

Article

Experimental and Mathematical Investigation of Anaerobic Granulate Density via Settling Velocity

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Abstract: The objective of this study was to determine the density of anaerobic granules on different heights of a full-scale Upflow Anaerobic Sludge Bed reactor. The density was defined through the settling velocities of anaerobic granules, measured in a full-scale Upflow Anaerobic Sludge Bed reactor. In this study, granular density was calculated with the measured settling velocities and developed mathematical model. The developed mathematical model is based on the Stokes model. In the experiment, granules were taken from different heights of an Upflow Anaerobic Sludge Bed reactor, from 0.6 to 7.6 m. The granules' diameters varied between 1 and 5 mm. The granules were taken from six different heights through the reactor. The settling velocity of the active granules (with gas in the granule pore and on the surface of the granule) was measured first. After the active granules' settling velocity measurement, the granules were placed in a vortex to obtain degassed granules (granules without any gas in the pores or on the surface), for which the settling velocities were also measured later. It is shown that granules' densities at different heights are independent of the reactor height.

Keywords: Upflow Anaerobic Sludge Bed reactor; anaerobic granular sludge; settling velocity; density



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1. Introduction

Industrial wastewater treatment is becoming more important every day [1–3]. The Upflow Anaerobic Sludge Bed (UASB) reactor is currently the most common reactor for treatment of industrial wastewaters [4]. The investigation of the density of anaerobic granules via settling velocity is presented in this paper. For optimal operation of UASB reactors a strong and active granular sludge bed is very important [5]. For optimal operation of a UASB reactor a well-developed granular sludge with high physical strength and settling velocity is necessary [6]. The advantages of anaerobic granular sludge are its high physical strength, resistance to shocks and toxins, and high liquid flows due to high settling velocity [7]. Through the height of a reactor the concentration of granules varies, and can usually be divided into three zones: (1) a dense sludge bed consisting of biomass aggregates in the bottom section of the reactor; (2) a sludge blanket containing finely suspended flocs or aggregates in the middle of the reactor; and (3) a zone of clarified water containing almost no solids on the top of reactor, as shown in Figure 1 [8].

Due to the high settling velocity of granules, a UASB reactor has the capacity for high liquid flows. One of the most important parameters in the initial granulation and development of granular sludge is the settling velocity [9,10]. The reported settling velocity of anaerobic granules is in the range of 18 to 100 m/h [11]. Anaerobic granules have good settling capability, which is very important for separating the solid and liquid states. Anaerobic granular sludge provides a high and stable rate of metabolism, and granules

have a long solid retention time in the reactor and the possibility of bio-augmentation. Polymeric extracellular matrix substances provide the granules with resistance to shocks and various toxins in the wastewater [7,9].

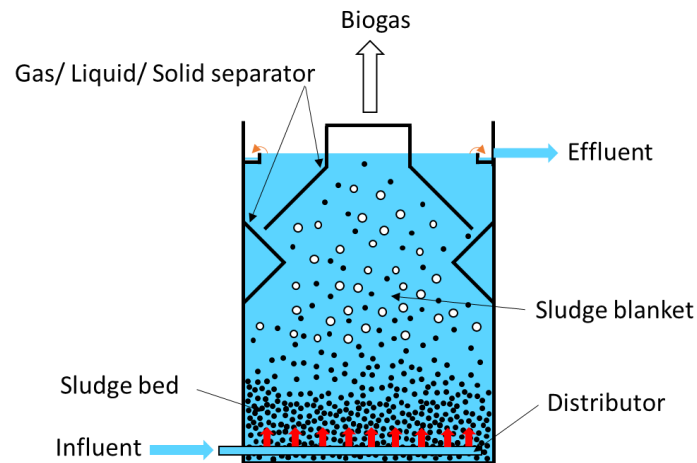


Figure 1. UASB reactor scheme.

