INTRODUCTION

Biofilms are considered as complex microbial structures containing mainly microorganisms, nucleic acids, proteins and extracellular polymeric substances (EPS). The sheer stress caused by the fluid flow over fixed biofilms is a factor of paramount importance which influences their development, mass transfer and detachment and, hence, affecting the bioreactor operation. The aim of this study was to investigate extensively the rheological properties of heterotrophic biofilms present in bioreactors, by performing tests and models development. The flow effect characterization on biofilms was performed under steady shear, oscillatory and transient measurements. Suspended biomass (SB) samples were also analyzed to complete the study, comparing their rheological behavior with that obtained from the biofilms.

EXPERIMENTAL SET-UP

Samples of various concentrations from aerobic heterotrophic biofilms of a flat plate bioreactor and suspended biomass from the same heterotrophic inoculum were analyzed.

Rheological tests were performed in a Bohlin CVO 120 HR rheometer using a cone-plate geometry and a solvent trap to avoid evaporation. The experimental assays were carried out in three different shear modes:

- Steady
- Oscillatory
- Transient

Steady shear flow model: The Herschel-Bulkley model (HBM) was adopted to characterize the behavior of biofilm and suspended biomass samples. The shear stress ($\tau$) and the viscosity ($\eta$) are described as (Mezger, 2006):

$$\tau = \eta \cdot \gamma \cdot \left( \frac{\gamma}{\gamma_0} \right)^{n-1}$$

$$\eta = \eta_\infty + \eta_0 \cdot \left( \frac{\gamma}{\gamma_0} \right)^{n}$$

where $\gamma$ is the shear stress (Pa), $K$ is the fluid consistency index (Pa s), $n$ is the flow behavior index (-), $\eta_\infty$ is the viscosity (Pa s) at high shear rate and $\eta_0$ is the viscosity (Pa s) at zero shear rate.

Oscillatory shear test:

- Steady amplitude sweep: Stepwise increasing stress (10 to 20 Pa, $\omega = 1$ Hz)
- Frequency sweep: Increasing frequency (0.01 to 10 Hz, 1% strain)

Transient shear test:

- Creep test: Constant shear stress (12 to 40 Pa during 180 s)
- Deformation

RESULTS AND DISCUSSION

Firstly, in the steady shear flow measurements, the deformation under a shear stressing flow was measured, recording the shear rate to obtain the basic flow behavior of the biofilm and suspended biomass (SB) samples, and characterizing the viscous and viscoelastic properties in detail. Secondly, dynamic strain-sweep measurements were performed to determine the linear viscoelastic regimen (LVR) and to examine the microstructure of biological samples. Finally, the time-dependent nature of the samples in the linear region was proved performing the creep and recovery tests at various shear stresses.

RHEOLOGICAL CHARACTERIZATION IN THE STEADY SHEAR FLOW

Two biofilm samples at different concentrations (X) were analyzed, exhibiting both similar behavior:

- Being shear-thinning fluids with yield stress, (characteristic of gel-like structures).
- The estimated HBM parameters revealed an influence of the biofilm concentration in the rheological behavior.

A comparison of the rheological properties between biofilms and SB was performed, since both biological samples are of analogous nature. Biofilm and SB samples with very similar VSS concentration (34.5 and 34.9 g L$^{-1}$ respectively) were contrasted:

$$\tau = \eta \cdot \gamma \cdot \left( \frac{\gamma}{\gamma_0} \right)^{n-1}$$

$$\eta = \eta_\infty + \eta_0 \cdot \left( \frac{\gamma}{\gamma_0} \right)^{n}$$

where $\gamma$ is the shear stress (Pa), $K$ is the fluid consistency index (Pa s), $n$ is the flow behavior index (-), $\eta_\infty$ is the viscosity (Pa s) at high shear rate and $\eta_0$ is the viscosity (Pa s) at zero shear rate.

RHEOLOGICAL CHARACTERIZATION IN THE OSCILLATORY SHEAR FLOW

The elastic behavior dominated the viscous one inside the LVR for both samples, showing their gel character, which agrees with other authors who studied mechanism and structure of biofilms (Wilking et al., 2011). Also, both samples had very close LVR limit values.

$$\tau = \eta \cdot \gamma \cdot \left( \frac{\gamma}{\gamma_0} \right)^{n-1}$$

$$\eta = \eta_\infty + \eta_0 \cdot \left( \frac{\gamma}{\gamma_0} \right)^{n}$$

where $\gamma$ is the shear stress (Pa), $K$ is the fluid consistency index (Pa s), $n$ is the flow behavior index (-), $\eta_\infty$ is the viscosity (Pa s) at high shear rate and $\eta_0$ is the viscosity (Pa s) at zero shear rate.

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RHEOLOGICAL CHARACTERIZATION IN THE TRANSIENT SHEAR FLOW

This time-dependent strain response undoubtedly pointed out that both samples presented viscoelastic fluid behavior, as reported in previous works of biofilms (Towler et al., 2003).

- Biofilm exhibited higher strain than SB for all tested shear stress. It is also observed in the parameters of Burger model:

$$\tau = \eta \cdot \gamma \cdot \left( \frac{\gamma}{\gamma_0} \right)^{n-1}$$

$$\eta = \eta_\infty + \eta_0 \cdot \left( \frac{\gamma}{\gamma_0} \right)^{n}$$

- Biofilm samples behaved differently than SB samples, showing a transient behavior.

CONCLUSIONS

The viscous and viscoelastic properties of biofilms and suspended biomass were investigated via rheological analyses under steady, oscillatory and transient shear flow. With this complete rheological characterization, models for the description of the biofilm as a pseudo-plastic fluid as well as a viscoelastic material were developed, allowing to define the biofilm as an independent fluid phase, which can be readily implemented coupled fluid dynamics codes. In addition, the findings suggest that the suspended biomass could be used for the characterization of the biofilms viscosity and flow curves, due to its feasibility to obtain the samples. For strain modeling, biofilm samples will be needed to accurately reproduce their transient behavior, since the important role of the EPS during the deformation was proven.

REFERENCES


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