X International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2021
K.-U.Bletzinger, E. Oñate, R. Wüchner and C. Lázaro (Eds)

DOUBLE LAYER TEXTILE COVERS FÜR BIOGAS STORAGE SYSTEMS UNDER ENVIRONMENTAL IMPACTS

STRUCTURAL MEMBRANES 2021

ROSEMARIE WAGNER*, KAI HEINLEIN**

* KIT - Department of Building technology
Englerstrasse 7 76131 Karlsruhe
e-mail: rosemarie.wagner@kit.edu, web page: http://fgb.ieb.kit.edu/

** KIT - Department of Building technology
Hertzstrasse 16 76187 Karlsruhe
e-mail: kai.heinlein@kit.edu, web page: http://fgb.ieb.kit.edu/

Key words: Textile Composites, Inflatable Structures, double layer membranes, contact, non-conservative loads.

Summary. Membrane biogas storage systems with suitable technical design represent an economically attractive and technically sensible method of biogas storage due to low investment and maintenance costs. A typical system is a double layer inflated membrane structure. The outer membrane acts as weather and environmental protection and is kept under tension by an internal pressure acting also onto the gas membrane as the gas tight enclosure of the fermenter in a biogas plant. However, according to the state of the art, a reliable load-compliant design of these covers is till now limited, since neither the loads acting due to weather influences and operating conditions onto the gas membrane nor their transmission and distribution to individual system components such as valves, ventilators and pressure control units are known in their interaction. In a double layer membrane covering the fermenter of a biogas plant the behaviour of the outer and gas membrane is hardy to describe without knowing the influences of the gas production and extraction, temperature, internal pressure and control devices in relation to the surrounding and operation conditions. The major difference to inflated structures is the time-temperature and volume depended gas and air pressure in the two chambers.

1 INTRODUCTION

After wind and photovoltaics, biogas is the third largest renewable energy source in Germany. The current development goes from the utilization of energy crops as a substrate for the fermentation process to the targeted utilization of biogenic residues and waste materials and a closed biological material cycle. Plants are also increasingly being used for the production of biomethane instead mainly for power generation, thus contributing to the energy transition. An economical solution for weather and odour protection via fermenters, post-fermenters and digestate deposits are membrane covers, which are designed as single-bowl or double-bowl membrane covers depending on the function. Membranes as polymer films or coated fabrics allow their use as flexible gas storage above the fermenters. Sufficiently large storage systems provide the possibility of compensation the fluctuations in power demand. The storage volume depends directly on the geometry of the covers, as a cone, spherical segment or hemisphere. The flexibilization in the purchase of biogas requires storage systems with large volumes. In the following, investigations are presented on an internal pressurized double layer membrane storage system, which corresponds almost to a hemisphere. In contrast to the usual membrane storage systems with a ratio of height / span of H / L ~ 1/4 - 1/3 increases their storage volume by two to three times if the ratio of height / span is H / L ~ 1/2. High gas storage facilities have a significantly larger wind attack area. The surface area of the gas membrane is about 50% larger compared to flat covers. The investigations were carried out at an experimental building, accompanied by laboratory tests and calculations.

2 DOUBLE LAYER MAMBRANE COVERS

Biogas storage systems with double layer membrane covers differ from conventional internal pressurized membrane structures, because these have comparatively small changes in their volume. In biogas covers with an outer and gas (inner) membrane, the gas membrane encloses a constantly changing volume with the substrate tank depending on gas production. The gas volume varies in the amount by substrate supply and extraction as well as gas production and extraction. The behaviour of the outer membrane and gas membrane under environmental impacts and operating conditions is still only partially known in all its complexity. It can be assumed that external impacts such as wind, snow and temperature are transmitted via the supporting air chamber between the outer and gas membrane into the gas chamber. An open question is how the external influences in the superposition with different operating states affect the behaviour of the membranes, the internal pressure in the air and the gas chamber. In order to get an idea of the interactions, measurements were carried out on an experimental building and different states were calculated. Quantities that interact with each other in a biogas storage system with a double layer membrane cover are divided into the environmental conditions, the mechanical and thermal behaviour of the outer membrane, the thermodynamic behaviour of the supporting air chamber, air volume in and out of the chamber, the mechanical and thermal behaviour of the gas membrane and the operating conditions in the gas chamber. A more detailed description is given in Table 1 and Figure 1.

Table 1: Characteristics of the different components

Environmental conditions	Atmosphere pressure, environmental temperature, solar radiation, wind speed and direction, snow and humidity.
Outer membrane	Stress-strain and thermal behaviour, radiation properties
Supporting air chamber	internal pressure, volume, temperature, air supply and outlet.
Gas membrane	stress-strain and behaviour, radiation properties, and folding processes.
Gas chamber	Substrate filling and extraction, gas production and extraction, temperature.

