescence stereomicroscope (ZX9 Olympus, Belgium) equipped with a CCD camera, a mercury vapour UV lamp (100W, emission range 100–800nm) and UV filters (passing bands: excitation 460–490nm, emission > 520nm. As showed in Figure 2, a circular zone with a lower density of aggregates was observed at the centre of the sample. This zone is where removal occurs. The radial position at which the residual density of aggregates becomes ≥ 50% is known as the critical detachment radius (Goldstein and DiMilla, 1997, 1998). The pictures of the sample before and after cleaning were processed with a specific application of the Matlab software (The Mathworks Inc.), which gives the ratio of the number of aggregates initially presents on the surface to the number of aggregates remaining after removal according to the radial position. A graph could then be plotted and the radial position corresponding to a residual density of aggregates of 50% was determined. The value of the critical radius was checked for consistency in the LUCIA software to insure the absence of artifacts such as the nucleation of air bubbles on the surface. At least 10 repetitions of each experiment (soiling-cleaning) were made, being distributed in at least three independent series and one soiled-surface sample was used per-flow rate.

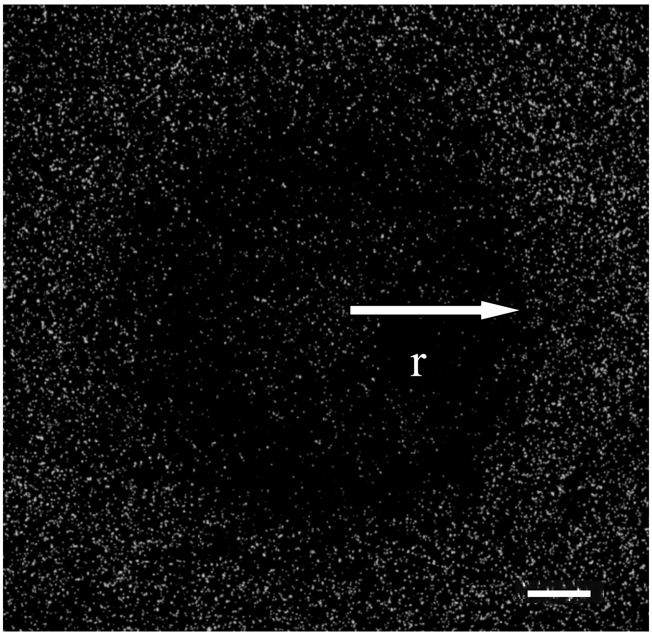


Fig. 2 Representative picture obtained on a glass substrate soiled with quartz particles, dried 30min and submitted for 5min to a flow rate of 390ml/min in the radial-flow cell. Scale bar: 1mm.

The critical radius of detachment which was the output parameter of the cleaning experiments can be associated to a critical wall shear stress which corresponds to the minimal hydrodynamic drag force required to detach a soil from its surface under the given experimental conditions (Jensen and Friis, 2004). However, recent studies showed that the conversion of critical radius into critical wall shear stress may be biased when the adhering aggregate height is not negligible with respect to the channel height and when the adherence is such that flow rates above 20ml/min are required (Detry et al., 2007; Detry et al., 2009a). Owing to the limitations imposed by both the hydrodynamic regime and soil thickness, the results of the present study are expressed in terms of critical radius, keeping in mind that for a defined flow rate, the higher the critical radius, the lower the adherence.

Methods of characterization

Characterization of the soiling entities. This concerns the entities, typically aggregates, left after drying subsequent to soiling with the quartz suspension.

Individual size measurements: For each type of sample, at least 50 entities were observed with a Nikon Eclipse E400 microscope (magnification 20X) equipped with a CCD camera, a mercury vapour UV lamp, a dichroic mirror (reflection band 446–500nm, transmission band 513–725nm) and UV filters (passing bands: excitation 447–517nm, emission 496–576nm).

The entities were first selected randomly; a targeted selection was also made to measure the extreme sizes.

The equivalent diameter of entity contours was determined using the LUCIA G image analysis software (LIM, Prague, Czech Republic) and the Eq. (2):

$$\text{diameter} = 2(\text{area} / \pi)^{1/2} \qquad (2)$$

The height of the entities was determined by focusing on the substrate and on the top granules after calibration of the microscope screw graduations with a polystyrene sheet (250 µm thickness corresponding to 147 ± 3 graduations).