The majority of previously published work suggested that the settling velocity of anaerobic granules is in line with Stokes' law, because the settling velocity is in the laminar flow range [12,13]. Some authors suggest that the Allen formula should be used, because the settling process falls in the intermediate flow range [9]. Researchers have shown a correlation between operational conditions (chemical oxygen demand, organic loading rate, superficial velocity) and granular size, and, consequently, with complete system performance [14]. Measuring the diameter of granules can be undertaken with different approaches, such as embedding granules in gelatine and scanning them with a scanner [15], or by stainless-steel sieves [12,13]. It is important to take into consideration the gas pockets that can often be observed in Scanning Electron Microscopy (SEM) images of granules, which makes granules less dense, and they can even float in water [16]. Some work has been undertaken on the characterisation of anaerobic granules, and on the determination of the density of granules [9,13,16–18]. Liu et al. [9] calculated a density of 1040 kg/m^3 for granules with diameters of 1.3 and 1.4 mm for activated sludge. The settling rates were determined by using a settling column filled with tap water, and were obtained by plotting the weight fraction of the sedimented sludge of the total weight of settled sludge, against the sedimented time. Batstone and Keller [18], measured the drained density of four types of wastewater. The drained density of granules used for treatment of effluent from a fruit and vegetable cannery was 1070 kg/m^3 , while granules used in breweries had drained densities of 1059 and 1056 kg/m^3 . Granules that treated protein-based wastewater had a drained density of 1042 kg/m^3 .

No research was found that examined granular density at different heights of a reactor. Because of this, in this study, the density of the granules was determined at six different heights of the reactor. Results show that the granules' density is a function of the granules' radius.

Calculating the granular density at different heights of the reactor has huge potential for later process development procedures, with the use of numerical models describing the hydrodynamics, thermodynamics, and chemical reactions in multiphase multispecies flow in a UASB reactor. Granular density is a very important input parameter in numerical simulation of multiphase multicomponent flow in a UASB reactor to optimise the UASB process or equipment geometry under different process conditions [19–21].

In this study, a mathematical model was developed for calculating the density of anaerobic granules derived from settling velocity. Granules' sedimentation is a direct consequence of granules' density. Granules' density is determined by the combination

of the density of microorganisms in the granule and the produced biogas bound on the granular surface and in its pores. Granules were taken from a full scale Biobed[®] UASB reactor (WTE Wassertechnik GmbH, Essen, Germany) with a volume of 750 m³, treating approx. 400,000 m³ of brewery wastewater annually. The developed model was able to calculate active and degassed granules' densities from their settling velocity. During this experiment, the settling velocity for activated and degassed granules was measured, and the density of activated and degassed granules was calculated (Figure 2). The density of the granules was determined at six different heights of the reactor and is expressed as a function of the granules' radius.

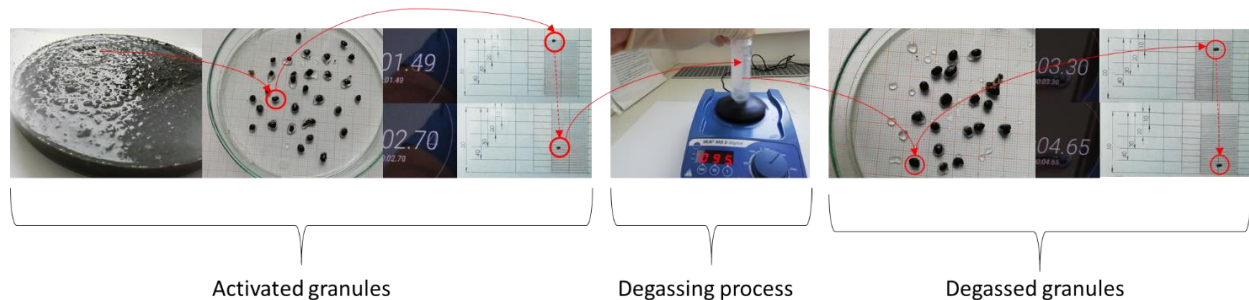


Figure 2. Methodology for activated and degassed granules' settling velocity measurement.