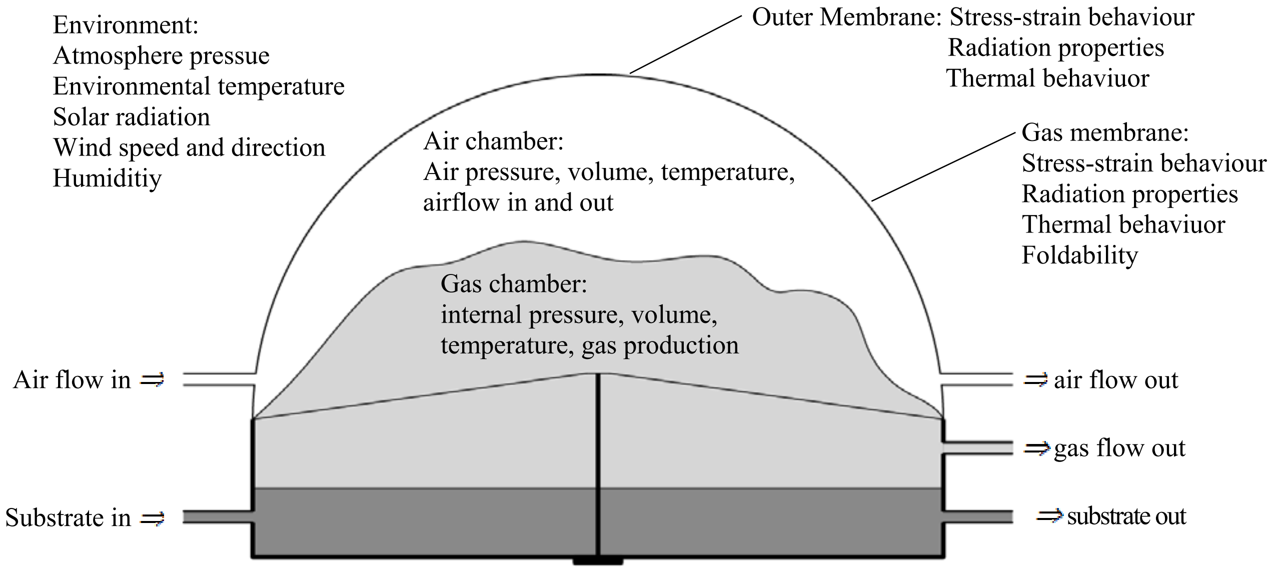

Figure 1: Characteristics describing the interaction between environment, membranes, air, gas and substrate volume [KIT-fgb]

3 EXPERIMENTAL DOUBLE LAYER STORAGE SYSTEM

An experimental double layer storage system was installed on the factory premises at Seybold GmbH & Co.KG., Düren, Germany. The whole experimental set-up had a steel cylinder with a height of 1.80 m and a diameter of 15.35 m as base. The outer membrane and the gas membrane were clamped air tight onto to upper edge of the steel cylinder. The height of the outer membrane is 7.35 m measured from the upper edge of steel cylinder and 6.90 m for the gas membrane. For assembly and operating conditions without internal pressure in the gas chamber, there is a mast in the centre of the steel cylinder. This mast is connected by belts to the upper edge of the cylinder. Without pressure in the gas chamber, the gas membrane lies on the belt position. The steel cylinder had an airtight door and could be entered. It was possible for the first time to observe the folding procedure of the gas membrane on the belt position and the unfolding by increasing the pressure. To study the different environmental parameters, the experimental set up was equipped with temperature sensors, pressure gauge, strain measurement and volume flow sensor at the openings in the chambers to let air in and out.

For the duration of the experiment, real conditions in the gas chamber were dispensed with, but could be simulated with air. One known gas production in real biogas storage systems is app. 280 m³/h and the extraction of biogas is ca. 300 m³/h, [1]. The filling process caused by gas production was reproduced by a radial ventilator. The ventilator had a maximum air flow rate of 1240 m³/h. Devices such as exhaust air valve and level measurement of the gas chamber had been the same used in common biogas storage systems. Although no real conditions in terms of gas production could be modelled the volume underneath the gas membrane will be name as gas volume in the following. The same type of ventilator was installed for filling the space between the outer and gas membrane, this will be named as air volume. The built-in ventilators are identical to those that are installed in conventional biogas storage systems. A total of 22 measured values were recorded and stored at intervals of seconds over a period of 1.5 years. In Figure 2 the main measurement devices are shown.