Size measurements on a large population. The equivalent diameter of entity contours was also determined on a broader set, using the image analysis of micrographs obtained using size of the soiled surface glass and polystyrene were compared by measuring the size of the zone of contact between the suspension droplet after drying and the surfaces with an optical microscope (10X objective). Size measurements were made in the same logic as described above in the case of the individual size measurement. For each type of sample, two slides ($75x25mm^2$) were examined. For each slide, five fields (1 field = 0.25cm²) were chosen randomly and a picture was taken at a random place in each field (one picture corresponding to 0.52mm²). An image analyzer software (LUCIA G) was used to measure the equivalent diameter of the entity contours as described above. The data were exported in a txt-file and processed using an excel tool, providing the size distribution (classes with a 10µm increment).

Scanning electron microscopy (SEM). The morphology of the soiling entities was examined by scanning electron microscopy (secondary electrons mode, external detector, DSM 982 Gemini from Leo, field-effect gun). The images presented here were obtained using an accelerating voltage of 1 kV. Samples were examined after deposition of a 10nm thickness chromium coating.

Contact angle and liquid surface tension. Static contact angles were measured using the sessile drop method with a goniometer (Krùss, France). Surface tensions of water and dextran solution were measured with a Prolabo Tensiometer (Tensimat n3) using Wilhelmy plate method.

RESULTS

Wetting properties

Table 1 presents the surface tensions of water and of dextran solution and their contact angles measured on the substrates, bare and conditioned with the dextran solution. There is no significant difference between the surface tension of water and dextran solution (80mg/l) which are 71.8 and 72.3mN/m, respectively. There is also no significant difference of contact angle between water and dextran solution, neither between bare and conditioned substrates. However, the difference between contact angles measured on glass and polystyrene is great, whatever the substrate pretreatment. It must be noted that contact angles measured on glass may be appreciably higher if the surface is left for a long time (about 1 day) in contact with the surrounding atmosphere, owing to adsorption of organic contaminants by the high energy solid.

Table 1. Surface tension of the liquids and contact angles on the substrates in the indicated state.

Liquids	Surface tension (mN/m)	Contact angles (°C)			
		Bare glass	Conditioned glass	Bare polystyrene	Conditioned polystyrene
Water	71.6 ± 0.8	11 ± 2	12 ± 2	72 ± 2	73 ± 3
Dextran solution (80mg/l)	72.3 ± 0.0	12 ± 1		74 ± 2	

*Mean ± Standard deviations

Size and shape of adhering aggregates

Representative micrographs of the quartz aggregates left after soiling and drying are presented in Fig. 3 and 4 for the different systems investigated. Optical micrographs are presented on the left hand side and SEM micrographs on the right hand side. A difference is noted between glass (Fig. 3) and polystyrene (Fig.4), regarding both the number of soiling objects (optical microscope) and their morphology (SEM). On glass many quartz particles are isolated, while they are aggregated on polystyrene. With glass, there is no clear influence of conditioning the substrate or the quartz particles with dextran. With polystyrene, there may be a difference depending on whether the substrate was conditioned or not with dextran.

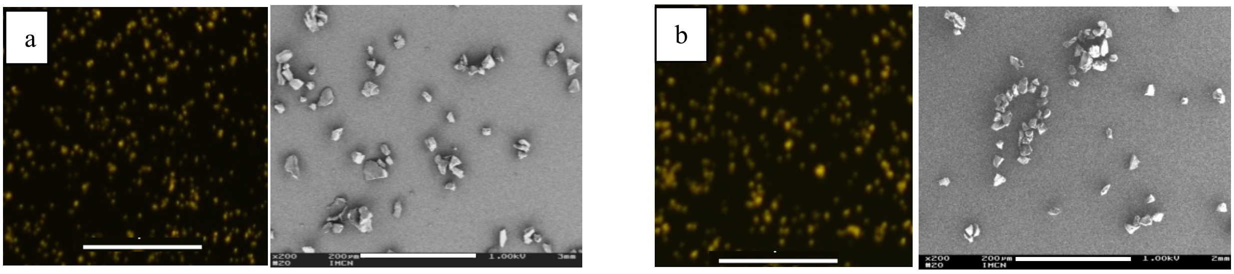
The relationship between the height of the soiling entities and the equivalent diameter of their contour is presented in Fig. 5. No distinction is made between different samples involving the same substrate. There was indeed no significant difference in the plots according the pretreatment of the substrate and of quartz particles. Both the height and the lateral size are larger on polystyrene compared to glass. On glass it could be observed by microscopy that the height of the aggregates never exceeded 2 layers of particles, independently of the lateral size. This can also be observed in Fig. 5 from the height of aggregates which is comprised between 15 and 38µm, knowing that the diameter of the quartz particles ranges from 7.5 to 32.7µm, with an average size of 17.1µm (see Section 2.3).

On polystyrene, the lateral size and the height of the entities increased to values much larger than the quartz particle size. Compared to glass, polystyrene is less wetted by the soiling suspension. As a consequence, the suspension drops tend to minimize their contact area with the surface, possibly rolling and coalescing, and gathered the quartz particles to leave larger aggregates after drying.

