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A NOVEL QUANTITATIVE EVALUATION METHOD FOR CLEANING PROCESSES ON OPEN SURFACES INDEPENDENT OF SOIL LAYER THICKNESS

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ABSTRACT

The use of optical systems is an approach to monitor the cleaning progress. But so far a constant thickness of the soil layer is a precondition for quantitative evaluation of cleaning effects. Our results give rise to the hypothesis that a constant soil thickness is not necessary, since the thickness might be calculated from the measured light intensity.

In a first experiment test coupons were soiled with a starch layer of varying thickness in order to calibrate the fluorescence intensity. The measured cleaning curves were fitted with a mathematical model which resulted in a linear dependency to the mass of soil. With these relations it was possible to determine cleaning effects in a second experiment with sufficient accuracy. A good 1:1 relation between the cleaning rates determined by weighed mass and by fluorescence intensity was found. Therefore a new approach is presented in this paper, which enables quantitative measurements without the prerequisite of constant thickness of soil layers.

INTRODUCTION

Regular and effective cleaning of food processing machines is essential to guarantee high food quality. In cleaning tests the potential of different optimization approaches to reduce the cleaning efforts can be assessed. These cleaning experiments are based on the ability to quantify the amount of soil on the test surfaces with sufficient accuracy. Furthermore the ability to monitor the cleaning process is a precondition to compare cleaning effects. The use of optical methods to identify soils on surfaces is a common technique (Whitehead, 2008; Withers, 1996). Additional research has been done to monitor the cleaning progress with the aid of purely optical methods (Augustin, 2010; Mauermann, 2010; Schöler, 2009). These optical methods have the advantage of avoiding an influence of the measuring system during cleaning and are also able to capture the cleaning kinetics.

The present methods are utilized on simplified geometric test shapes with great efforts to apply a defined soil thickness for each test. In these cases the comparison of different cleaning effects is based on the assumption that the applied soil mass is equal for each test. Inaccuracies during the soiling process may lead to variations in the cleaning results. Soiling complex shapes with a constant soil thickness all over the sample seems to be ineffective due to the efforts that have to be made.

To adapt optical methods to monitor the cleaning progress on complex shapes a method which considers variations in soiling is required. Studies have revealed that the phosphorescence and fluorescence intensity could be used to measure film thicknesses (Haugland, 1999; Tibiriçá, 2009; Hidrovo, 2001). The intensity could be used to calculate spatial resolved the initial soil thickness. In a further step the spatial resolved cleaning progress could be adjusted by the obtained thicknesses. In that way quantitative measurements on complex shapes should be possible.

A first approach to achieve this purpose is described in this paper. The objective of this work is to show that with the main cleaning rate (Bode, 2005; Schlüssler, 1970) the cleaning characteristic of the test soil starch can be described. Furthermore we want to show that by means of the relation between fluorescence intensity and soil mass the main cleaning rate can be calculated from the fluorescence intensity. For this purpose we conducted two experiments. From the first the relation between fluorescence intensity and soil mass was derived. With the given relation we calculated from the fluorescence intensity the main cleaning rates in a second experiment. In this experiment we studied the influence of the water pressure on cleaning, since this dependency is described in literature (Buchwald, 1973; Leu, 1998). So it was possible to crosscheck our results. The optically obtained cleaning rates were compared with the cleaning rates calculated from the initial soil mass to show the applicability of this method.

