LANDTECHNIK 76(4), 2021, 156–165
DOI:10.15150/lt.2021.3272

LANDTECHNIK
AGRICULTURAL ENGINEERING

Investigation of the flow behaviour of liquid manure under the influence of pulsating air

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Subject of the present work is the influence of pulsating air on the outflow behaviour of liquid manure in the agriculture. Therefore a test bench and a computational fluid model was developed. Considering the shear thinning flow behaviour of the liquid manure an alternative fluid for the test bench were used. As a result of the work a pressure range for the pulsating air were determined. The main results are the minimum and maximum air pressure.

Keywords
Liquid manure, 2-phase flow, non-Newtonian

Introduction

Liquid manure is spreaded in agriculture as well as in grassland cultivation. The result of that is a high air pollution with emissions of ammonium and methane gas. In Germany the rules for extraction of liquid manure were tightened in 2015 (DüV 2017), amongst other the emissions of ammonium and nitrogen have to be reduced. To handle that the distribution of liquid manure is realised by a system of towed hoses. The liquid manure is first crushed and then applied to the ground through the influence of gravity within the outgoing hoses.

In hilly regions and uneven terrain, the distribution of liquid manure is unbalanced over the working width caused of the dependency on gravity. Furthermore the hoses are often choked. The result is a user-unfriendly maintenance and cleaning effort.

The goal of the research project was to avoid chocking of the liquid manure hoses. Thus the liquid manure distributor has to be optimised from a fluid mechanic perspective and an additional pulsating air flow should be implemented. In this context computational fluid simulations and investigations on the developed test bench were made. The pulsating air avoids the previous chocking in the liquid manure flow and supports a steady flow of the liquid manure. Chocking of the hoses is prevented. In addition, the pulsating air has a positive influence on the flow behaviour of the liquid manure. A chocking of the distributor and the cutting part of the machine will be prevented.

Characterisation of the Test Fluid

Within a scope on a literature search the flow properties in dependency of total solid content, temperature and animal were determined. The results of the search is given in table 1. The researched data come from the years 1969 to 2009. Between 1969 and 1986 in particular, the accuracy of the measurements improved, which is why more up-to-date values are more meaningful. It also shows that hog manure has a lower consistency factor and a higher flow exponent than cattle manure. Based on this data, a suitable replacement fluid for the test bench was searched for. For the investigations, cattle and hog manure came into consideration, both of which show a non-Newtonian flow behaviour. In contrast to Newtonian flow behaviour, there is no directly proportional relationship between shear

received 10 July 2020 | accepted 6 August 2021| published 23 December 2021

stress and shear rate. Depending on the TS content, the flow behaviour follows the Herschel-Bulkley power law or the Ostwald-de Waele power law, see equations 1 and 2. Here τ is the shear stress, τ_0 the yield point, k the consistency factor, $\dot{\gamma}$ the shear rate and n the flow exponent. In consultation with the project partner, a dry matter content of 8% was taken as the basis. According to Hörnig (1969), in this case, Eq. 2 can be expected. Using the quotient of shear stress and shear rate, the dyn. viscosity μ can be calculated, see Eq. 3.

$$\tau = \tau_0 + k \cdot \dot{\gamma}^n \quad \text{(Eq. 1)}$$

$$\tau = k \cdot \dot{\gamma}^n \quad \text{(Eq. 2)}$$

$$\mu = \frac{\tau}{\dot{\gamma}} \quad \text{(Eq. 3)}$$

Table 1: Properties of liquid manure and replacement fluids (liquid soap and water-agar, own measured)

Fluid	**Dry matter content %**	**Consistency factor k in Pa s^n**	**Flow exponent n**
Hog manure at 24,6°C (Hörnig 1969)	8	0.299	0.438
Hog manure (Eckstädt 1978)	9.49	0.4235	0.6943
Hog manure (Hörnig 1982)	8	0.893	0.439
Hog manure at 20°C (Türk 1986)	8	0.8707	0.5856
Hog manure at 25°C (Langner 2009)	5.09	0.1407	0.552
Hog manure at 25°C (Langner 2009)	12.9	3.9	0.5798
Cattle manure at 19,7°C (Hörnig 1969)	7.78	17.4	0.246
Cattle manure at 19,7°C (Hörnig 1969)	9.59	56.8	0.258
Cattle manure (Hörnig 1982)	8	7.096	0.286
Cattle manure at 30°C (El-Mashad et al. 2005)	9.1	21.3	0.211
Liquid soap at 20°C	-	15.9	0.337
Water-Agar at 20°C	-	2.428	0.284