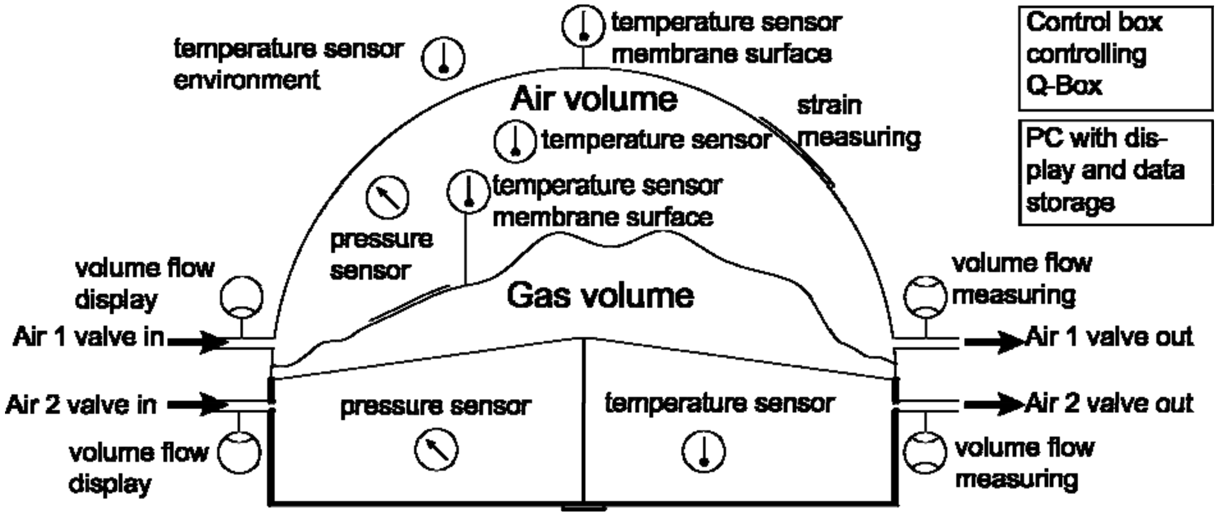

Figure 2: Cross section of the experimental set-up with the main measurement devices, [KIT-fgb]

The chosen ventilators provide three different controls of air supply such as:

- Control of the internal pressure
- Control of the air flow a constant rotation speed and
- Control of a constant volume flow

The internal pressure was controlled by differential pressure measurement devices in the air and gas volume. It was possible to use the measured pressure values for controlling the ventilators. The pressure sensor gives a digital signal to the ventilator and this leads to an adjustment of the volume flow to keep the internal pressure constant. This type of air supply is hereinafter referred to as constant pressure.

A typical weather situation is shown in Diagram 1 as a windy noon in March 2019 in a time period of 2 hours. The wind speed was measured by a wind measurement installed on the roof of a nearby building. The ventilators had set to constant internal pressure. The gas volume was filled and the relation of air volume to gas volume was 1/8. The internal pressure in the air chamber varies between approx. 230 Pa and 270 Pa. The control of the internal pressure is set to a setpoint of 250 Pa. The wind speed is between 2 m/s and 10 m/s. This leads to a pressure difference in the gas chamber of 40 Pa, between approx. 310 Pa as the minimum value and approx. 350 Pa as the maximum value. The volume flow into the support air chamber has a difference of approx. 125 m^3/s, with the minimum value of approx. 5 m^3/h and a maximum volume flow of approx. 130 m^3/h. In the gas chamber, the volume flow changes from a minimum of 1 m^3/h to approx. 150 m^3/h.