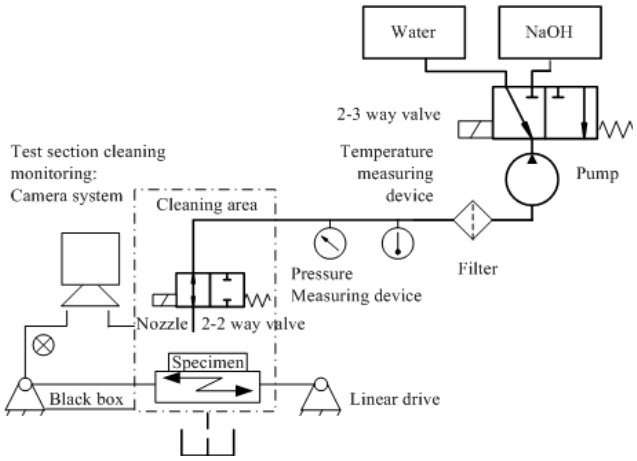

Fig. 1 Cleaning test rig with cleaning monitoring system

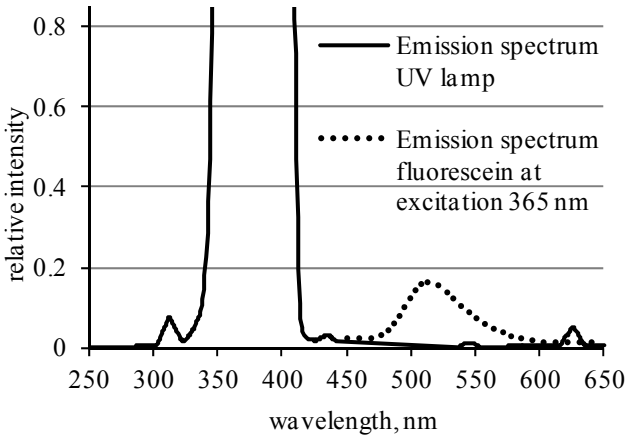

Fig. 2 Emission spectra of the UV lamp and the tracer

EXPERIMENTAL TECHNIQUES

Preparation of soil

The food model soil was potato starch (Cargill Deutschland GmbH, Krefeld, Type 30002) mixed with 0.012% (w/v) fluorescein sodium (C.I. 45350) as optical tracer. The emission spectrum of the tracer at an excitation of 365 nm is shown in Fig. 2. The starch (7% w/v) was dissolved in distilled water (10^{-3} mol/l KCl) and cooked at 90 °C for 30 min, while steering it simultaneously as described in Mauermann (2011).

Soiling

Test coupons (40 x 20 x 1 mm, AISI 316L 2B, electro polished, arithmetic mean surface roughness $S_a = 0.266$ µm) were coated with soil by using an apparatus described in Mauermann (2011). For applying different amounts of soil the soiling layer thickness is adjusted by a coating gap between coupon surface and wiper. The gap was gradually adjusted from 50 to 200 µm. The applied mass of soil is linear to the gap.

After coating, the test coupons were stored at 23 °C, 50% relative humidity for 24 hours. The applied soil mass was determined by differential weighing of the test coupons before soiling and after drying. The initial surface mass m_0 of soil is achieved by dividing the mass by the surface area 8 cm².

Cleaning test rig

For cleaning and detection the cleaning test rig shown in Fig. 1 and described in Mauermann (2010) was used. A single test coupon driven by a linear drive (31.5 cm/s) passes the 90° flat-fan nozzle periodically (Lechler GmbH, Metzingen, Type 660.446) at a distance of 200 mm and enters the black box. Inside the black box is an UV lamp (Philips Deutschland GmbH, Hamburg, Type PL-S 9 W/2P BLB) for excitation of the soil.

The spectral emission intensity of the lamp is shown in Fig. 2 as measured with Hitachi F-4500 FL Fluorescence Spectrophotometer (Hitachi High-Technologies Corporation). After every cleaning cycle the surface of the test coupon is captured by a digital camera (Konica Minolta Dimage A2) with fixed adjustments for exposure time and aperture (2 s, F8, ISO 100). Only during the initial cycle (cleaning cycle no. zero) the nozzle valve is closed and the soiled surface is captured under dry conditions. On the return path the valve is always closed. The duration of a cleaning cycle is 16 s. To assure that all starch is removed after the visual end of the cleaning process, four more cleaning cycles are conducted. The pressure can be adjusted up to 7 bar. Pressure and temperature of the cleaning fluid (sodium hydroxide 0.5% (w/w), 28 ± 2 °C) are measured in-line while cleaning.

Data analysis

The determination of the residual soil during cleaning is based on an optical method which determines the fluorescent intensity of the tracer in the soil. All acquired pictures of the cleaning test were analyzed by a computer program, written with MATLAB®.