Measurements made on a larger population showed that the density of soiling entities on glass (51±4 $drops/mm^2$) was higher compared to polystyrene (33±4 $drops/mm^2$). The lateral size distributions of the soiling entities are presented in Fig. 6, without making a distinction between different samples involving the same substrate. Again larger soiling entities were found on polystyrene compared to glass. The D50% were 55µm and 30µm on polystyrene and glass, respectively. The glass substrate gave a high proportion of entities with a lateral size smaller than 40µm.

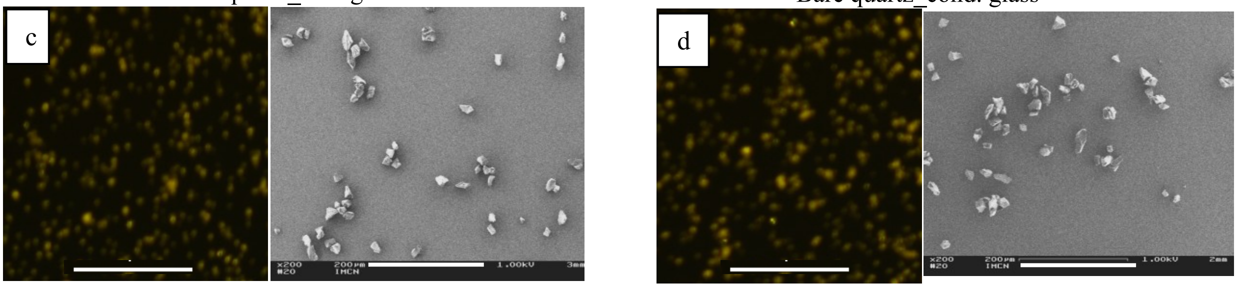
Quartz aggregates removal

The critical detachment radii are presented in Fig. 7 for the substrates treated in different ways, using quartz suspension



