Production and utilization of methane from cowshed gas on farms

M.Sc. **Felix von Arnim**, M.Eng. **Christina Gerdes**, Prof. Dr.-Ing. **Marcus Geimer**, KIT Karlsruhe

Abstract

Methane from cattle farming has a significant influence on climate change. In order to reduce this influence and utilise the potential of methane as an energy source on farms at the same time, the enrichment and separation of cowshed gas was investigated using a diffusion tower and a cryogenic cooling system, both on a laboratory scale. A diffusion enrichment of the methane content (initial concentration < 0.01 Vol. %) from the cowshed gas as described in [1] could not be achieved. The separation of methane from cowshed gas using cryogenic cooling was possible with high purity but high energy consumption. However, increased enrichment using other methods and a continuous process in general can lead to successful enrichment and separation of methane from cowshed gas, the utilisation of this methane on farms and the reduction of methane emissions.

Keywords: cowshed gas, green house gas, low-concentration methane, diffusion, enrichment, separation, cryogenic cooling

Introduction & Motivation

The greenhouse gas (GHG) methane (CH_4) is estimated to have a global warming potential (GWP100) 27 times higher than carbon dioxide (CO_2) over a period of 100 years [2]. The reduction of CH_4 emissions is therefore particularly important for achieving the climate targets. Agriculture plays a special role here, as it is strongly influenced by GHG emissions, has the potential to provide GHG sinks and is also one of the relevant emitters [3]. In 2023, German agriculture - excluding emissions from fossil combustion - was responsible for approx. 52.2 million tonnes (mt) of CO_2 equivalents (CO_2-eq), which accounts for approx. 7.7 % of Germany's total GHG emissions for 2023 [4]. Methane emissions accounted for 64.7 % of the agricultural sector's GHG emissions in 2023. Figure 1 shows the development of the GHG emissions from agriculture per sector and the large proportion of livestock farming. Minimising these emissions is therefore the biggest factor in reducing emissions in agriculture [4]. The main source of methane release are fermentation processes that take place during the digestion of animals and the storage of manure. These caused 35.5 million tonnes of CO_2-eq in 2022 [4], with approx. 95 % coming from dairy cows, heifers and beef cattle [5].

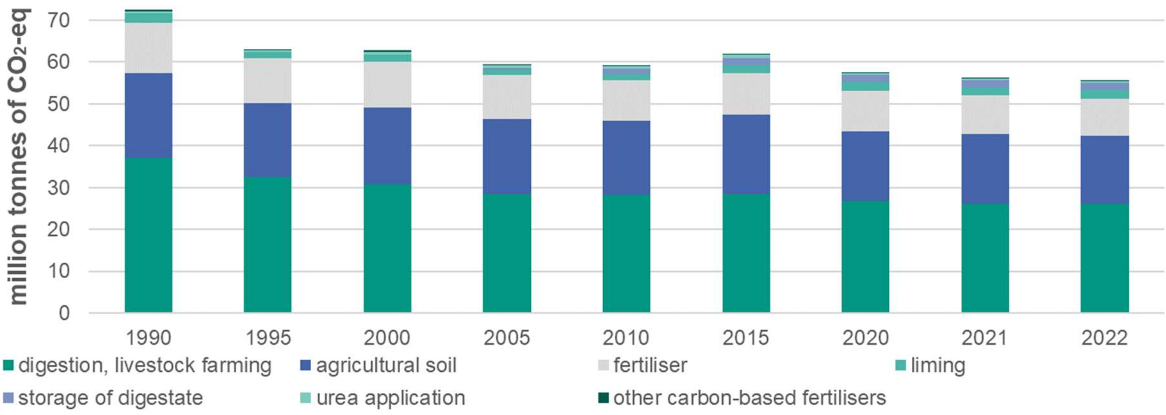

Figure 1: Greenhouse gas emissions from agriculture in Germany by 2022 according to [4]

Dairy cows consume plant-based feed, whereby up to 12 % of the energy contained in the feed is released into the environment in the form of methane via the ructus [6]. The methane concentration in the ructus of a dairy cow is between 0.55 – 0.65 vol.-% at a distance of up to 1 m from the mouth [7]. In respiration chambers, the concentration is between 0.04 and 0.06 vol.-% [8].

GHG emissions from cattle farming are considered unavoidable [9]. They can be reduced by up to 30 % through feeding methods, for example, but the feeding methods can influence the health of cows in a negative way [10]. In 2030, emissions from agriculture must not exceed 56 million tonnes of CO_2-eq, and should be further reduced by 2045 [11]. The GHG reduction target of all sectors in Germany is 65 % compared to 1990 so that GHG emissions previously considered as unavoidable offer new reduction potential [12]. Efforts should be made to capture the gas close to the earth in order to prevent it from entering higher atmospheric layers. At over 50 MJ/kg, methane also has a higher calorific value than diesel [13] and is regarded as a renewable energy source due to its regenerative source, which makes it an interesting future energy source for agricultural machinery, for example.

