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A comparison of local phosphorescence detection and fluid dynamic gauging methods for studying the removal of cohesive fouling layers: Effect of layer roughness

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ABSTRACT

The performance of industrial cleaning in place (CIP) procedures is critically important for food manufacture. CIP has yet to be optimised for many processes, in part since the mechanisms involved in cleaning are not fully understood. Laboratory tests have an important role in guiding industrial trials, and this paper introduces and compares two experimental techniques developed for studying CIP mechanisms: local phosphorescence detection (LPD), and scanning fluid dynamic gauging (sFDG).

To illustrate the comparison, each technique is used to investigate the influence of soil topology on the cleaning of pre-gelatinised starch-based layers from stainless steel (SS 316) substrates by aqueous NaOH solutions at ambient temperature. The roughness of the soil surface is varied by incorporating zinc sulphide particles with different particle size distributions (range 1–80 μm) into the starch suspensions. The soil roughness increased with the use of larger particles, increasing the 3D arithmetic mean roughness (S_a) of the dry layers (range 0.37–3.33 μm). Rough layers were cleaned more readily than those containing small inclusions, with a good correlation between the cleaning rates observed during LPD and FDG measurements. The LPD technique, which is an instrumented CIP test, gives a better indication of the cleaning time, while sFDG measurements provide further insight into the removal mechanisms.

Keywords: Cleaning; Starch; Roughness; Local phosphorescence detection (LPD); Fluid dynamic gauging (FDG); Shear stress

1. Introduction

Cleaning-in-place (CIP) operations are widespread in the food sector. Ensuring the effectiveness of these procedures is essential for hygienic operation and sustainable food manufacturing. CIP operations require appreciable capital investment and resources including chemicals and energy, with concomitant impacts on waste and carbon footprint. There is therefore an on-going need to optimise these processes, both by industrial testing and through research into the mechanisms involved in cleaning.

Fryer and Asteriadou (2009) introduced a prototype cleaning map as a tool to aid qualitative categorisation and comparison of cleaning scenarios likely to arise in the food

Abbreviations: CIP, cleaning in place; CFD, computational fluid dynamics; FDG, fluid dynamic gauging; LPD, local phosphorescence detection; NaOH, sodium hydroxide; PMMA, poly(methyl methacrylate); PVC, poly(vinyl chloride); RO, reverse osmosis; sFDG, scanning fluid dynamic gauging.

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Nomenclature

Roman

D_h	hydraulic diameter [m]
d_n	nozzle inner diameter [mm]
f	Darcy friction factor
h	nozzle-layer separation [mm]
h_o	nozzle-substrate separation [mm]
I^*	normalised phosphorescent intensity
I_s	phosphorescent intensity [*arb.*]
I_{so}	initial phosphorescent intensity [*arb.*]
m_f	mass flow rate [$g\,s^{-1}$]
m_s	mass of soil [g]
m_{so}	initial mass of soil [g]
p_o	ambient pressure in FDG tank [Pa]
p_1	pressure downstream of FDG nozzle [Pa]
Δp_H	hydrostatic pressure difference [Pa]
r_c	Weibull process characteristic rate
Re	Reynolds number
R_{FDG}	FDG removal rate [$\mu m\,s^{-1}$]
R_{LPD}	LPD removal rate [$\mu m\,s^{-1}$]
S_a	3D arithmetic mean roughness [μm]
S_{pk}	3D peak roughness [μm]
t	time [s]
t_c	Weibull process characteristic time [s]
v	liquid velocity [$m\,s^{-1}$]

Greek

δ	layer thickness [μm]
ρ	liquid density [$kg\,m^{-3}$]
τ_w	Shear stress on the wall [Pa]

Superscripts and subscripts

max	maximum
mean	arithmetic mean

industry and related sectors. They characterised CIP actions according to the nature of the soil and of the cleaning solution. The cohesive soils studied in this work, requiring chemical agents to swell and soften the material before removal, fit into their Type 3 cleaning scenario. While the cleaning map approach provides a simple means of categorising cleaning scenarios, other factors will also influence the ease of cleaning. Amongst these, the topography of the soil layer, and in particular its roughness (Albert et al., 2011), has received little attention. Whilst industry cannot generally influence the topography of the soil deposit, the roughness of this fouling layer may influence its interaction with the cleaning solution, the forces exerted by the fluid, and consequently the effectiveness of CIP operations.