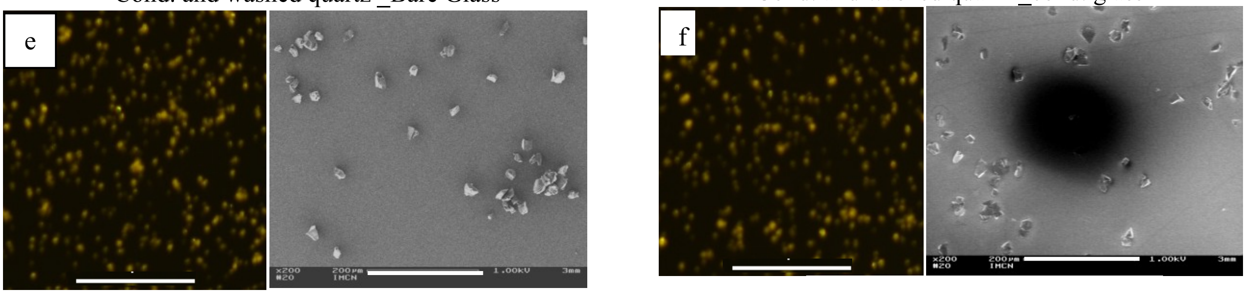
Bare quartz_bare glass

Bare quartz_cond. glass



Cond. and washed quartz _Bare Glass

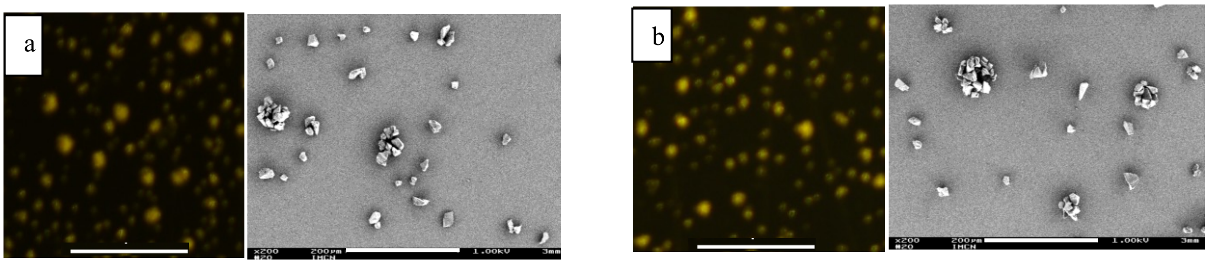
Cond. and washed quartz _cond. glass



Cond. quartz_Bare glass

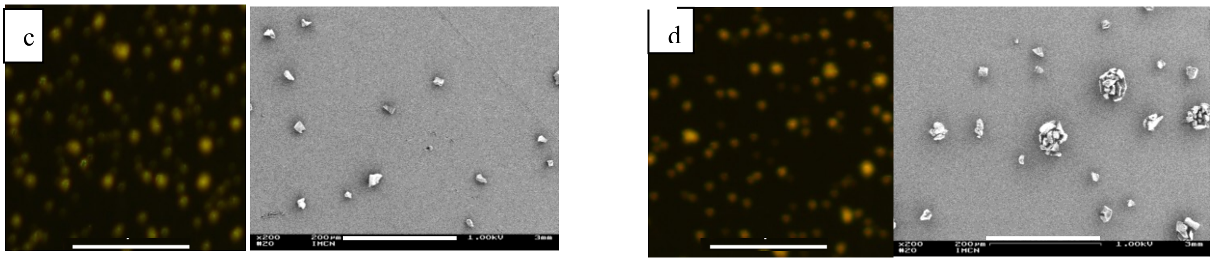
Cond. quartz_cond. glass

Fig. 3 Illustration of the types of deposits formed on glass with the different treatments. For each image pair: left = stereomicroscope picture, scale bar 1mm; right = SEM picture, scale bar 200µm



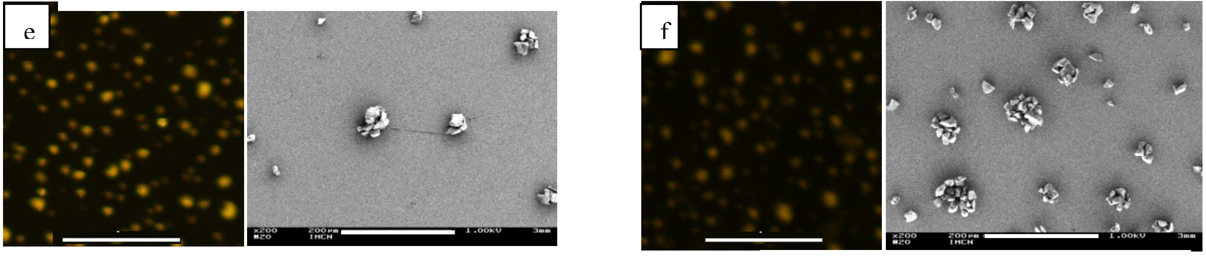
Bare quartz Bare Polystyrene

Bare quartz Cond. Polystyrene



Cond. and washed quartz _Bare Polystyrene

Cond. and washed quartz cond. Polystyrene



Bare quartz Bare Polystyrene

Cond. Quartz Cond. Polystyrene

Fig. 4 Illustration of the types of deposits formed on polystyrene with the different treatments. For each image pair: left = stereomicroscope picture, scale bar 1mm; right = SEM picture, scale bar 200 µm

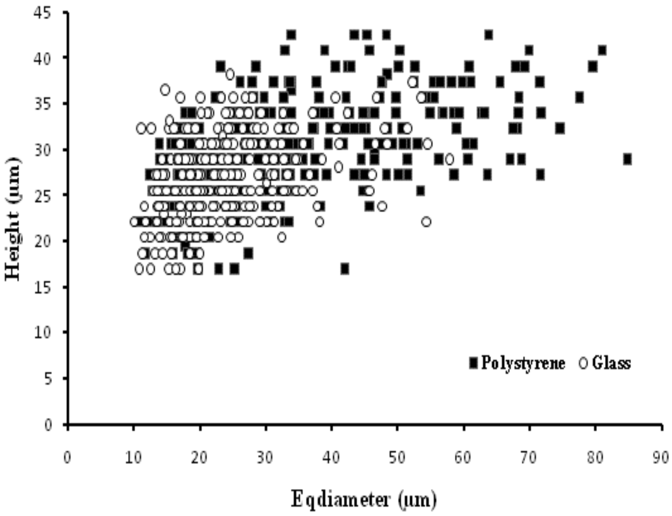


Fig. 5 Height of the soiling entities formed on glass and polystyrene plotted as a function of their lateral dimension (equivalent diameter of the contour)

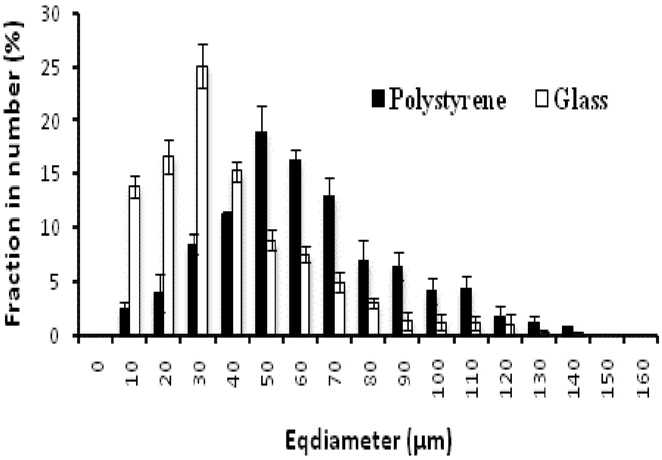


Fig. 6 Histograms (% in number) of the lateral size of the soiling entities formed on glass and polystyrene (equivalent diameter of the contour)