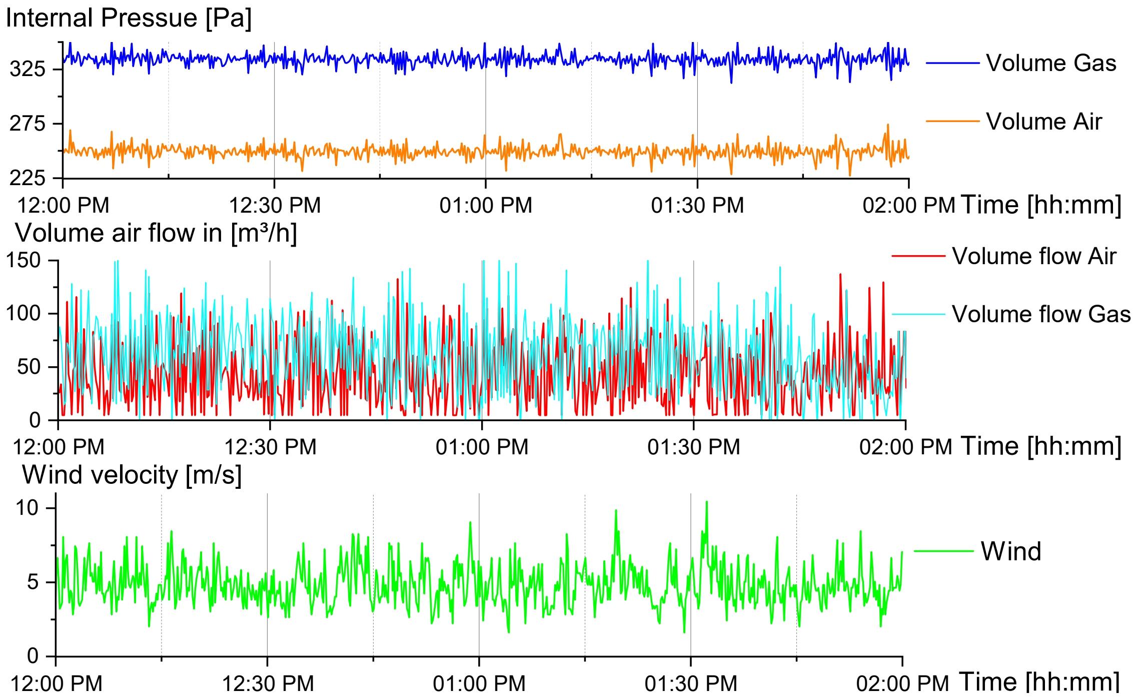

Diagram 1: Internal pressure, volume flow and wind speed on a windy day in March 2019,pressure controlled

A filled gas volume shows in Diagram 1 the same deviation of the internal pressure compared to the air volume. The volume flow is higher into the gas chamber because of the larger volume compared to the air chamber.

The second option is to operate the ventilator permanently at a constant rotation speed. This is done very often in real biogas storage systems. This type of regulation is hereinafter referred to as frequent controlled. The pressure regulation can be approximately equated with the conditions of the simplified gas law. The assumption is acceptable if the exhaust air valves in the air and gas chamber are closed. The product of internal pressure and volume is constant.

In Diagram 2, for example, the changes in the internal pressure and the volume flow into the air and gas chamber over 1 hour and 30 min are shown as examples of a filled gas chamber. The measures were recorded also during a windy day in March 2019. The wind speed varies between approx. 2 m/s and 10 m/s in the time period. The ventilators for the air supply into the air and gas chamber are set to a constant speed. In order to comply with these, the volume flow into the air chamber varies between approx. 5 m^3/h and 145 m^3/h in the same period. The target value of the air pressure was 270 Pa and varies depending on the volume supply and gust of the wind between 235 PA and 340 Pa. The internal pressure in the gas chamber varies between 325 Pa and 420 Pa with a target value of 350 Pa. The volume flow into the gas chamber varies between approx. 1 and 250 m^3/h. Other environmental variables such as air pressure of the atmosphere, solar radiation and the temperatures of the environment, on the membranes as well as in the air and gas chamber were almost constant.

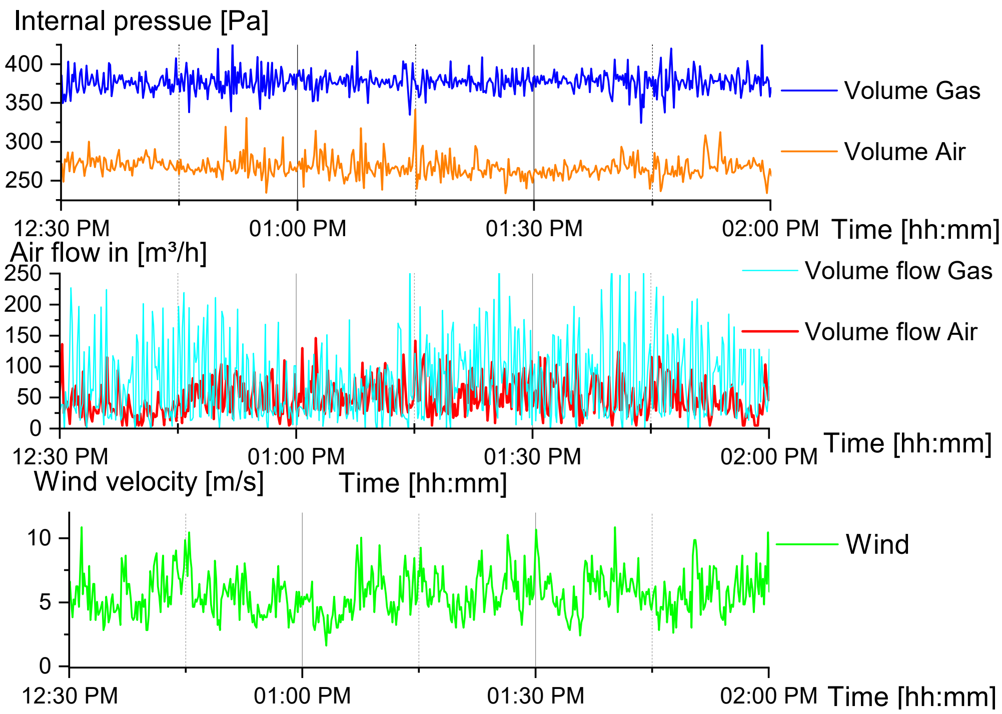

Diagram 2 Internal pressure, volume flow and wind speed on a windy day in March 2019 frequent controlled

The third option is to operate the ventilators with a constant volume flow. Via a volume flow sensor, the actual volume flow is detected and passed on as a signal to the ventilator. This is processed and the speed of the ventilator is controlled in such a way that a constant volume flow is generated. This type of air supply was dispensed with for measuring different situations.

