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Scale-up of mixing processes of highly concentrated suspensions using electrical resistance tomography

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ABSTRACT

Qualification and quantification of mixing processes are crucial requirements for process engineering and energetic optimization in chemical and pharmaceutical industry as well as in wastewater treatment and biogas production. The analysis of mixing processes in stirred systems becomes a challenging task, especially when using opaque substrates. With Electrical Resistance Tomography (ERT), a powerful measuring technique is provided to allow a comprehensive and non-intrusive quantification of mixing processes of complex suspensions. Combined with advanced cross-correlation techniques, ERT offers the possibility to derive the axial flow velocity profile inside a stirred system. Investigations in different scales are an essential prerequisite regarding the evaluation and optimization of large-scale mixing processes under consideration of similarity laws. The experimental tests presented in this paper are carried out in reactor systems with volumes of 0.1 m^3 and 1 m^3. The validity of scale-up methodologies was ensured by comparable flow conditions and velocity distributions between the lab and pilot plant scale. For biogas plants, as an example of the importance of efficient mixing, the scale-up principles 'geometric similarity', 'constant impeller tip speed', 'similar viscosity and flow characteristics' as well as 'scale-up of particles and fibers of the dispersed phase' are proved to be valid by the Fraunhofer Institute for Ceramic Technologies and Systems (IKTS). Within the scope of further investigations, reliable information related with Computational Fluid Dynamics (CFD) are ought to be derived for the continuing evaluation of mixing processes at any scale to establish a foundation for the dimensioning and operation of stirring systems, especially for highly concentrated, non-Newtonian fluids.

1. Introduction

Experimental investigations are an important prerequisite for an optimal dimensioning of stirring systems for opaque, fibrous and highly concentrated substances. Multiphase systems, like fermentation residues in biogas plants, consist of a non-Newtonian suspension with a dispersed phase, e.g. corn silage or wheat straw and a gaseous phase. Common measurement systems for the quantification of mixing processes, such as sensors and tracers, are often characterized by locally limited evaluation capabilities. Due to the lack of qualified models for the calculation and simulation of mixing processes featuring fibrous and highly concentrated substances, which are characterized by a distinct non-Newtonian flow behavior, CFD cannot be utilized as an appropriate basis for the dimensioning of stirring systems at the moment. The insufficient consideration of the granulometric parameters and the challenging determination of the rheological properties as well as the fact that CFD models, which are applied to simulate mixing processes of multiphase systems, are still not state-of-the-art [1,2], leads to incorrect interpretations especially regarding simulations of mixing processes of highly viscous, non-Newtonian and particle-loaded fluids. Therefore, reliable predictions concerning the dimensioning and operating of such mixing processes are not possible.

The main issue of one joint research project, in collaboration with our cooperation partners KSB AG and TU Berlin, is to show and develop functional relations between the substrate properties, the stirring parameters, the flow velocities, the mass transfer as well as the biogas yield as a foundation for the identification of optimum flow conditions for stirring systems used in biogas plants. Extensive

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Nomenclature

c_w	drag coefficient (dimensionless)
D	reactor diameter (m)
d	impeller diameter (m)
d_H	impeller diameter in the large scale version (m)
d_M	impeller diameter in the small scale version (m)
d_P	particle diameter (m)
$E(x)$	expected value (dimensionless)
f_s	sampling speed (s)
H	height of the reactor (m)
K	consistency index (Pa s^m)
k	sample length (dimensionless)
L	distance between two ERT sensor planes (m)
L_H	dimensions in the large scale version (m)
L_M	dimensions in the small scale version (m)
$M'_{1;3}$	first raw moment (m)
m	flow behavior index (m m^{-3})
m	number of current driven electrode pairs (dimensionless)
n	number of voltage measurement electrode pairs (dimensionless)
n_H	agitator speed in the large scale version (s^{-1})
n_M	agitator speed in the small scale version (s^{-1})
P_H	power requirement in the large scale version (W)
P_M	power requirement in the small scale version (W)
P_V	power per unit volume (W m^{-2})
$P(x, y)$	pixel P at the point (x,y) (dimensionless)
r	reactor radius (m)
Re_P	particle Reynolds number (dimensionless)
Re_R	impeller Reynolds number (dimensionless)
$S_{m,n,x,y}$	sensitivity coefficient (dimensionless)
τ	time delay (s)
$V_{(m,n)}$	voltage (V)
u	impeller tip speed (m s^{-1})
u_H	impeller tip speed in the large scale version (m s^{-1})
u_M	impeller tip speed in the small scale version (m s^{-1})
V	reactor volume (m^3)
V_H	reactor volume in the large scale version (m^3)
V_M	reactor volume in the small scale version (m^3)
v	velocity (m s^{-1})
v_H	velocity in the large scale version (m s^{-1})
v_M	velocity in the small scale version (m s^{-1})
x	arithmetic mean value (m)
$x_{m;3}$	volume-weighted particle size (m)
$\dot{\gamma}$	shear rate (s^{-1})
η	dynamic viscosity (Pa s)
μ	scale-up factor of geometric similarity (-)
ρ_l	liquid density (kg m^{-3})
σ	electrical conductivity (S m^{-1})
$\sigma_{P(x,y)}$	electrical conductivity of the pixel P(x,y) (S m^{-1})