The captured pictures were cut to the size of the test coupons, converted to grey using the MATLAB® command *rgb2gray* and scaled from 0...255 to 0...1. The mean grey-value on the overall picture is an indication of the amount of residual soil. Resulting from unavoidable diffuse reflections, the grey-value of a complete clean coupon is unequal to zero, but constant for a specific surface roughness. The initial grey-value varies from the applied amount of soil (Fig. 4). For determining the cleaning characteristics the Weibull model (Eq. (1)) proposed by Dürr (1999) is used.

$$r(x) = e^{-\left(\frac{x}{t_c}\right)^{r_c}} \qquad (1)$$

This model requires a cleaning progress from 1 (completely soiled) to 0 (completely cleaned). Due to that all grey-values (except for the dry one from cleaning cycle no. zero) of the test coupons were normalized using the following equation:

$$r(x) = \frac{(grey\text{–}value)_{image\_x} - MIN(grey\text{–}value)_{images(x>0)}}{MAX(grey\text{–}value)_{images(x>0)} - MIN(grey\text{–}value)_{images(x>0)}} \quad (2)$$

The maximum grey-value refers to the wetted coupon from cycle one. Preliminary examinations have been made to determine the influence of the first cleaning cycle on the grey-value. The mean value for reduction of the grey-value after the first cleaning cycle was 19% with a confidence interval of 1.27% (n=32, z=8). We also made preliminary examinations where we excluded significant differences in the grey-values (after the first wetting) between the wetting by the spray nozzle (cleaning) and by soft immersing of the coupons in a beaker of 0.5% sodium hydroxide. Hence the normalization beginning with cycle one is suitable and leads to a better fitting of the Weibull model.

At the end of a cleaning test the grey-value approaches a final value. This final value equates with the minimum in the picture series. A non soiled coupon and a completely cleaned coupon are resulting with sufficient accuracy in the same grey-value.

The normalized grey-values from Eq. (2) were plotted against the number of cleaning cycles to achieve a cleaning curve. The curve is fitted in MATLAB® with the function *nlinfit* to the Weibull model, returning parameters t_c and r_c.

A main cleaning rate $\overline{R}_{95}$ is calculated by Eq. (3), defined as removed amount of soil per time.

$$\overline{R}_{95} = \frac{0.95 \cdot m_0}{x_{95}} \quad (3)$$

This main cleaning rate $\overline{R}_{95}$ represents an average cleaning speed from 100% to 5% residual soil. Accordingly the removed soil is 95% of the initial surface mass m_0. The parameter cleaning time x_{95} is the number of cleaning cycles which are necessary to remove 95% of the soil mass. It is calculated according to Eq. (4).

$$x_{95} = t_c(-\ln 0.05)^{\frac{1}{r_c}} \quad (4)$$

Test series 1 for calibration

26 test coupons were soiled with the following coating gaps: 50, 70, 100, 150 and 200 µm. After drying the coupons were cleaned with a pressure of 3 bar. For each coupon the surface mass (by weighing), the grey-value of the dry coupon and the cleaning time x_{95} were determined.

Test series 2 for validating the approach

16 test coupons were soiled with coating gaps of 100, 150 and 200 µm. The cleaning was performed with pressures of 1, 2, 3, 4 and 7 bar. For each pressure step 3 coupons (respectively one from each coating gap) were cleaned. For each coupon the surface mass (by weighing and by the calibrated fluorescence intensity), the grey-value of the dry coupon and the cleaning time x_{95} were determined.

RESULTS

Test series 1 for calibration

Figure 3 shows the surface mass versus cleaning time x_{95} of every single coupon of series 1. The measured surface mass m_0 varied from 0.2 to 1.3 mg/cm². The cleaning time depends linearly on the applied mass of soil. Derived from this relation a mass independent main cleaning rate $\overline{R}_{95}$ (the slope of the straight line in Fig. 3) is applicable.

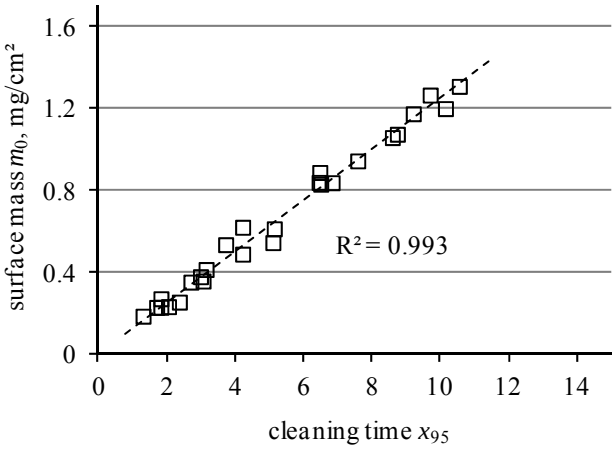

Fig. 3 Dependency of cleaning time and applied surface mass

In Fig. 4 the grey-values of all dry coupons (cleaning cycle no. zero) from test series 1 are plotted against the surface mass. The higher the amount of applied soil, the higher is the grey-value. Derived from the linear dependency of grey-values to surface masses from 0 to nearly 1 mg/cm² a constant of proportionality k is calculable. We determined k to 0.53 cm²/mg only by using the coupons of test series 1.