2. Experimental Analysis

2.1. Granule Sampling in a UASB Reactor

The experiment was conducted on a production scale Biobed[®] UASB reactor with a volume of 750 m³ under identical conditions. The parameters that were controlled were the shape and size of anaerobic granulated biomass. Four principal assumptions were made, similar to in the work conducted by Liu et al. (2006), in order to develop a mathematical model: (I) the granules are considered to be spheres; (II) the granular settling process is considered to be a free settling process; (III) are only two-phases of flow are in the reactor, consisting of wastewater (liquid) and granules (solid); and (IV) the granules are either full of biogas or full of water. The biomass samples were taken from sampling ports at six heights of the reactor between 0.6 and 7.6 m, and were transported in an insulated container to the laboratory (Figure 3). The results show differences between the densities of anaerobic granules at different heights of the reactor. Five litres of granulated biomass were taken from each height of a working reactor and then transported in an insulated container to the laboratory. Five minutes after sampling, the sludge was diluted with anaerobic water; then, the granules were separated and their diameters were measured individually.

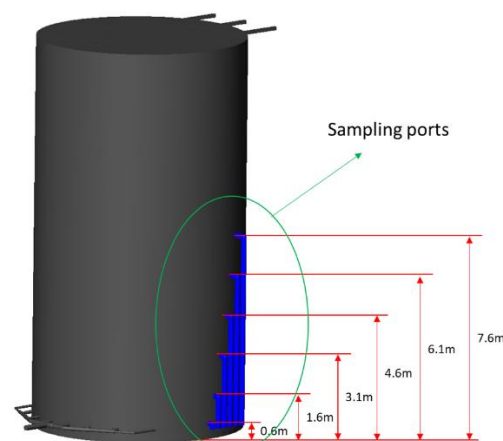


Figure 3. UASB reactor with sampling ports.

2.2. Settling Velocity Measurements

The experiment to determine biomass density was conducted with active and degassed biomass. The same granules were used in both steps of the experiment. The experiment was carried out in a glass tower ($330 \times 260 \times 60$ mm), filled with distilled water, and a Sony camera and computer with analysis software were used, as shown in Figure 4. The experiment was similar to that of Hriberšek et al. for aerobic floc [22], but was first used for anaerobic granules. The granules were dropped individually into the glass tower via a dosing device. Twenty granules were used from each reactor height. The camera shot granules at a depth of 240 mm, where the granules reached their terminal settling velocity. The images gathered with the camera were analysed to determine the settling velocity of each granule. The settling velocity of the active biomass was measured first. Then, the granules were placed in a centrifuge tube filled with anaerobic water, and then mixed with an IKA MS 3 digital vortex mixer for 15 s at 2000 rpm to remove all the produced biogas from the granular surface and pores. After this process, settling velocity was measured again, and was considered as the settling velocity of degassed anaerobic granules. The radius of the measured granules was between 0.5 and 2.5 mm. From the measured diameter and settling velocity, the density of the anaerobic granules was calculated with a derivation of the Stokes model.