A substitute fluid for use on the test bench should have the following properties:

- Mapping of the viscosity range of cattle and hog manure according to Table 1.
- Availability in the quantity 0.2 m^3 to 0.4 m^3 under 500 €.
- Resistance to ageing or no deterioration within 3 months
- No thixotropic behaviour, i. e. time-dependent flow behaviour is undesirable

Liquid soap and a mixture of agar-agar with water were considered as substitute fluids, the corresponding parameters are also listed in Table 1. Agar-agar (hereafter referred to as agar) is obtained from the cell walls of various types of algae and is used, among other things, in the food industry as a thickening agent. The slightly basic character of liquid soap leads to undesirable chemical reactions on metallic components of the test bench and would cause premature wear on the test bench. Therefore, liquid soap is eliminated from the selection. Subsequently, research was conducted into a suitable mixture of agar and water. A ratio of 1.2 mass % agar to 98.8 mass % water turned out to be ideal. The course of the dynamic viscosity over the shear rate was determined on a rotational viscometer and is shown in figure 1.

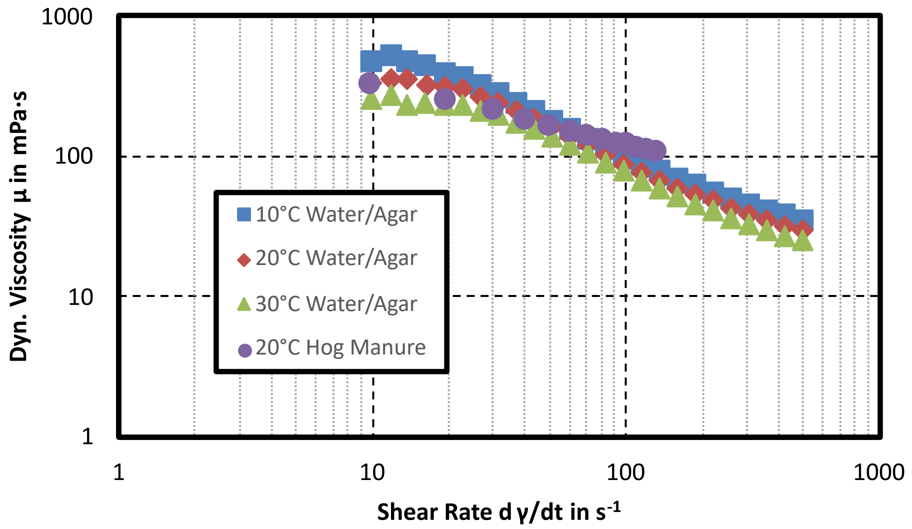

Figure 1: Dyn. viscosity vs. shear rate for a mixture of 1.2 % agar and 98.8 % water and in comparison, hog manure (Türk 1986)

Test Bench Structure

The influence of pulsating air on the flow behaviour of the test fluid was to be investigated using an experimental set-up. Two material flows are fed into the liquid manure distributor. On the one hand, the liquid manure to be spread, and on the other, air under overpressure. The air is compressed in an upstream compressor and fed to the rotor of the liquid manure distributor. The rotor rotates at a constant speed n and thus cyclically passes over the slurry outlets of the liquid manure distributor. While the rotor passes over the outlet, it is pressurised with compressed air. As soon as the rotor releases the outlet again, slurry flows through the outlet. The cyclical nature of this process and the fact that the rotor has four outlets for the compressed air results in a pulsation of the compressed air in the outlets of the liquid manure distributor. Figure 2 shows a sectional view of the liquid manure distributor.