treated in different ways. Remember that a larger critical detachment radius at a given flow rate reveals a lower hydrodynamic drag force required to detach soiling particles from the substrate. Increasing the flow rate allows increasing drag forces to be applied. For glass no detachment radius could be measured after cleaning at flow rates of 90 to 190ml/min, but a detachment of small clusters of particles from the aggregates situated near the inlet occurred at both flow rates (results not showed). Detachment radii could be measured after cleaning at 390ml/min. For polystyrene, the detachment radius was larger than the microscope view field. Detachment radii could be measured when the flow rate was set at 90 an 190ml/min.

These results show that the soiling moieties were adhering much more firmly on glass compared to polystyrene. They indicate that conditioning the substrate with dextran increased slightly but always the adherence of quartz particles to polystyrene (Fig. 7B), while the opposite was observed when conditioning glass with dextran (Fig.7A). In contrast the presence of dextran in the quartz suspension did not seem to have an effect on adherence, whatever the substrate and whether the latter was conditioned or not with dextran.

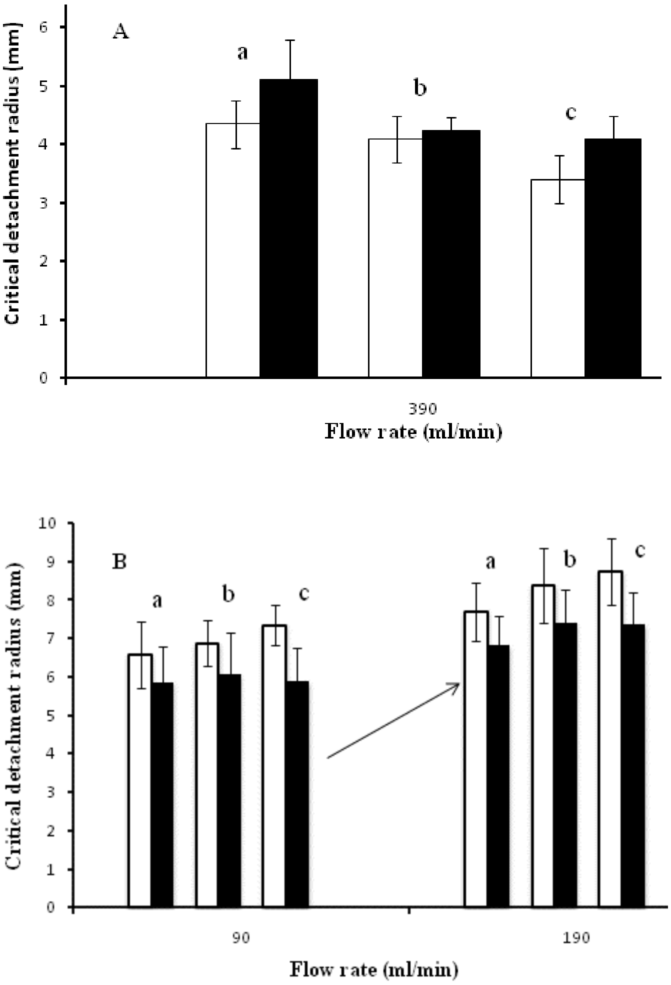


Fig. 7 Critical detachment radius measured on substrates soiled with the quartz particles suspensions: (A): glass, cleaning at 390ml/min; (B) polystyrene, cleaning at 90 and 190ml/min. White, bare substrate; black, substrate conditioned with dextran; a, quartz suspended in water; b, quartz suspended in dextran solution; c, quartz pretreated with dextran solution and washed.

DISCUSSION

Influence of the substrate

The difference of wetting between the substrates were reflected in the size and shape of the soiling entities formed after spraying the quartz particles suspensions on glass and polystyrene, as shown in Fig. 3, 4 and 5. The morphology of soiling entities results from drop spreading, which decreases as the surface contact angle increases and, capillarity effects which develop upon drying (de Lazzer et al., 1999; Kralchevsky and Nagayama, 2001; Rabinovich et al., 2002). When the sprayed suspension drops impact onto the surface, they spread or not and start to evaporate, which leads to the formation of meniscuses and to the appearance of capillary forces at particle-particle and particle-substrate interfaces.

