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Flow following sensor particles—Validation and macro-mixing analysis in a stirred fermentation vessel with a highly viscous substrate

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ABSTRACT

A group of flow following sensor particles was validated under real flow conditions in a highly viscous substrate in a 1000 L model fermenter vessel, equipped with a pitched blade impeller, which was operated at two different axial positions in an intermittent mixing regime. The neutrally buoyant sensor particles track basic hydrodynamic and process parameters, namely hydrostatic pressure (giving the axial position), temperature and acceleration. The sensors are connected to a measurement electronics, which is enclosed in a robust capsule that can resist the harsh conditions in an industrial mixing process. The results show that the sensor particles still reflect the flow conditions in the vessel qualitatively. Moreover, the sensor particle data allow estimation of macro-mixing parameters, such as circulation time distributions and average circulation times.

1. Introduction

Advanced monitoring of the spatio-temporal distribution of process parameters in large-scale vessels and containers such as storage tanks as well as stirred chemical or bioreactors offers a high potential for the investigation and further optimization of plants and embedded processes. This applies especially to stirred bioreactors and more specifically to large-scale fermentation biogas reactors, where the process performance including the biological processes highly depends on mixing parameters of the complex bio-substrates [1]. Thus, beyond investigation of biochemical parameters, such as the fermentation rate, pH distribution as well as O_2 and CO_2 concentration, also understanding of non-biological parameters, such as fluid dynamics (flow velocity profiles, circulation times, energy dissipation), suspension mixing (homogeneity, location of dead zones and short-circuits) and heat transfer (temperature profiles), is necessary to analyze the impact of mixing on the biological system. Moreover, this enables evaluation of the efficiency of the mixing and heating regimes. However, in most industrial scale applications the acquisition of these parameters and their spatial distributions in the large-scale vessels is hampered by the limited access to the process itself, because sensor mounting or cable connections are not feasible or desired. Therefore, state of the art instrumentation of such reactors is commonly limited to few spatial positions where it is doubtfully assumed that the measured parameters are representative for the whole reaction mixture.

Typical available single point flow measurement techniques (hot-wire anemometry, pitot tubes, LDA, LDV and ultrasound doppler velocimetry) as well as spatially resolving measurement techniques (videometry, thermography, PIV, LIF and tomography techniques) [2] are in most cases not applicable to industrial size processes, due to the size of industrial reactor vessels and the opacity of the fluids and vessel walls. Another technique that has been used in larger vessels up to 20 m^3 is movement tracking of discrete macroscopic particles or flow followers. With such sensors it is possible to get flow pattern information from ensemble measurements [2]. The flow followers usually have one distinct property that is used to detect the particle and extract the flow property from the particle trace, such as color (video tracking) [3], an emitted radiofrequency [4–6], magnetic permeability [7] or radioactivity (CARPT,

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Nomenclature

D,d_1	vessel diameter, m
d_2	impeller diameter, m
d_p	particle diameter
d_*	dimensionless particle diameter
f_{acq}	acquisition rate of the sensor particle electronics, Hz
g	gravitational acceleration, 9.81 m s^{-1}
h	immersion depth, m
H_0	filling level in the fermenter vessel, m
h_{2m}	axial impeller position at half blade height, m
n	rotational rate of the impeller, s^{-1}
r	radial coordinate in the vessel, m
Re, Re$_p$	Reynolds number, particle Reynolds number
St	Stokes number
T	temperature, °C
u_t	terminal settling velocity
u_*	dimensionless terminal settling velocity
DM	dry matter, %
z	axial coordinate in the vessel, m
$\dot{\gamma}$	shear rate, s^{-1}
μ	fluid dynamic viscosity, mPa s
μ_0	fluid dynamic viscosity during the particle settling process, mPa s
μ_{eff}	effective fluid dynamic viscosity in the vessel, mPa s
ρ_f	mean fluid density, kg m^{-3}
ρ_p	sensor particle density, kg m^{-3}
ψ	particle sphericity