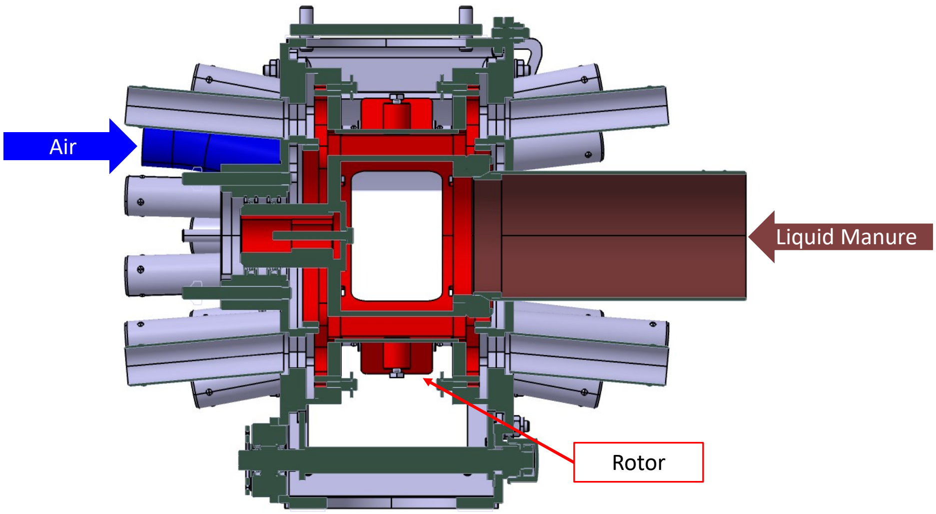

Figure 2: Sectional view of the executed liquid manure distributor (© Riedel)

Since the real liquid manure distributor has 32 outlets, a simplification of the experimental setup was necessary. On the realised test bench, one side has two outlets, an inlet opening is located on the opposite side. Via the inlet opening, the substitute fluid agar-water is supplied from a storage volume with the help of a submersible pump. The internal rotor is designed in such a way that the air supply is also possible from a conventional workshop compressed air network. The flow area is visually accessible by means of various acrylic glass attachments. The prototype for the test rig and the test bench structure are shown in Figures 3 and 4. Figure 5 shows more details of the distributor used on the test bench. The compressed air supplied from the outside is distributed via the internal rotor. The compressed air flows in the rotor to the pressure pieces. A backflow of liquid into the air section is prevented by means of two non-return valves inside the pressure pieces. The pressure pieces are each sealed by means of a rectangular sealing ring, the axial contact pressure is applied by means of spiral springs

Table 2 compares relevant parameters of the real liquid manure distributor with those of the experimental setup. The aim of the experimental investigations was to reproduce the flow conditions in the outlet similar to those of the executed distributor. Due to the different number of outlets in the experiment compared to the real distributor, the conditions at the inlet of the distributor are different (evident in the different Reynolds numbers at the inflow). The volume flow at the test bench was adjusted with the help of a bypass, the target value was the volume flow at the second outlet. Two ultrasonic flow sensors were used to measure the volumetric flow of the liquid. The Reynolds number Re is calculated according to Eq. 4, with the flow velocity u and the diameter d. A temperature of 20 °C is taken as the reference temperature for the properties of the reference liquid (density ρ and dyn. viscosity μ). According to Hörnig (1969, 1982) and Eckstädt (1978) the calculation of the Reynolds number Re in the case of non-Newtonian velocity flow is carried out according to equation 5.

$$Re = \frac{u \cdot d \cdot \rho}{\mu} \quad \text{(Eq. 4)}$$

$$Re = \frac{u^{2-n} \cdot d^n \cdot \rho}{k} \quad \text{(Eq. 5)}$$

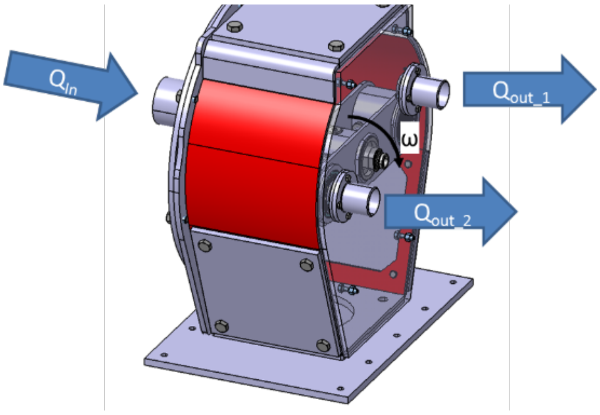

Figure 3: CAD representation of the test bench distributor, the side wall on the outlet side is shown transparent for display reasons (© Riedel)