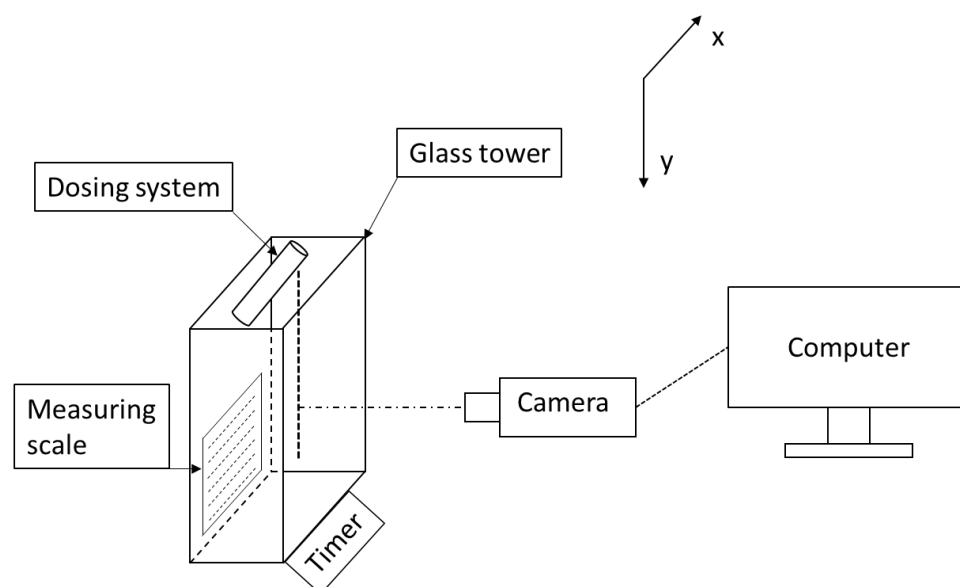


Figure 4. Experimental set-up for the velocity measurement.

Wastewater velocity through a UASB reactor in the Laško wastewater treatment plant was between 1.65 m/h with a water flow of $83 \text{ m}^3/\text{h}$ and 0.418 m/h with a water flow of $21 \text{ m}^3/\text{h}$.

The average settling velocity of active granules was 82.7 m/h, and the average settling velocity for degassed granules was 93.8 m/h.

3. Mathematical Model

Granular density was measured in previous works [9,13,16,18]. In this work, a mathematical model was developed for calculating the density of the granules. With this model it is possible to calculate the density of active granules, the density of degassed granules, and the density of solid granules (only granules without water in their pores). It is also possible to calculate the amount of biogas accumulated on granules and in granule pores. Modelling will allow us to calculate granular density on different predetermined heights of a reactor. The results will show if densities are different through the reactor's height, and how the reactor height affects granular density.

A simple model for equilibrium forces that affect granules was used in the presented mathematical model. The density of granules is not much different from water density; therefore, the forces in equilibrium are gravity, buoyant force, and fluid resistance.

$$m \times a = F_g - F_{bf} - F_d \quad (1)$$

where m is the mass of a granule, a is the acceleration of a particle, F_g is the gravity force of the granule, F_{bf} is the buoyancy force of the granule and F_d is the drag force of the granule.

For constant movement Equation (1) becomes:

$$F_g = F_d + F_{bf} \quad (2)$$

The parameters from Equation (2) are:

$$F_g = \rho_{kBP} \times g \times V_k \quad (3)$$

$$F_{bf} = \rho_0 \times g \times V_k \quad (4)$$

$$F_d = C_d \times A \times \frac{\rho_0 \times v_1^2}{2} \quad (5)$$

where ρ_{kBP} is the density of the granule and biogas bound on the granule, g is gravitation acceleration, V_k is the granule's volume, ρ_0 is water density, C_d is the drag coefficient of the granule, A is the granule cross-section area, and v_1 is the settling velocity of the granule.

Equations (2)–(5) can be transformed to the following equation:

$$v_1 = \sqrt{\frac{4 g D |\rho_{kBP} - \rho_0|}{3 C_d \rho_0}} \quad (6)$$

where D is the diameter of the granule.

Assuming that the granule is porous, and that in active granules the pores are filled with biogas and in degassed granules the pores are filled with water, the density of an active granule can be calculated as:

$$\rho_{kBPA} = (1 - X_{BP}) \times \rho_{gr} + X_{BP} \times \rho_{BP} \quad (7)$$

where ρ_{kBPA} is the density of the active granule (the density of the granule + the density of the biogas bound on the granule and in its pores), X_{BP} is the ratio between the amount of biogas bound to the granule and the granule's mass, ρ_{gr} is the density of the granule, and ρ_{BP} is the biogas density.