This paper reports a short study of the effect of soil roughness on removal during contact with alkaline solutions at ambient temperature, and compares the information provided by two different testing techniques. Cleaning is an interdisciplinary topic (Wilson, 2005) and combines aspects of materials science, fluid flow, surface science and rheology. The need to study and optimise cleaning processes has led to the development of a number of specialised research techniques, including flow cells (Bakker et al., 2003; Detry et al., 2007), packed beds (Jurado et al., 2007), ultrasonic techniques (Lohr and Rose, 2003), laser sensors (Mendret et al., 2007), micromanipulation devices (Liu et al., 2006), local phosphorescence

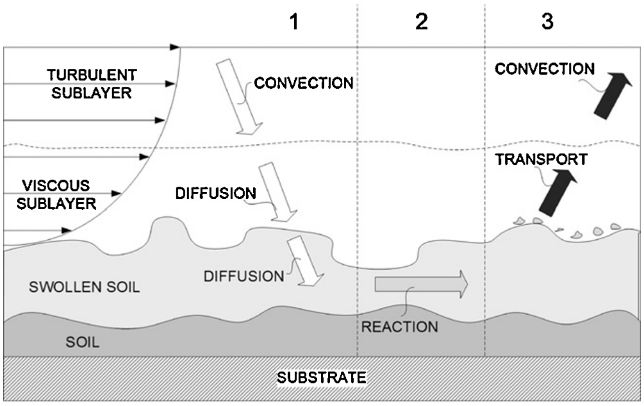

Fig. 1 – Mass transfer processes in the near-wall region during CIP.
Reproduced with permission from Schöler et al. (2012).

detection (LPD; Schöler et al., 2009) and fluid dynamic gauging (sFDG; Gordon et al., 2010).

The objectives of this work are to:

i. Discuss, compare and contrast the LPD and sFDG techniques within the context of industrial CIP research.
ii. Illustrate this comparison by conducting a brief study into the cleaning of starch-based layers from stainless steel substrates. This study will investigate the influence of soil topography on cleaning, using both the LPD and sFDG techniques.

The LPD technique measures the amount of soil on a surface by periodic illumination of a phosphorescent tracer (Schöler et al., 2009). In the experiments reported here, LPD is used to map the distribution and quantify the cleaning of starch-based deposits in a pilot-scale CIP apparatus in situ and in real time. The soil is modified by the inclusion of tracer particles, which are also used to impart surface roughness. The FDG technique measures the thickness of soft soil layers immersed in liquid by sucking liquid into a nozzle placed close to, but not touching the soil (Gordon et al., 2010). The sFDG technique employs a mobile gauging nozzle that can make local measurements of soil thickness and strength at several locations. Soil 'strength' here is a measure of how the soil responds to a shear stress imposed on it by the cleaning liquid: this is calculated from an analytical result, supported by computational fluid dynamics (CFD) simulations (Chew et al., 2004). FDG does not require modification of the deposit, but thickness measurements do require the deposit to retain its shape during the 5–10 s test duration.

Fig. 1 shows a cross-section through a pipe wall during CIP, reproduced from Schöler et al. (2012). In general, either transport to (process #1), reaction within (#2) or transport from (#3) the soil can control the rate of removal during CIP. Which of these processes controls removal depends strongly on the nature of the soil and substrate, as well as on the chemical, thermal and mechanical conditions. Schöler et al. (2012) showed that, for similar starch-based layers to those employed in the current work, process #3 controls the rate of material removal.