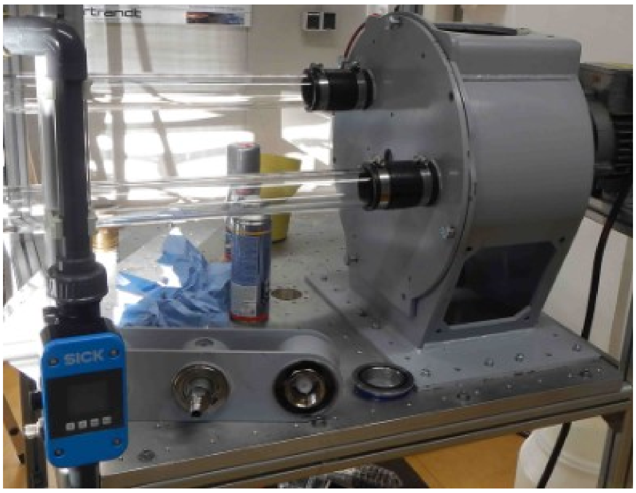

Figure 4: Test stand construction (rotor and acrylic glass panels still dismantled) (© Riedel)

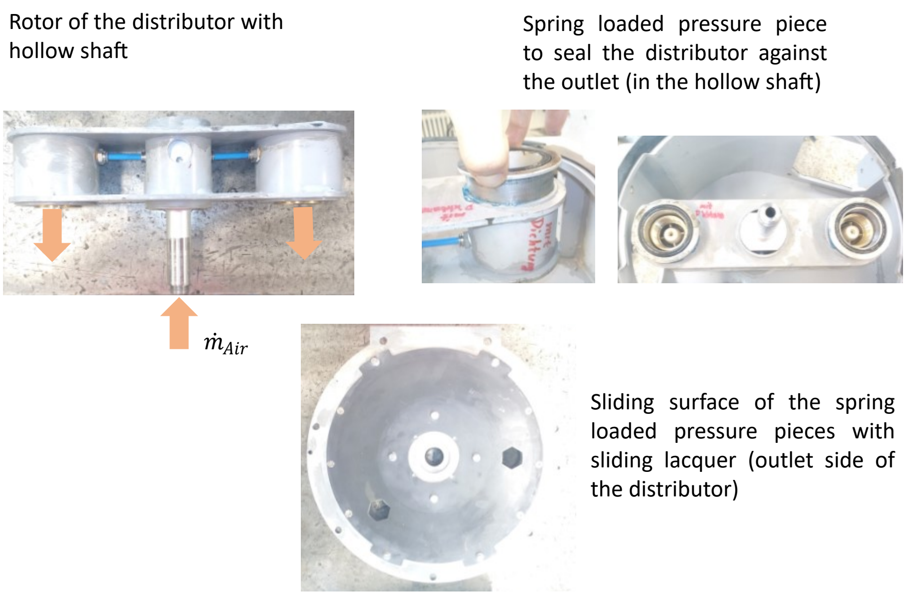

Figure 5: Individual components of the test bench (© Riedel)

Table 2: Setting parameters for investigating the influence of air

Parameter	Real liquid manure distributor	Experimental setup
Inlet Diameter d_1 in mm	115	60
Outlet Diameter d_2 in mm	34	36
Number of outlets	32	2
Inlet volume flow Q_1 in ltr/min	1884	140
Outlet volume flow Q_2 in ltr/min	58,9	70
Reference fluid	Hog manure, dm = 8 % (Türk 1986)	Water-agar
Reynolds number inlet Re_1	1592	132
Reynolds number outlet Re_2	182	202
Rpm rotor or cutterbar n in min^{-1}	300	300