The density of the degassed granule can be calculated as:

$$\rho_{kBPN} = (1 - X_{BP}) \times \rho_{gr} + X_{BP} \times \rho_0 \quad (8)$$

where ρ_{kBPN} is the density of the degassed granule (the density of the granule and density of the water in the granule's pores),

Knowing the settling velocity of an active granule and the settling velocity of a degassed granule, the density of active and degassed granules can be derived and calculated from Equation (6), and results in the active granule density in Equation (9) (subscript A—active), and Equation (10) with subscript N is the density of the degassed granule:

$$\rho_{kBPA} = \rho_0 + \frac{3 \times v_{1A}^2 \times \rho_0 \times C_{dA}}{4 \times g \times D} \quad (9)$$

$$\rho_{kBPN} = \rho_0 + \frac{3 \times v_{1N}^2 \times \rho_0 \times C_{dN}}{4 \times g \times D} \quad (10)$$

For gravitational acceleration (g) the value used was 9.81 m/s^2 . The settling velocity was measured in anaerobic water which has the density (ρ_0) of 1000 kg/m^3 . To calculate the drag coefficient the following model was used [23]:

$$C_d = \left(\frac{24}{Re_p} \right) \times \left(1 + 0.15 \times Re_p^{0.687} \right) \quad (11)$$

where Re_p is the Reynolds number of the granule.

The Reynolds number for particles (Re_p) was defined on the basis of the granule's diameter, and calculated as follows:

$$Re_p = \frac{\rho_0 \times D \times v_1}{\mu} \quad (12)$$

where μ is the dynamic viscosity of water, with a selected value of 0.00101 Ns/m^2 .

The ratio between the amounts of biogas bound to the granule and granule mass can be derived from Equations (9) and (10):

$$X_{BP} = \frac{\rho_{kBPA} - \rho_{KBPN}}{\rho_{BP} - \rho_0} \quad (13)$$

The density of biogas (ρ_{BP}) is 1.1 kg/m^3 [24]. From Equation (7) the final granule density is expressed in the following final form:

$$\rho_{gr} = \frac{\rho_{kBPA} - X_{BP} \times \rho_{BP}}{1 - X_{BP}} \quad (14)$$

4. Results

The settling velocity of anaerobic granules was calculated with experimentally collected results. The settling velocity was measured for active and degassed granules at different heights of the reactor. The settling velocity results from each height of the reactor are presented in Table 1. Degassed (Deg.) granules settle much faster than active (Act.) granules, due to the lack of produced biogas. Biogas is bound on the granule's surface and pores. According to our calculations, the amount of biogas in granular pores and bound to the surface of granules varies from 0.019% of granular mass to 1.3% of granular mass. The ratio of bound biogas to the granular mass is not related to the granular diameter.

Table 1. Settling velocity of active and degassed granules.

Reactor Height	0.6 m		1.6 m		3.1 m		4.6 m		6.1 m		7.6 m	
Granule	Act.	Deg.	Act.	Deg.	Act.	Deg.	Act.	Deg.	Act.	Deg.	Act.	Deg.
Minimum settling velocity [m/h]	60.00	71.25	65.92	63.64	67.72	75.65	67.50	76.97	65.45	74.88	55.77	80.53
Maximum settling velocity [m/h]	102.09	107.23	101.65	112.84	113.51	124.12	91.53	100.29	111.60	118.93	98.82	121.98
Average settling velocity [m/h]	80.66 ± 12.42	88.96 ± 11.19	81.50 ± 11.12	93.39 ± 11.38	89.16 ± 14.18	99.52 ± 13.14	80.20 ± 5.85	89.32 ± 7.17	85.03 ± 16.12	95.61 ± 15.78	79.42 ± 10.48	96.19 ± 13.25

Then, the drag coefficient and Reynolds number for particles were calculated with the use of Equations (11) and (12). According to the Reynolds number, the density of active and degassed granules can be calculated with the use of Equations (9) and (10) (Table 2). From active and degassed granules' density, the ratio between amounts of biogas bound to a granule and granule mass can be calculated using Equation (13). The results of the ratio between the amounts of biogas bound to granules and granule mass are shown in Table 3.

Using Equation (14), the granular density was calculated for each height of the reactor, and is presented in Figure 5.

Table 2. Density of active and degassed granules on each height of the reactor.