For the hydrophobic polystyrene some droplets could have come into contact with each other as a result of rolling on the substrate, resulting in drop coalescence and in the formation of larger aggregates. The particle-substrate capillary forces are appreciably lower than the particle-particle capillary forces. As a consequence, particles are free to gather into compact aggregates.

Hydrophilic glass is well wetted by water and dextran solution. Water drops spread thus over the surface and presumably dry more quickly. Moreover the particle-substrate capillary forces are similar to particle-particle capillary forces. After drying they leave a larger number of soiling entities, which have a smaller size: aggregates constituted of maximum 2 layers of particles and even isolated particles (Fig. 3)

The dependence of the morphology of adhering soiling entities on the substrate is thus explained by the contact angle which affects suspension drop spreading and influences the relative of capillary forces at the particle-substrate and particle-particle interfaces upon drying.

Influence of substrate wetting on cleanability

The removal of soiling entities may be facilitated by the development of lower capillary forces at the substrate-particle interface upon drying, which creates and a less intimate contact between the particles and the substrate. This may explain the lower adherence on polystyrene compared to glass. Detry et al. (2009c) compared two spreading medium (ethanol vs water) and showed that when capillary forces are controlling the adhesion of particles aggregates, the adherence is higher when the spreading medium has a higher surface tension.

The lower adherence of quartz soil on polystyrene compared to glass may also be due to the round shape and larger thickness of the soiling entities. Aggregate properties are indeed known to affect the relation between flow rate and critical radius detachment. Removal of particle agglomerates presenting a higher contact area than frontal area is known to require higher hydrodynamic forces than detachment of pairs or particles (Yamamoto et al., 1994). Rounder fibroblasts are for instance more affected by a change in flow rate than flatter ones (Brooks and Tozeren, 1996; Bundy et al., 2001). Similar effects can be expected for the rounder aggregates formed on hydrophobic polystyrene after soiling compared to the flatter deposits formed on glass in the same conditions. Bacteria (more rigid and less viscoelastic than fibroblasts) are more affected than them by a change in flow rate (Bundy et al., 2001). In the case of quartz particle, other factors such as their roughness and their non spherical shape will influence their contact area and their adhesion strength (Das et al., 1994; Ziskind et al., 1995).

Influence of soluble polysaccharides

The surface tension of dextran solution (80mg/l) was 72.3mN/m, close to the value of 71.6mN/m for water. This factor could be generate an effect of the nature of the quartz suspension used for soiling. There was indeed no significant difference of contact angle between water and dextran solution.

However adsorbed dextran might influence the soil adherence. Fig. 7 shows that conditioning the substrates with dextran solution decreases slightly but systematically the detachment radius on polystyrene and thus increase slightly the soil adherence (fig. 7B), while the opposite was observed on glass (fig.7B), whatever the mode of quartz particle conditioning. Detry et al. (2011) made a similar study by preconditioning polystyrene with a supernatant of starch suspension, which contains soluble macromolecules, and observed a decrease of starch granule adherence. It was concluded that macromolecules may act as an adhesive joint, the properties of which seem to be influenced by the detailed history of drying and exposure to humidity. In our study, dextran was used as soluble macromolecule at a concentration (80ml/l) which may be too low to have a marked effect. A thorough study must be conducted to elucidate the effect of soluble polysaccharides concentration on particulate soils adhesion.

CONCLUSIONS

The effect of soluble polysaccharides represented by dextran on particulate soils removal from hydrophilic and hydrophobic open solids surface has been studied. Surface observation after soiling and exposure to a confined radial shear flow showed the importance of surface wettability and capillary forces. Surface hydrophobicity was shown to influence the morphology of the aggregates formed by droplet spreading. Droplet spreading and the competition between capillary forces at the particle-surface and particle-particle interfaces affect the shape and compactness of the adhering aggregates, the efficiency of shear forces upon cleaning and finally, the adherence of soiling particles. In particular, the rounder aggregates formed on hydrophobic polystyrene after soiling are more sensitive to wall shear stress than flatter ones formed on glass in the same conditions.

The aggregates observed after soiling differed considerably between glass and polystyrene, whether the surface and/or the quartz particles are conditioned with dextran. Conditioning polystyrene with dextran increased slightly the adherence of quartz particles. The opposite was observed when conditioning glass with dextran, whatever the mode of quartz particle conditioning. The effect of conditioning quartz particles with dextran at the concentration used was not significant. A study on a wide range of concentration of dextran is underway in order to better elucidate the effect of soluble polysaccharides on the adhesion of particulate soils.