Results

On the test bench, it was demonstrated that it is possible to flush the outlets free with the help of compressed air. The main questions in this context were:

- If air separation occurs in the upper part of the outlet pipe
- If the air causes foaming

To classify the results, a section in the second outlet pipe one metre downstream of the distributor has been considered. The setting parameters are listed in table 3. One test series with water and one with the water-agar mixture were carried out. In both cases, a separation of the gas phase is visible from an overpressure of p_{Air} = 400 mbar (Figures 6 and 7). The pulsating air flows in the upper part

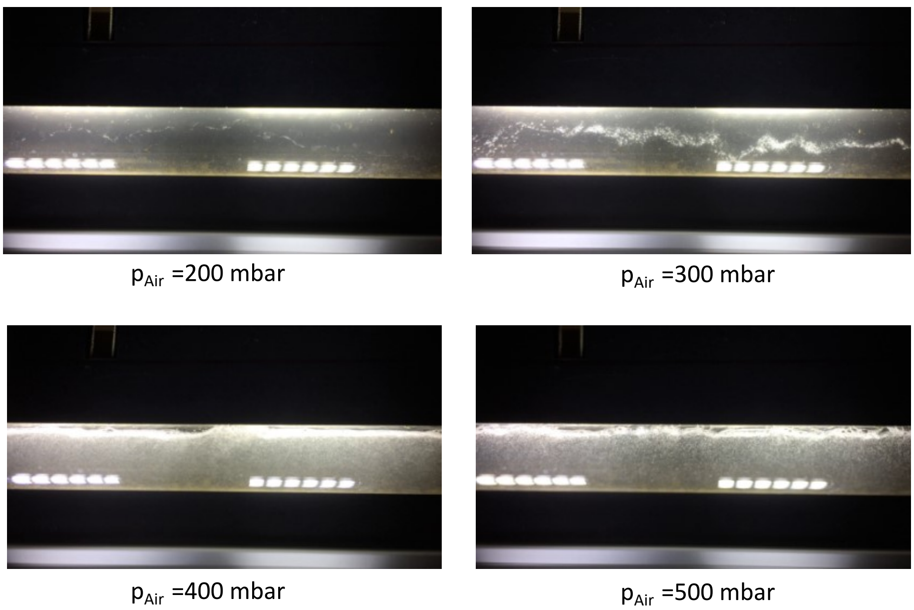

Figure 6: Influence of pulsating air on flow conditions in the outlet (water Q=70 ltr/min) (© Riedel)