Reactor Height	0.6 m		1.6 m		3.1 m		4.6 m		6.1 m		7.6 m	
Granule	Act.	Deg.	Act.	Deg.	Act.	Deg.	Act.	Deg.	Act.	Deg.	Act.	Deg.
Minimal density [kg/m ³]	1008	1011	1009	1013	1009	1015	1008	1011	1009	1012	1009	1012
Max. density [kg/m ³]	1029	1036	1027	1030	1030	1035	1027	1029	1022	1026	1016	1025
Average density [kg/m ³]	1017 ± 5.5	1020 ± 6.5	1019 ± 4.6	1022 ± 5.0	1018 ± 6.4	1022 ± 5.6	1015 ± 5.6	1018 ± 6.0	1015 ± 3.6	1018 ± 3.6	1013 ± 2.1	1017 ± 3.9

Table 3. Ratio between the amount of biogas bound to granules and granule mass.

Reactor Height	0.6 m	1.6 m	3.1 m	4.6 m	6.1 m	7.6 m
X_{BP} max [%]	0.086	0.19	0.12	0.061	0.028	0.15
X_{BP} min [%]	0.68	0.59	0.84	0.43	0.61	0.94
Average X_{BP} [%]	0.35 ± 0.17	0.38 ± 0.13	0.41 ± 0.22	0.24 ± 0.12	0.24 ± 0.2	0.42 ± 0.24

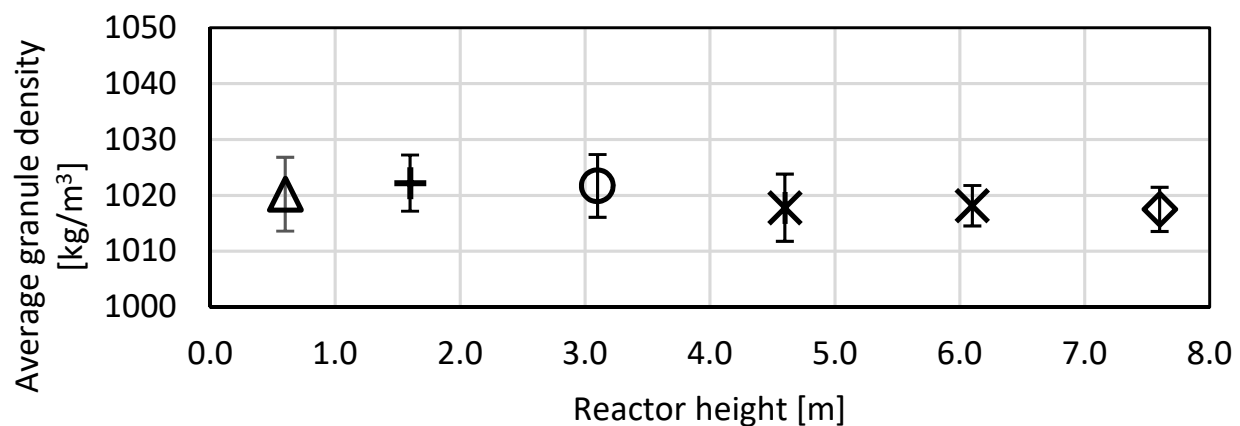


Figure 5. Granular density according to the height in the reactor.

In Figure 5, the average density of granules is shown according to the reactor height. At the bottom of the reactor is a granular bed into which wastewater is pumped. Biogas production at the bottom is low, and, because of this, the granular density is higher than the granular density at higher levels of the reactor. At higher levels of the reactor, biogas is bound to granules and in their pores, so the average density is lower than at the bottom levels. Moreover, granules with higher density need more biogas bound to them and in their pores to get to the higher levels of the reactor.