Acronyms

CFD	Computational Fluid Dynamics
ERT	Electrical Resistance Tomography
LBP	Linear Back Projection
MSBP	Modified Sensitivity Back Projection
PIV	Particle Image Velocimetry
RNG	Re-Normalization Group
SNR	Signal-To-Noise Ratio

experimental investigations using ERT at Fraunhofer IKTS, are used to qualify and quantify mixing and fluid flow processes. An essential requirement for the applicability of the results is the scale-up of industrial mixing processes to laboratory or pilot plant scale by using validated scale-up principles. The aim of the scale-up of mixing processes in biogas plants is the indemnification of comparable velocity distributions in the small scale (M) and large scale (H) versions of the process vessel of interest.

A basic prerequisite for the scale-up of industrial processes is given by the similarities between the small scale and the large scale version. Using geometric, kinematic and dynamic similarity for scale-up of tumbling mixers were first proposed by Wang and Fan in 1978 [3]. The geometric similarity involves keeping all dimensions of the reactor as well as the dimensions of the stirring system in a fixed ratio, the so-called scale-up factor μ or M_L (Eq. (1))

$$M_L=\frac{L_H}{L_M}=\mu=const. \tag{1}$$

where L_H is the dimension in the large scale version of the reactor and L_M is the dimension of the small scale version of the reactor.

Furthermore, it is necessary that there is a similarity of the flow field between the reactors in the different scales (kinematic similarity). That means that the time intervals, in which particles cover geometrically similar distances, are in a constant ratio.

The scale-up criteria, which are relevant for mixing processes, are summarized in the so-called Penney-Chart [4–6]. It represents the ratio of specific power requirement of the large scale and the small scale version of the process vessel as a function of the cubic scale-up factor for different scale-up criteria (Fig. 1).

The criterion of a constant power per unit volume P_V of the stirring systems in different scales, has been the basis for the transfer of operating parameters from small scale (M) to large scale (H) over the last decades (Eq. (2))

$$P_V=\frac{P_M}{V_M}=\frac{P_H}{V_H}=const. \tag{2}$$

where the ratio P_M/V_M *and* pH/V_H is the power input per volume of the small scale vessel and of the large scale vessel respectively. This scale-up criterion is used extensively for agitated vessels as the power estimation is simple and accurate. But the usage of this criterion gives only a poor approximation to the mixing quality and it is incapable of correlating the different local conditions within the reactor [7].

According to ZAUNER [8], scale-up of crystallization, precipitation and mixing-controlled processes with a constant specific power input leads to a different flow pattern and therefore different mesomixing and macromixing in the reactor. Experimental tests at Fraunhofer IKTS showed that the transfer of a constant power per unit volume of the stirrer from lab-scale to industrial scale leads to an enormous power consumption of the stirring system. The application of the

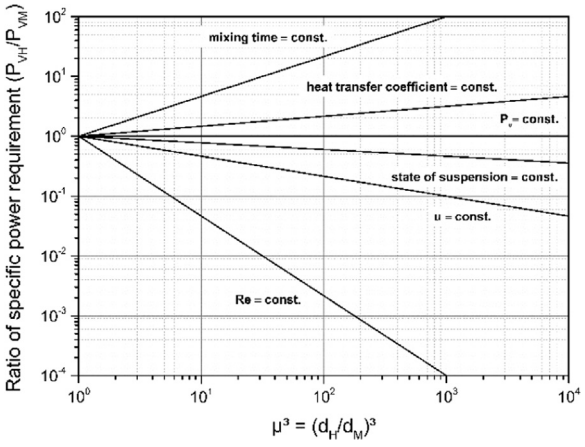

Fig. 1. Penney-Chart (in the style of HOUSON [4]).