NOMENCLATURE

d	particle diameter, µm
D	separation height of particles, m
d^*_p	dimensionless diameter of the particle
d_p	diameter of the particle (m)
h	disk spacing, m
r	radial position, m
ri	inlet radius, m
t	time to traverse the separation height of particles, s
τ_w	mean wall shear stress (Pa)
V*	friction velocity ($m.s^{-1}$)
v	kinematic viscosity ($m^2\ s^{-1}$)
Vp	speed of an isolated Particle, m/s^1
µ	viscosity, Pa.s
ρ_m	density the fluid, kg/m^3
ρ_p	density of the dispersed particle, $kg/\ m^3$

Subscript

Cond.	conditioned
RFC	radial-flow cell
SEM	scanning electron microscopy
TLC	thin layer chromatography

REFERENCES

Andre, C., Laux, D., Ferrandis, J.Y. and Blasco, H., 2011, Real-time analysis of the growth of granular media by an ultrasonic method: Application to the sedimentation of glass balls in water, *Powder Technology,* 208, pp. 301–307.

Blel, W., Legentilhomme, P., Le Gentil-Lelièvre, C., Faille C., Legrand J. and Bénézech, T., 2010, Cleanability study of complex geometries: Interaction between B. cereus spores and the different flow eddies scales, *Biochemical Engineering Journal,* 49, pp. 40-51.

Blel, W., Bénézech, T., Legentilhomme, P., Legrand, J. and LeGentil-Lelièvre, C., 2007, Effect of flow arrangement on the removal of Bacillus spores froms tainless steel equipment surfaces during a Cleaning In Place procedure, *Chemical Engineering Science,* 62, pp. 3798-3808.

Brooks, S.B. and Tozeren, A., 1996, Flow past an array of cells that are adherent to the bottom plate of a flow channel, *Computers & Fluids,* 25(8), pp. 741-757.

Bundy, K.J., Harris, L.G., Rahn, B.A. and Richards, R.G., 2001, Measurement of fibroblast and bacterial detachment from biomaterials using jet impingement, *Cell Biology International*, 25(4), pp. 289-307.

Caccavo, J.R., 1999, Protein-mediated adhesion of the dissimilatory Fe(III)-reducing bacterium Shewanella alga BrY to hydrous ferric oxide, *Applied and Environmental Microbiology,* 65(11), pp. 5017-5022.

Das, S.K., Schechter, R.S. and Sharma, M.M., 1994, The role of surface roughness and contact deformation on the hydrodynamic detachment of particles from surfaces, *Journal of Colloid and Interface Science*, 164, pp. 63-77.

Décavé, E., 2002, *Comportement cellulaire sous écoulement hydrodynamique: aspects expérimentaux et théoriques*, PhD Thesis, Université Joseph Fourier, Grenoble, France.

de Lazzer, A., Dreyer, M. and Rath, H. J., 1999, Particle-Surface Capillary Forces, *Langmuir*, 15, pp. 4551-4559.

Detry, J. G., Rouxhet, P. G., Boulangé-Petermann, L., Deroanne, C. and Sindic, M., 2007, Cleanability assessment of model solid surfaces with a radial-flow cell, *Colloids and Surfaces A: Physicochem. Eng. Aspects*, 302, pp. 540–548.

Detry, J. G., Jensen, B. B. B. Sindic, M. and Deroanne, C., 2009a, Flow rate dependency of critical wall shear stress in a radial-flow cell, *Journal of Food Engineering*, 92, pp. 86-99.

Detry, J. G., Deroanne, C., Sindic, M. and Jensen, B. B. B, 2009b, Laminar flow in radial flow cell with small aspect ratios: Numerical and experimental study, *Chemical Engineering Science*, 64, pp. 31-42.

Detry, J.G., Jensen, B.B.B., Sindic, M. and Deroanne, C., 2009c, Flow rate dependency of critical wall shear stress in a radial-flow cell, *Journal of food engineering*, 92, pp. 86-99.

Detry J. G., Sindic M., Servais M. J., Adriaensen Y., Derclaye S., Deroanne C. and Rouxhet P. G., 2011, Physico-chemical mechanisms governing the adherence of starch granules on materials with different hydrophobicities, *Journal of Colloid and Interface Science,* 355, pp. 210–221

Docoslis, A., Giese, R. F. and van Oss, C. J., 2000, Influence of the water–air interface on the apparent surface tension of aqueous solutions of hydrophilic solutes, *Colloids and Surfaces B: Biointerfaces,* Vol. 19, 2, pp. 147-162

Flint, S.H., Brooks, J.D. and Bremer, P.J., 1997, The influence of cell surface properties of thermophilic streptococci on attachment to stainless steel, *Journal of Applied Microbiology*, 83(4), pp.508-5017.

Goldstein, A. S. and DiMilla, P. A., 1997, Application of Fluid Mechanic and Kinetic Models to Characterize Mammalian Cell Detachment in a Radial-Flow Chamber, *Biotechnology and Bioengineering*, 55(4), pp. 616-629.