4 STRUCTURAL ANALYSIS

The dependence of the internal pressure on the power and controlling mode of the ventilators as well as the gust of the wind makes it clear that both the air pressure and the gas pressure are non-constant quantities, but extremely dependent on the environmental conditions, the respective operating conditions such as full gas storage, empty gas storage, gas extraction and gas production. The question rightly arises whether the known design concepts for air halls and other internal pressure-based structures are to be taken onto double membranes over biogas storage systems or whether the load assumptions and safety factors are to be adapted to the special operating conditions. One question is, for example, how the gas volume affects the behaviour of the outer membrane under the influence of wind when the gas chamber is filled.

The difficulty here is to record the operating condition of the biogas, is it produced or removed when the wind gusts acting on the outer membrane. These states lead to changes in the gas volume and thus in the internal pressure. For the following investigations, it is assumed that constant conditions exist in the gas chamber. There is no gas production and extraction.

To calculate the stresses and deformations due to wind pressure, there are various possibilities. These differed in the modelling of the entire membrane cover, the material law, the consideration of the gas law, the change of direction of the wind loads in the case of large deformations of the outer membrane and the contact in the area of the wind gusts of the outer and gas membrane. A comparison of the various calculation methods requires load assumptions on the one hand and material laws on the other.

4.1 Description of the load case

For comparison the different method analysing the stress-strain behaviour of the double layer membrane cover two load cases are considered in a load case combination. The dead load of the cover is known and one typical wind load case is assumed, given as the result of a wind tunnel test.

The dimensions, the cutting pattern of the membrane covers and the weight of the measuring equipment's were known and the models for the numerical simulation of the stress-strain behaviour were calculated as internal pressurized membranes with the target values of the respective internal pressure. The peculiarity of the membranes is the design of the polar cap. This had a diameter of approx. 1.10 m for the outer and gas membrane and was made of 2 layers of membrane material per polar cap. The warp direction runs from the pole in the radial direction and the weft thread runs perpendicular to it. The weight of the membrane was 0,15 kN/m² including seams and equipment and the weight of each pol cap 0,3 kN/m².

The location of the experimental biogas storage system shows different wind influences due to the building around. Gusts were observed at higher wind speeds, which led to visible deformations of the outer membrane.

Wacker Bauwerksaerodynamik GmbH [2] investigated the environment as part of the joint research project with a model of the experimental structure in the wind tunnel. Figure 3 shows the model for the wind tunnel studies on the left and the comparison to the behaviour on site as a taken picture on the right. From the wind tunnel tests, depending on the wind direction, wind load distributions were determined acting on the outer membrane. One of the research questions was to find out if the visible deformations results in a change of the wind impact onto the membrane, the internals pressure and the load carrying behaviour of the membranes.

Figure 3: Model of the wind tunnel test [2, p. 10 Abb. 9], left; picture of the experimental set-up [KIT-fgb]

For the comparison of the different methods of numerical simulation the wind pressure is assumed by 0,32 kN/m². This corresponds to a wind speed of 12.8 m/s and is half the value of the maximum wind load according to the German standard for the given location. The wind resistance coefficients are taken from the results of the wind tunnel tests by Wacker Bauwerksaerodynamik GmbH, see Figure 4. The wind load is asymmetric caused by the surrounding building.

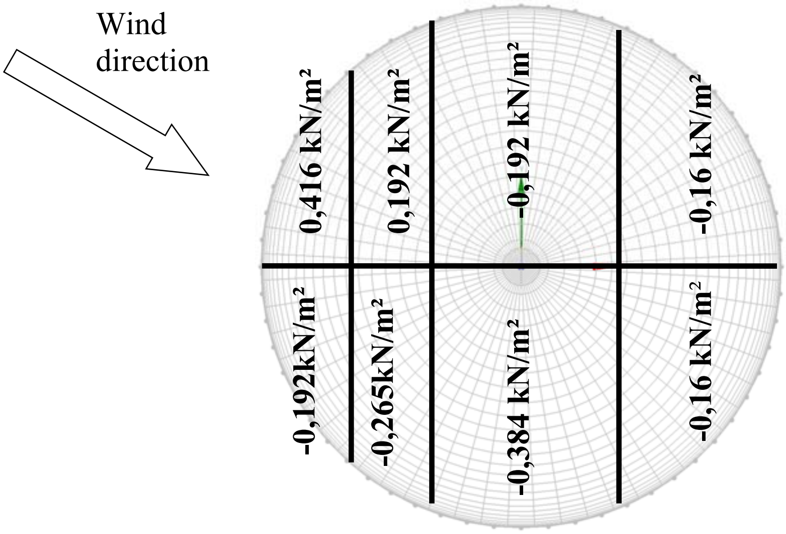

Figure 3: Considered wind load case [KIT-fgb]

4.2 Material properties

The material properties of coated fabric are essentially determined by the structure of the fabric and the behaviour of the coating. In order to analyses the behaviour of the membranes under the influence of wind in the calculations with a certain degree of detailing, biaxial tensile and shear tests were carried out. These tensile and shear tests were made with the same membrane that was used as the outer membrane on the experimental biogas storage system.