Abbreviations

ADC	analog to digital converter
CARPT	computer automated radioactive particle tracking
CFD	computational fluid dynamics
DC-DC	direct current (DC) voltage converter
ERT	electrical resistance tomography
FRAM	ferroelectric random access memory
I^{2}C	inter-integrated circuit (serial data bus)
LDA	laser doppler anemometry
LDV	laser doppler velocimetry
LIF	laser induced fluorescense
ORP	oxidation reduction potential
PEPT	positron emission particle tracking
PIV	particle image velocimetry
USB	universal serial bus (serial data bus system)

PEPT) [8,9]. However, the application of these techniques is limited to model fluids, which enable optical camera operation or transmission of radio signals. On the other hand, tracking equipment such as aerials, magnetic detectors and radioactivity detectors have to be replaced at different positions to capture the whole reactor volume, which is seldom feasible in industrial applications, due to heavy, compact constructions and large dimensions of the vessels. In conclusion, there is a need for advanced and distributed measurement techniques for investigation and monitoring of industrial processes, also expressed in [10].

Autonomous sensor technologies enable the metrological acquisition of spatially distributed parameters by means of intelligent instrumented flow followers with potential application in industrial vessels. Autonomous sensor concepts and remote sensing gained increasing attention in recent years, since the ongoing miniaturization of sensors and the increasing capability of highly integrated circuits have enabled the design of multi-parameter systems for the acquisition, storage and communication of physical, chemical or biological process parameters that can be combined in a small-scale and compact system design [11].

However, only some approaches for industrial applications and harsh environments have been published yet. An autonomous sensor network specified to monitor grain storage in hoppers or silos by using radio frequency channels was introduced in [10]. Further work towards development of ad-hoc sensor networking, 3D localization and process monitoring of instrumented flow followers in industrial environments is presented in [12] and [13]. Rather passively tracking sensor concepts without embedded communication and swarm capabilities, namely ‘Smart’ sphere and a sensor fish, have been proposed in [14–16]. The ‘Smart’ sphere is a wire independent temperature and pressure measuring particle that has been tested at lab-scale in chemically non-aggressive environments such as in a rotary drum mixer, a wind channel and a water column. The sensor fish is a robust and floatable autonomous sensor design for characterization of physical stresses that fishes have to suffer during passage of complex hydraulic environments, such as dams and turbines.

Nevertheless, neither the acquisition of spatially distributed parameters in the fluid flows of large-scale industrial processes nor the evaluation of the hydrodynamics of the process from the measured data has been addressed in the field of autonomous sensor systems, since the first radio pill experiments [4–6].

A group of self-powered and neutrally buoyant sensor particles has been developed for the long-term measurement of spatially distributed process parameters in the chemically and mechanically harsh environments of agitated industrial vessels. The autonomous sensor concept is based on a first prototype that was successfully tested under flow conditions in a stirred vessel of Newtonian liquid, namely water (for more information we refer to [17]). Each sensor particle comprises of an onboard measurement electronics that logs the signals of measurement devices, namely temperature, absolute pressure (immersion depth, axial position) and 3D acceleration. The whole electronics is enclosed in a robust neutrally buoyant capsule. The design of the sensor particle was carried out under considerations of the Stokes number to allow sufficiently free movement with the fluid flow. One intended application is in a large-scale process such as a stirred fermentation biogas reactor, but generally the sensor particle is not limited to this type of process.

In this article, we present the first validation results of the sensor particles from experiments in real flow conditions of a highly viscous bio-substrate in a stirred 1000 L pilot fermenter vessel. Also the flow following behavior and its limitations are characterized and discussed, since the sensor particles can be assigned to the group of particle tracer technologies. Generally, the ability of particles to follow changes in the velocity field is characterized by the Stokes number. Therefore, the Stokes number of the sensor particles is estimated and compared to established particle tracer techniques such as LDA and PIV [2] as well as other techniques that also apply macroscopic particle tracers, namely radio pills [4–6].

The results show that the sensor particles follow the main circulation flows and thus reflect the flow conditions in the vessel qualitatively. Moreover, the macro-mixing of the process can be evaluated from the measured sensor particle data sets.

2. Sensor particle design and application

2.1. Sensor particle hardware

The system incorporates a group of autonomous sensor particles and a corresponding base station. The current design of the sensor particle is based on the first particle prototype, which is explicitly described in [17]. A block diagram of the system is shown in Fig. 1. Each sensor particle comprises of a robust and neutrally