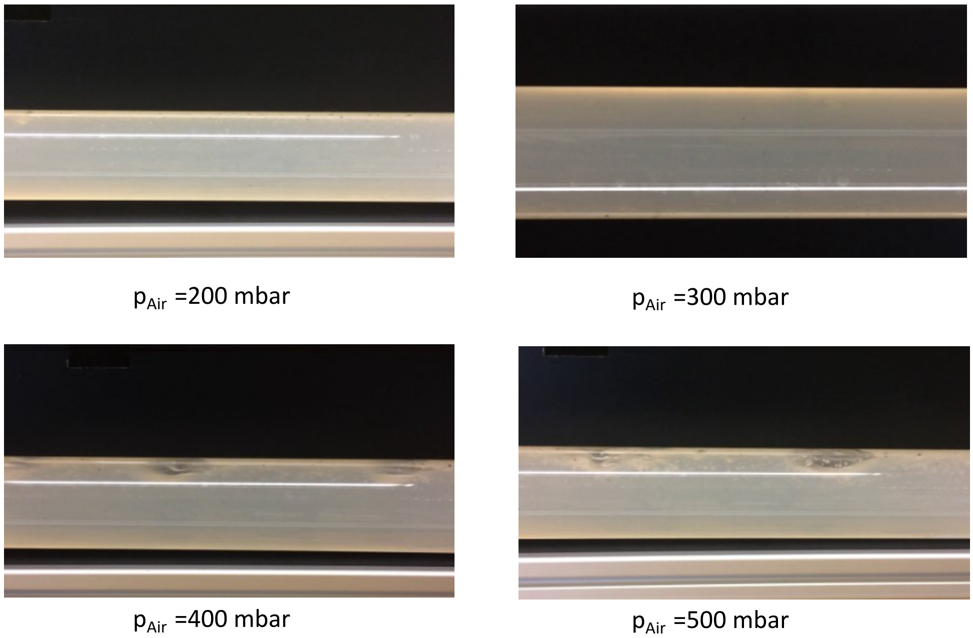

Figure 7: Influence of pulsating air on flow conditions in the outlet (water-agarQ=70 ltr/min) (© Riedel)

of the tube. From this, the conclusion can be drawn that lower areas with blockages are not covered by the air. At the same time, it was observed that no air goes into solution, as no foaming was evident in any case. The separation of the two phases, liquid and gas, is clearly visible. Individual air bubbles in the liquid flow could be observed at a lower overpressure of the air. This is the case at a pressure value of less than 300 mbar. Here, it can be assumed that the air also captures blockages in the pipe and helps to loosen them.

Table 3: Setting parameters for investigating the influence of air

Trial no.	**Volume flow Q2 through the outlet in ltr/min**	**rpm of the rotor in min^{-1}**	**Overpressure of the compressed air in mbar**
1	70	300	200
2	70	300	300
3	70	300	400
4	70	300	500

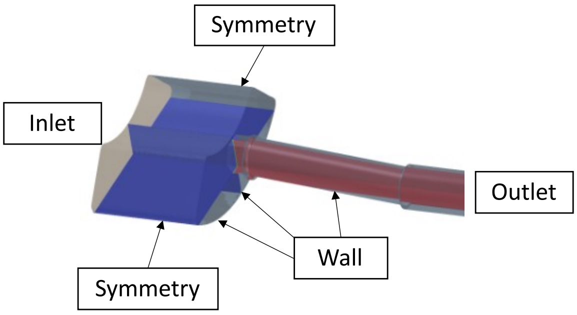

Figure 8: Boundary conditions on the CFD-model (© Riedel)

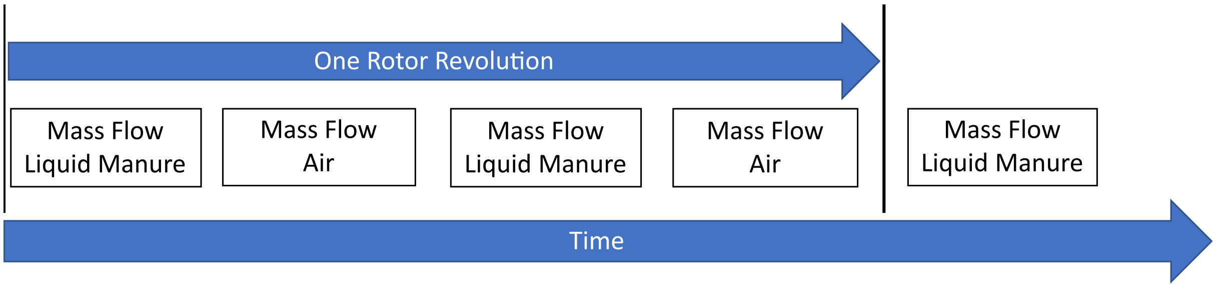

Figure 9: Cyclic inlet boundary condition to map rotor rotation (© Riedel)

Furthermore, it should be investigated how much overpressure of air is necessary to maintain the required liquid manure mass flow. Each time the rotor passes over, the flow at the outlet is interrupted for a short time. This interruption causes a negative pressure in the outlet and consequently leads to a reduced liquid manure mass flow. The additional compressed air is intended to prevent this effect.