The elastic stiffness parameter in warp and weft direction as well as the Poisson ratio were derived from biaxial test based on specific time-loading diagram. This diagram represents the stress ratio in the outer membrane under dead load, internal pressure and wind load. A much-discussed question is the influence of shear stiffness on load-deformation behaviour. The determination of the material characteristics was carried out at the department's own biaxial test facility. For the load tests on shear, the membrane material was cut in the thread orientation by 45 ° twisted. Warp and weft thread run diagonally to the load direction. Their direction is indicated in Figure 4 by the red arrow (warp direction) and by the red wave symbol (weft direction).

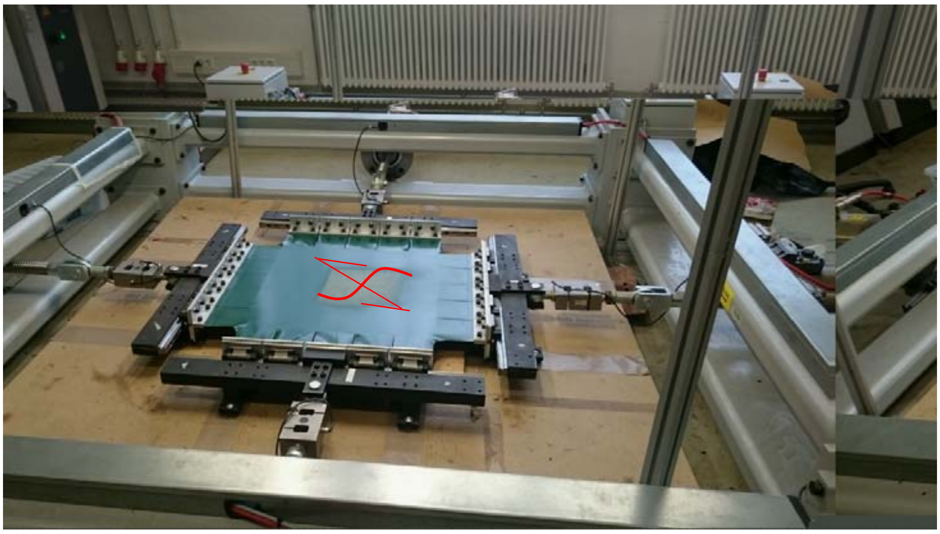

Figure 4: shear test of the outer membrane [KIT-fgb]

This experimental setup allows the determination of the thread twisting, according to constant stresses in warp and weft direction. From the thread twisting, a shear stiffness can be determined in a linear relationship between shear stress and angle twisting. For tensile stresses between 0-20 kN/m, a medium shear modulus of 12 kN/m was found. The linear stiffness matrix used for the calculations is as following given for outer and gas membranes as well as for the pol caps:

$$\text{Membrane} \quad \mathbf{E}_1 = \begin{bmatrix} 800 & 100 & 0 \\ 100 & 500 & 0 \\ 0 & 0 & 11 \end{bmatrix} \text{ and pol cap } \mathbf{E}_2 = \begin{bmatrix} 1600 & 200 & 0 \\ 200 & 1000 & 0 \\ 0 & 0 & 24 \end{bmatrix} \qquad (1)$$

5 COMPARISON

In the following five different approaches of calculation are compared. These differed in the simplification of the model, the consideration of the simplified gas law and contact of the outer and gas membrane as well as the carrying of the wind load vectors normally to the deformed geometry. The application of the outer membrane to the gas membrane and the change of direction depending on the deformed geometry are based on algorithms developed by technet GmbH [3] as part of the joint research project. For the following comparison, the volume of the steel container is dispensed with.

5.1 Simplified model without gas membrane

For load combination deadload, internal pressure as external load and wind the deformations of the outer membrane (red) is given in Figure 5 as result of the above-mentioned load cases and load case combination. The deformations are hardly impossible if the gas volume is filled. The outer membrane penetrates into the gas membrane (green). To avoid this unrealistic behaviour of the outer membrane the internal pressure has to be at least higher than 0,5 kN/m². The deformations are possible for an empty gas chamber, with a filled gas chamber, the outer membrane lies on the gas membrane and leads to an interaction.