Goldstein, A. S. and DiMilla, P. A., 1998, Comparison of Converging and Diverging Radial Flow for Measuring *Cell, Adh. AIChE Journal*, 44(2), pp. 465-473.

Jensen, B.B.B., Stenby, M. and Nielsen, D.F., 2007, Improving the cleaning effect by changing average velocity, *Trends in Food Science & Technology.* 18, pp. S52–S63.

Jensen, B.B.B., Friis, A., Bénézech, T., Legentilhomme, P. and Lelièvre, C., 2005, Local wall shear stress variations predicted by computational fluid dynamics for hygienic design, *Trans. IchemE Part C: Food and Bioproducts Processing*, 83(C1), PP. 53-60.

Jensen, B. B. B. and Friis, A., 2004, Critical wall shear stress for the EHEDG tests method, *Chemical Engineering and Processing*, 43, pp. 831-840.

Jones, R., Pollock, H. M., Cleaver, J. A. S. and Hodges, C. S., 2002, Adhesion Forces between Glass and Silicon Surfaces in Air Studied by AFM: Effect of Relative Humidity, Particle Size, Roughness, and Surface Treatment, *Langmuir*, 18, pp. 8045-8055.

Kralchevsky, P. A. and Nagayama, K., 2001, Capillary Bridges and Capillary-bridge Forces. In: Kralchevsky, P.A.and Nagayama, K., eds. *Attachment of Colloid Particles and Proteins to Interfaces and Formation of Two-Dimensional Arrays,* Amsterdam: Elsevier, pp. 469-502.

Lelièvre, C., Legentilhomme, P., Gaucher, C., Legrand, J., Faille, C. and Bénézech, T., 2002, Cleaning in place: effect of local wall shear stress variation on bacterial removal from stainless steel equipment, *Chemical Engineering Science,* 57, pp. 1287-1297.

List, W. and Müller, J., 2005, Reinigungsvalidierung unter besonderer Berücksichtigung von Proteinrückständen, Pharm. Ind., 67, pp. 1359-1365.

Lower, B.H., Yongsunthon, R., Vellano III, F.P. and Lower, S.K., 2005, Simultaneous force and fluorescence measurements of a protein that forms a bond between a living bacterium and a solid surface, *Journal of Bacteriology*, 187(6), PP. 2127-2137.

Ma, X. and Pawlik, M., 2005, Effect of alkali metal cations on adsorption of guar gum onto quartz, *Journal of Colloid and Interface Science*, 289, pp. 48–55.

Maciborski, J. D., Dolez, P. I. and Love, B. J., 2003, Construction of iso-concentration sedimentation velocities using Z-axis translating laser light scattering, *Materials Science and Engineering,* A361, pp. 392–396.

Podczeck, F., 1999, Investigations into the reduction of powder adhesion to stainless steel surfaces by surface modification to aid capsule filling, *International Journal of Pharmaceutics*, 178, pp. 93-100.

Rabinovich, Y. I., Adler, J. J., Esayanur, M. S., Ata, A., Singh, R. and Moudgil, B. M., 2002, Capillary forces between surfaces with nanoscale roughness, *Advances in Colloids and Interface Science*, 96, pp. 213-230.

Speranza, G., Gottardi, G., Pederzolli, C., Lunelli, L., Canteri, R., Pasquardini, L., Carli, E., Lui, A., Maniglio, D., Brugnara, M. and Anderle, M., 2004, Role of chemical interactions in bacterial adhesion to polymer surfaces, *Biomaterials*, 25 (11), pp. 2029-2037.

Stephan, O., Weisz, N., Vieths, S., Weiser, T., Rabe, B. and Vatterott, W., 2004, Protein Quantification, Sandwitch ELISA, and Real-Time PCR Used to Monitor Industrial Cleaning Procedures for Contamination with Peanut and Cellery Allergens, *Journal of AOAC International*, 87, pp. 1448-1457.

Tadros, T. F., 1980, Particle-surface adhesion, In: L. J. M. Berkeley R.C.W., Melling J., Rutter P.R., Vincent B., eds. Microbial Adhesion to Surfaces, Chichester: Ellis Horwood Ltd, Chichester pp. 93-116.

Yamamoto, T., Periasamy, R., Donovan, R. and Ensor, D.,1994, Flow cell for real time observation of single particle adhesion and detachment, *Journal of Adhesion Science and Technology*, 8(5), pp. 543-552.

Ziskind, G., Fichman, M. and Gutfinger, C., 1995, Resuspension of particulates from surfaces to turbulent flows - Review and analysis, *Journal of Aerosol Science*, 26(4), pp. 613-644.