Granular density was calculated for 20 granules with various radiuses at each reactor height. At height of 0.6 m, the radius of granules varied between 1 and 2.23 mm, and density varied from 1011 to 1036 kg/m³, with an average of 1020 kg/m³ ± 6.5 kg/m³. At height of 1.6 m, the radius of granules varied between 0.86 and 2.5 mm, and density varied between 1013 and 1030 kg/m³, with an average value of 1022 kg/m³ ± 5.0 kg/m³. At the height of 3.1 m of the reactor, granular radius varied between 1.0 and 2.5 mm and density between 1015 and 1035 kg/m³, with an average of 1022 kg/m³ ± 5.6 kg/m³. At 4.6 m high in the reactor, granules had a granular radius from 1.0 to 2.5 mm. Density varied from 1011 to 1029 kg/m³ with an average of 1018 kg/m³ ± 6.0 kg/m³. At 6.1 m high in

the reactor, the granular radius ranged from 1.0 to 2.73 mm and granular density ranged between 1012 and 1026 kg/m³ with an average of 1018 kg/m³ $\pm$ 3.6 kg/m³. The reactor height of 7.6 m had a granular radius between 1.0 and 2.5 mm. The density of the granules was from 1012 to 1025 kg/m³ with an average of 1017 kg/m³ $\pm$ 3.9 kg/m³.

All measured densities for different size classes of granules are shown in Figure 6, as the average density of granules as a function of specific granule size with a confidence level of 95%. It can be seen from Figure 6 that the density of the smaller granules is higher than that of the larger granules. The main reason for this is the size of the pores in the granules. Larger granules have larger pores and a larger interfacial area, so more biogas is trapped in the pores. This result is consistent with the findings of Schmidt and Ahring [11]. The regression of the measured data is represented by a trend line. The trend line in Figure 6 has an R-squared value of 0.8754. The R-squared evaluates the dispersion of the data points around the fitted regression line. For the measured data set, higher R-squared values represent smaller differences between the observed data and the fitted values.

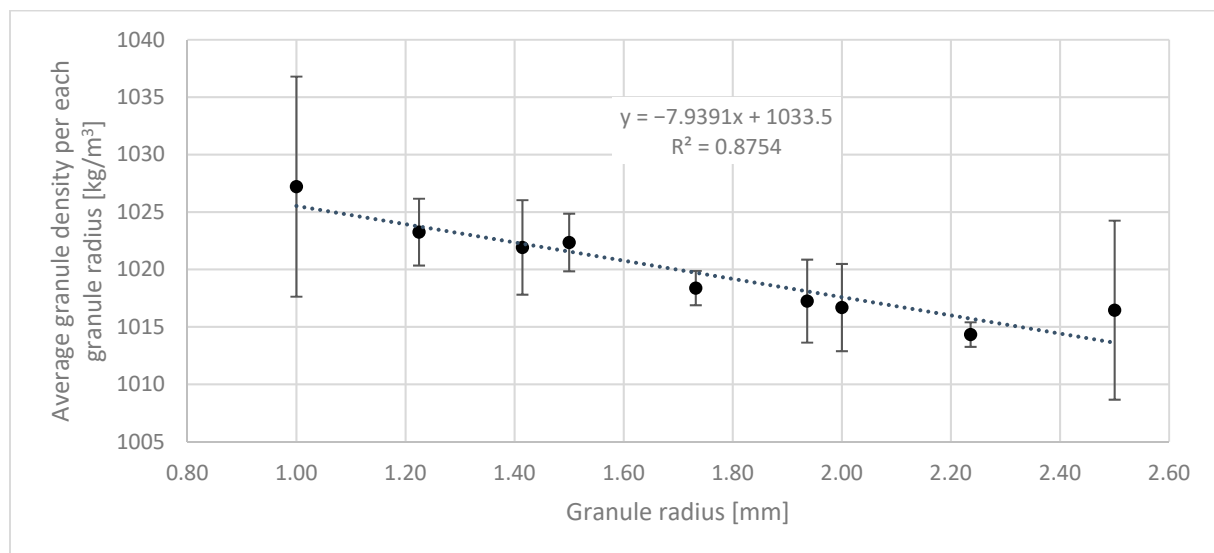


Figure 6. Average granule density depending on granule radius.