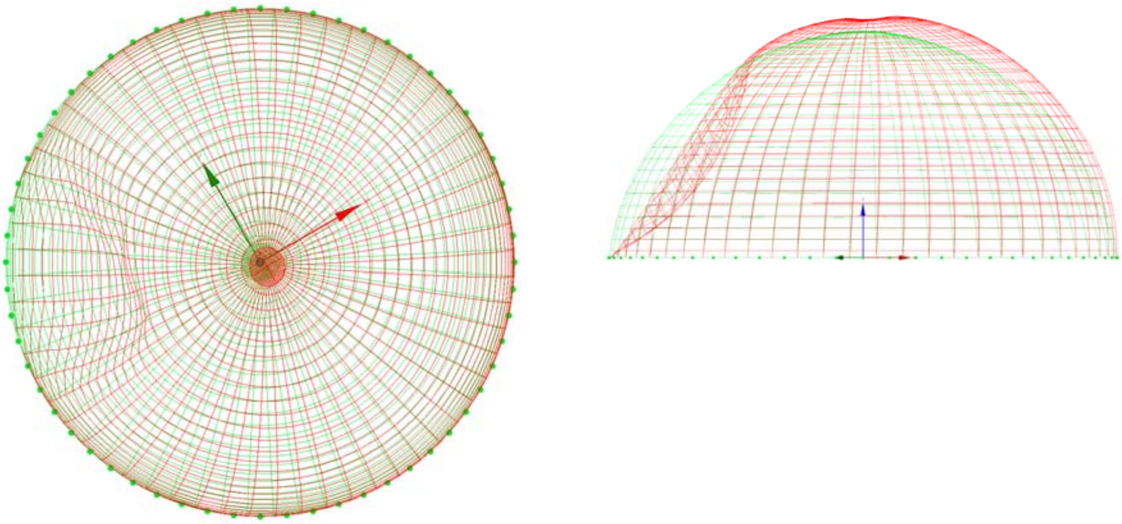

Figure 5: Deformed geometry of the outer membrane (red] and undeformed geometry of the gas membrane (green) [KIT-fgb]

5.2 Double layer membrane with contact, pressure controlled

The calculations are carried out with the boundary condition that the outer membrane can have contact to the gas membrane under wind pressure. The above mentioned two different pressure control options are considered such as pressure and frequent controlled. The internal pressure in the air and gas chamber corresponds to the setpoints of the internal pressure set regulating the pressure in the experimental biogas storage system with 0.35 kN/m² = 350 Pa for the gas volume and 0.25 kN/m² = 250 Pa for the air volume if the pressure is kept constant. The deformations are little smaller compared to the system without gas membrane. The contact of the outer membrane to the gas membrane validates the approach of the interaction between air and gas volume, The stress distribution in the warp direction of the outer membrane changes. The maximum stress is 7,65 kN/m at seam between membrane cover and the pol cap if the influence of the gas volume is neglected. The max. value is hidden by the value 6,1 kN/m in Figure 6. The maximum stress of 4,2 kN/m is in the outer membrane at the clamping of the membrane to the steel cylinder if the gas membrane and the gas volume are included and contact between the two membranes is considered. The internal pressure is kept constant for both calculations.

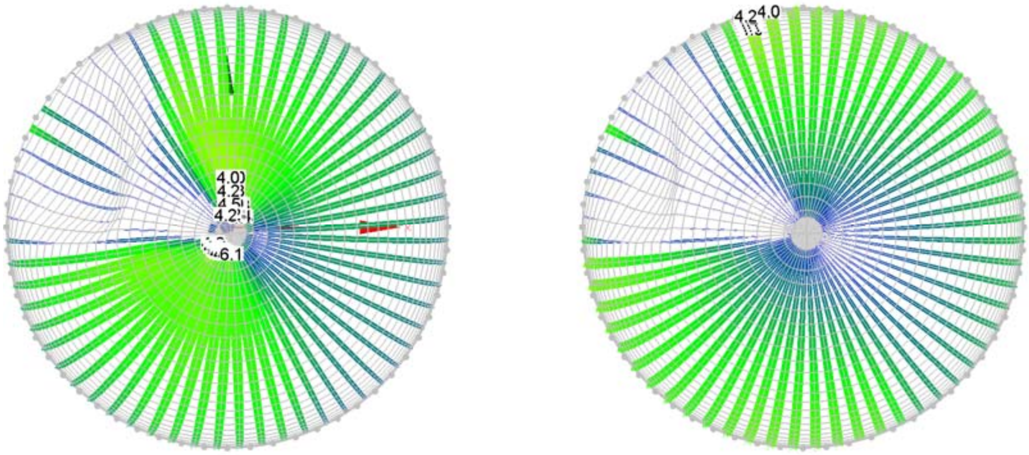

Figure 6: Deformed geometry of the outer membrane [left] and deformed geometry of the outer membrane with contact onto the gas membrane under constant internal pressure, (right), [KIT-fgb]