The investigations were carried out with the help of three-dimensional numerical fluid mechanics and the software Star-CCM+. For reasons of simplification, the calculations were carried out with a section of the overall model of the real liquid manure distributor, whereby an outlet was taken into account, see Figure 8. A time-varying boundary condition was selected at the inlet to represent the rotor rotation and thus also the alternating admission of slurry or air. Depending on the speed of the rotor and the geometry of the rotor, a liquid manure mass flow or an air mass flow is specified at the inlet. Figure 9 shows this variation of the inlet boundary condition schematically.

The parameters relevant for the numerical model are listed in Table 4. The air mass flow has been varied until the required liquid manure mass flow at the outlet has been reached. Figure 10 shows the results. From an air volume flow (conversion with air density) of 86.4 ltr/min. and an overpressure of 100 mbar, the required liquid manure mass flow is achieved.

Table 4: Parameters of the 3D-CFD model

Parameter	Value or property
Grid size	1,67 Mio. cells
Numerical models	Three-dimensional, non-Newtonian flow behaviour according to eq. 2 (cattle slurry, μ_{max}=10000 Pa s), laminar, two-phase (volume of fluid method), transient
Duration of the calculation	5 rotor revolutions corresponds to t=1s
Boundary condition at the outlet	Ambient pressure (100 kPa)
Boundary condition at the wall	No-slip ($\nabla \cdot \mathrm{u} = 0$)
Boundary condition at the inlet	Liquid manure or air mass flow, varied

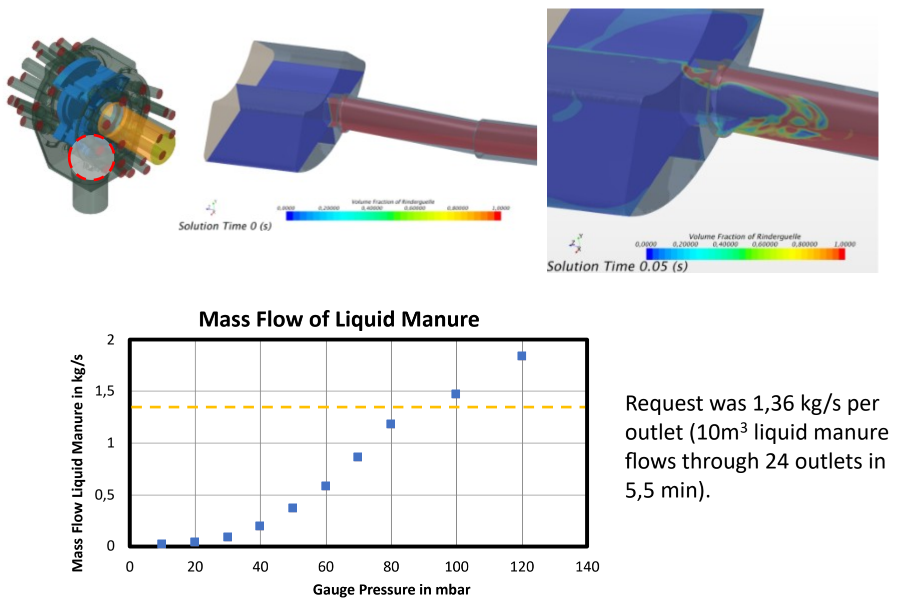

Figure 10: Minimum air pressure or volume flow to maintain the required liquid manure mass flow rate (© Riedel)

Conclusions

In the present work, the influence of pulsating air on the outflow behaviour of liquid manure was investigated. The fluids used were water, agar water and, in the case of the simulation, cattle liquid manure. Investigations were carried out on a test bench and on a flow simulation model. The main results are the minimum and maximum air pressure. Thus, from an overpressure of the air of about 100 mbar, the liquid manure mass flow is maintained. If the overpressure rises to more than 300 mbar, a phase separation is observed in the outlet pipe. In the sense of clearing the outlet pipe, phase separation should be avoided. Accordingly, an overpressure range of 100 to 300 mbar is considered ideal.

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Acknowledgements

This work was carried out within the framework of the funding measure “Central Innovation Programme for SMEs” (ZIM) from the BMWi, for which we would like to express our gratitude. We would also like to thank our two project partners Eidam Landtechnik and the Forschungsgemeinschaft Mitteldeutschland (FGMD).