In the next step, the average granule density equation dependent on the granule radius can be expressed from measured data with Equation (15):

$$\overline{\rho}_{gr} = -7.9391 \left(\frac{D}{2} \right) + 1033.5 \quad (15)$$

In Figure 7, the ratio between the amount of biogas bound to granules and granule mass depending on the radius of a granule is shown for each reactor height. Granular size is not dependent on reactor height. In Figure 7, it is shown that all radiuses of the granules can be found at every height of the reactor. The ratio between the amount of biogas bound to granules and granule mass is between 0.05% and 0.95%, and the reactor height and granular size do not have any impact on the amount of biogas bound to a granule.

In Figure 8, the ratio between the amount of biogas bound to granules and granule mass depending on granule density is shown for all tested granules. The ratio between the amount of biogas bound to the granules and granule mass does not have any impact on the density of the granules on any level of the reactor.

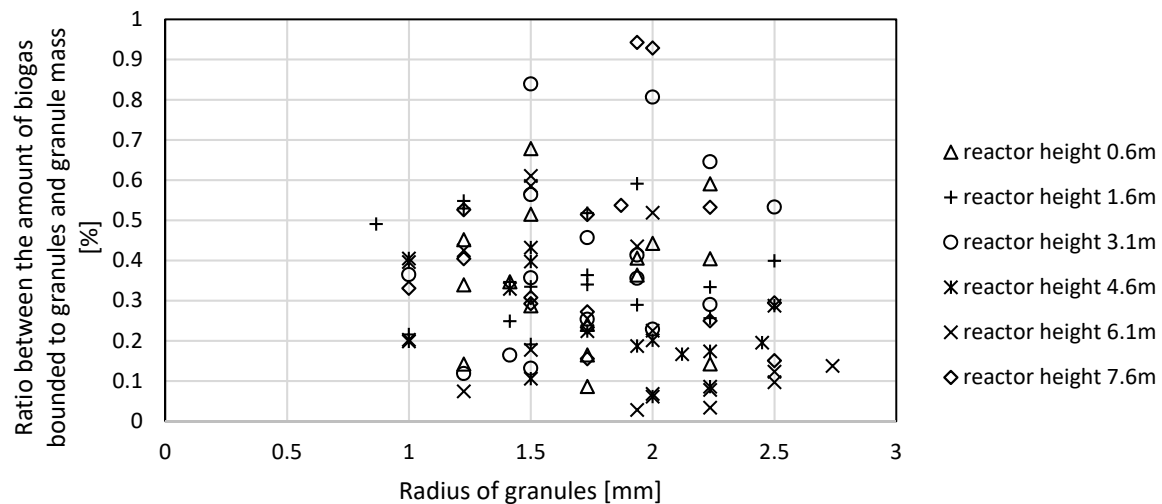


Figure 7. Ratio between the amount of biogas bound to granules and granule mass depending on the radius of a granule.



Figure 8. Ratio between the amount of biogas bound to granules and granular mass depending on the density of the granule.

5. Conclusions

A comprehensive study of anaerobic granules in a UASB reactor was conducted in this work. Granular density was calculated via settling velocity at different heights of the reactor. The derived model for calculating the granule density depends only on the granule size (radius or diameter of the granule), and can be integrated easily into various numerical models for modelling the process in the UASB reactor using the multi-fluid or fluid-particle approach. Granules with a smaller diameter have higher density than granules with a larger diameter. This relationship between granule size and density can be attributed to the fact that smaller granules have a smaller interface with the fluid than larger granules due to their porosity, and, therefore, trap less gas in their volume than larger granules.

The density of anaerobic granules does not vary at different heights of a UASB reactor. The average calculated density of granules at different reactor heights is between 1018 and 1022 kg/m³. In granules, the amount of biogas bound to the granular surface and in pores is not related to granular size or the height of the reactor. The height of the reactor does not have an impact on granular size.

Wastewater velocity through a reactor represents 0.51–2.0% of active granular settling velocity and 0.45–1.76% of degassed granular settling velocity.

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