Test series 2 for validating the approach

The grey-values from test series 2 are also plotted in Fig. 4. They match with a good accuracy to these from test series 1.

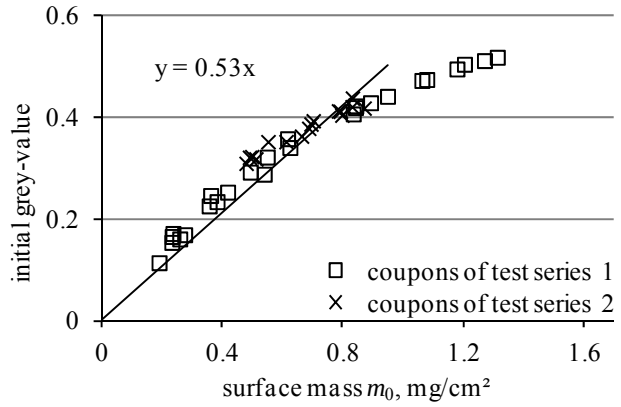

Fig. 4 Grey-values of all coupons versus surface mass

For validation, the reference main cleaning rates for the pressure varying experiments (test series 2) were determined by Eq. (3). The weighted mass of soil was used to calculate the amount of removed soil. Figure 5 presents the averages of these main cleaning rates plotted against the different pressures with standard deviations. An increasing pressure results in an increasing main cleaning rate.

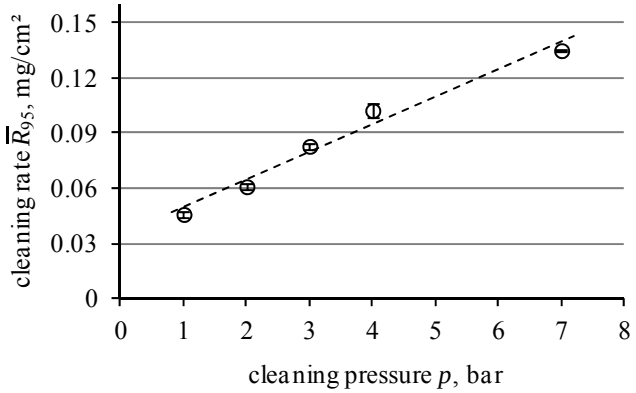

Fig. 5 Pressure dependency of the main cleaning rate by means of weighted mass

On the basis of the calibration from test series 1 we calculated a virtual surface mass from the grey-value for the pressure varying coupons of test series 2 by using Eq. (5).

$$\tilde{m}_0 = \frac{(grey-value)_{image\_0}}{k} \qquad (5)$$

Following, we used the virtual surface mass in Eq. (3) for calculating the main cleaning rates for the different pressures. The results presented in Fig. 6 (y-axis) show nearly a 1:1 characteristic of the pressure influence on the main cleaning rates as by the weighted mass (reference, x-axis).

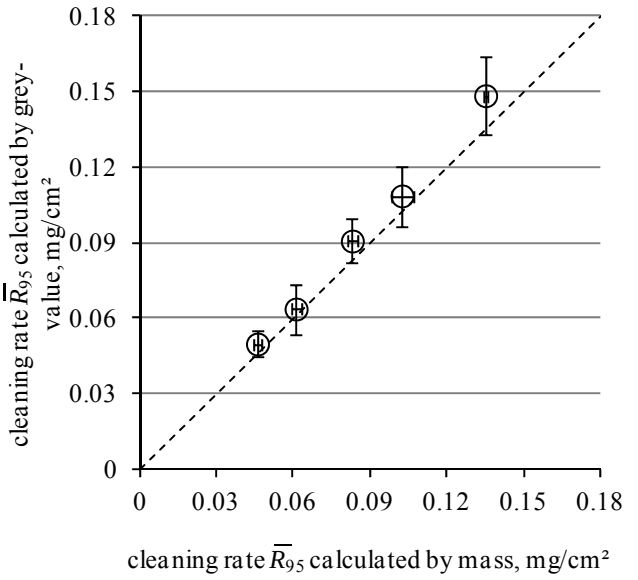

Fig. 6 Relationship between the main cleaning rates by means of weighted mass and grey-value

DISCUSSION

The main cleaning rate is a characteristic parameter for the type of soil and the cleaning parameters (Schlüssler, 1970). Equal cleaning parameters lead to the same main cleaning rate despite varying surface mass. Any significant variation from the main cleaning rate results from changes in cleaning parameters, assuming unvarying surface properties and an unvarying type of soil.