5.2 Double layer membrane with contact, frequent controlled

The analysis considering the both enclosed volumes is also possible fulfilling the simplified gas law keeping the product of pressure multiplicated with volume constant and providing contact of the membranes. The pressure management requires a constant rotation speed of the ventilators and leads to slightly different pressure in the two chambers compared to pressure control. The analysis of the stress and strain behaviour is carried out with pressure of 270 Pa = 0,27 kN/m² for the air volume between outer and gas membrane and 0,36 kN/m² for the gas volume. The decrease of the air volume if the gas law is considered, results in a higher internal pressure in both chambers. The pressure in the air chamber rises up to 0,284 kN/m² = 284 Pa, the decrease of the volume is only 0,084 m³ from 100.028 m³ without wind load to 99.944 m³ with wind load. The pressure change in the gas chamber is from 0,36 kN/m² up to 0,45 kN/m². This is comparable with the maximum pressure measured on site and approximately the same wind load. The volume change is from 785.297 m³ to 784.512 m³ which is 0,785 m² and also very little. It is showing the sensitivity of the gas chamber in terms of the change in the volume caused by the productions or exhaust of gas during extreme weather conditions. The last comparison is between the system analysed with closed gas volume, contact and nonconservative load, see Figure 8. The difference is in load vectors, which have the direction perpendicular the undeformed geometry of the outer membrane in the left picture. The wind load in the right picture follows the deformation of the surface.

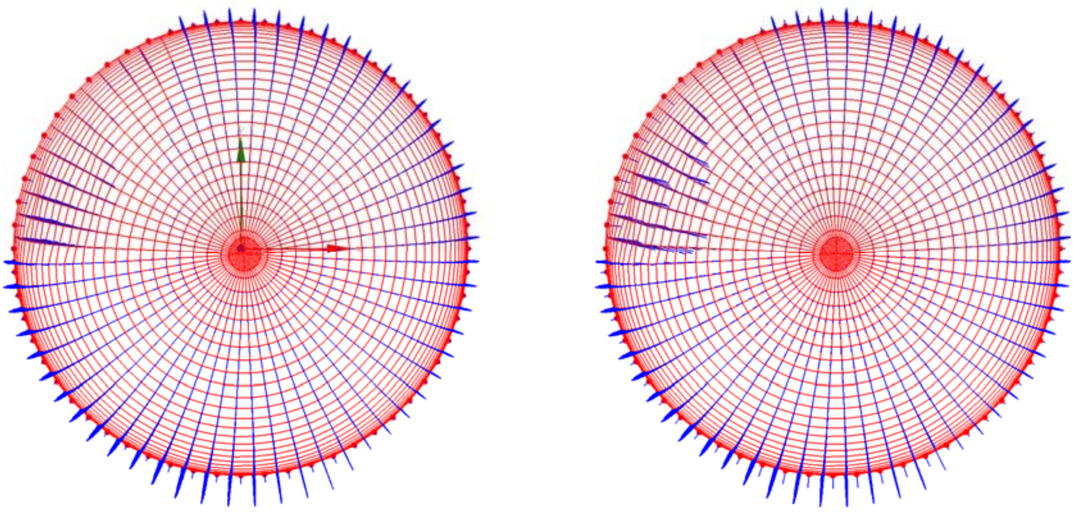

Figure 7: Deformed geometry of the outer membrane with conservative wind load (right) and nonconservative wind load (left) [KIT-fgb]

6 CONCLUSIONS

The calculation of the stress and strain behaviour of a double layer membrane structure can be carried out with different simulation models. The results in deformation are depending on the model. If only the outer membrane is considered, the internal pressure needed to be higher avoiding large deformation. This are prevented if the outer membrane gets in contact with gas membrane and the pressure in the gas chamber is higher than the dead load of the membrane. A still unsolved question is the movement of the gas membrane if the dead load of the gas membrane is in equilibrium with pressure in the air- und gas chamber.

7 ACKNOWLEGEMENT

The results presented in this report had been generated within the R&D Project "Erforschung neuer Lösungen für textile Biogasspeichersysteme", duration 2016 – 2019. The project was founded by the Federal Ministry of Food and Agriculture. Project executing organisation was Fachagentur für nachwachsende Rohstoffe, FNR. Project partners had been technet GmbH, Stuttgart, Wacker Bauwerksaerodynamik GmbH, Birkenfeld, Seybold GmbH Co. KG, Düren.

REFERENCES

[1] ManBio–Entwicklung von technischen Maßnahmen zur Verbesserung des Gasmanagement von Biogasanlagen, Ed.: Deutsches Biomasseforschungszentrum gGmbH, Leipzig 2017.
[2] Erforschung neuer Lösungen für textile Biogasspeichersysteme: Untersuchung der meteorologischen Einflüsse, Ed.: Wacker Bauwerksaerodynamik GmbH, Birkenfeld 2020.
[3] Erforschung neuer Lösungen für textile Biogasspeichersysteme: Entwicklung von Grundlagen für eine Softwarelösung, Ed.: technet GmbH, Stuttgart 2020.