For applying the main cleaning rate to determine mass independent effects of cleaning parameters, the cleaning time should depend linear on the surface mass (Fig. 3). It might be assumed that the intersection at zero surface mass is zero. By knowing the surface mass it is easy to determine the main cleaning rate for each individual coupon and to measure the influence of the varied parameter.

Accordingly with the main cleaning rate it is possible to measure cleaning effects in a quantitative way independent from the applied amount of soil. In this paper we showed the applicability of this approach for our type of soil and the cleaning of open surfaces with water jets.

Figure 5 shows the quantitative pressure influence on the main cleaning rate very clearly. The increasing main cleaning rate indicates a faster cleaning due to the higher pressure. Our results of the improvement of the cleaning by increasing the water pressure are similar to those of other authors (Buchwald, 1973; Leu, 1998).

Figure 4 shows two ranges. In the first one from 0 to nearly 1 mg/cm² a linear dependency is adoptable. In the second range, greater than 1 mg/cm², the saturation of the CCD-Chip of the camera will be achieved. The maximum grey-value in our case is approximately 0.55 by extrapolating the data to higher surface masses. We explain the differing of the grey-value from the maximum value 1 by the weighted averaging MATLAB® function *rgb2gray*.

The used tracer has an emission maximum at 513 nm (Fig. 2), which corresponds to green. In our case the green pixels are saturated, while the red and blue ones are not, leading to a grey-value smaller than one.

Nevertheless, it is also possible to find a mathematical model (e.g. polynomial) which describes the relation between surface mass and intensity in a quantitative way beyond the linear region too.

In our case we used a simple linear regression with an intersection equal to zero for the coupons of series 1. The relation of the grey-value to the surface mass depends strongly on the used illuminating and capturing system. The equipment we used in this work is very simple and can be still improved. For that reason the numerical value of k is only valid for our test series. With this correlation we were able to determine a virtual surface mass from the grey-value without weighing.

The main cleaning rates in Figure 5 show small deviations from the 1:1 correlation. The use of the measured grey-value for determining a virtual surface mass leads to the same results for the pressure influence of the main cleaning rate as by the weighted surface mass. This indicates that the novel method is applicable.

The variations for the main cleaning rates by grey-value are higher due to the uncertainties of determining the virtual surface weight.

CONCLUSIONS

1. Due to the cleaning characteristic of the test soil starch it is possible to determine cleaning effects by means of the main cleaning rate. With the main cleaning rate it is possible to determine cleaning effects in a quantitative way independent from the applied surface mass for cleaning of open surfaces with water jets.
2. We conclude that with a calibration it might be possible to determine the main cleaning rate and furthermore the cleaning effects in a purely optical way.
3. The usability of this optical method depends on some preconditions. First of all the main cleaning rate of the tested soil has to be independent from soil mass. This has to be tested for every test soil by measuring the cleaning time over a wide range of soil mass. Secondly the capturing system should be calibrated so that from the measured emission intensity the surface mass can be determined.
4. For applying the method on complex shapes a spatial analysis with an adequate regional resolution of the intensity is necessary.

In this paper we have shown the applicability of the method on small test coupons with a simple calibrated capturing system. Further research will be done to develop a better calibrated capturing system to measure higher surface masses directly from the intensity.

Additionally we will test the method on complex shapes, also to examine possible problems with irregular illumination.

NOMENCLATURE

k	constant of proportionality between surface mass and grey value, cm²/mg
m_0	initial surface soil mass, mg/cm²
n	number of samples, dimensionless
p	cleaning pressure, bar
r	remaining soil, dimensionless
r_c	slope of the cleaning characteristic, dimensionless
$\overline{R}$	main cleaning rate, mg/cm²
R^2	coefficient of determination, dimensionless
S_a	3D arithmetic mean roughness (ISO 4287), µm
t_c	typical cleaning time constant, dimensionless
x	cleaning cycles, dimensionless
x_{95}	number of cleaning cycles to remove 95% of soil, dimensionless
z	number of experiments, dimensionless

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