The aim of the MethAnLand project was therefore to use process engineering measures to capture, enrich and utilise the methane released in a cowshed. It was initially assumed that the methane accumulates under the roof ridge of the cowshed due to density differences between methane and oxygen (O_2). This is because methane has the lowest density of the cowshed air components at 0.718 $\mathrm{kg/m^3}$. It can then be extracted under the roof ridge in a similarly high concentration as in respiration chambers of 0.04 to 0.06 vol.-%. After collection, methane enrichment should be efficient and technically easy to realise on the farm. A degree of enrichment up to the lower explosion limit (LEL 4.4 %) [14] was aimed for safety reasons. The enrichment was carried out using the diffusion tower presented in the next chapter, the basic idea of which is based on the work of [1] and [15]. There, an enrichment of 0.1 vol.-% every 10 m tower height is envisaged. However, as the test rig of [1] is only 2 m high, this statement is analysed in this paper in addition to the question of whether enrichment is possible at all. Furthermore, the methane in the MethAnLand Project was then to be separated by cryogenic cooling for the use as an energy source. The different boiling and melting temperatures of the air components and methane were utilised here. The gas mixture was separated into its individual components by gradual cooling and heating [16]. The overall project results section shows that this method is successful but energy-intensive and that separation with the highest possible methane content makes technically the most sense [16].

The extracted methane could either be fed into biogas plants, used in combined heat and power plants (CHP) or further processed into liquid bio methane (LBM), also known as bio-LNG, or in compressed natural gas (CNG) to use it as fuel in agricultural machinery. Overall, a reduction in nationwide GHG emissions of up to 5.3 % is possible [4].

Testbench diffusion tower at Institute Mobile Machines

The construction of the testbench is based on the enrichment results of [1]. The aim was to enrich the methane of cowshed gas with a diffusion tower. The enrichment method was equal to [1]. The project aimed to measure whether and how fast methane from cowshed gas rises to the top and if other components of the cowshed gas influence this diffusion process. The speed of enrichment is directly related to the space required for enrichment, but these space requirements and plant sizes increase the costs of the process. The diffusion tower must be high enough to overcome the sensor tolerance. For the methane measurements the PIR 7000, type 334 from Dräger was used. Its repeatability with normal response behaviour is ≤ ± 0.5 % LEL (lower explosion limit) [17] which leads to a sensor tolerance of ≤ ± 0.022 vol.-%. Especially due to the low relative methane amount a tower with the height of 3 m (diameter of 0.5 m) was used to overcome the sensor tolerance. Based on the assumptions of [1], an enrichment of 0.03 vol.-% (≈ 0.68 % of LEL) should be measurable in the diffusion tower with a height of 3 m. Accordingly, an enrichment outside the sensor tolerance should be measurable.

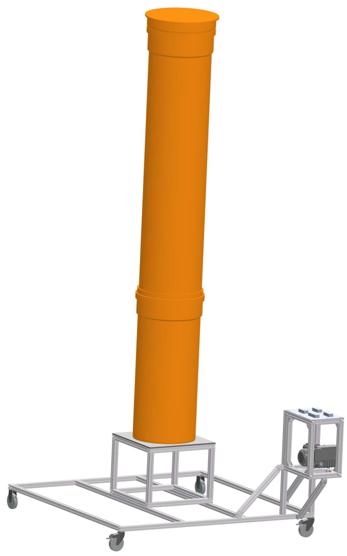

Figure 2: Diffusion tower

Figure 2 shows a CAD-model of the diffusion tower. Hard plastic drain pipes were used as shell of the tower and the top cover. The diffusion tower itself was placed on a pedestal to enable cable and tube entry from below via a base plate and cable passageways. For safety reasons a pressure relief valve and a fan were added at the bottom of the tower. For the pedestal and the construction inside the tower to fix the sensors on (the sensor tree), aluminium profiles were used. A pump and pressure reducer were used to clean the tower with fresh air and to control the entrance cowshed gas flow.

Inside the tower three methane sensors (PIR 7000 from Dräger, type 334) were installed in three different levels, at a height of 0.2 m; 2.0 m and 2.9 m (position 1 to 3). In case of methane amounts above 3.5 % these sensors give an alarm signal to avoid methane amounts above the LEL of 4.4 % [14]. Additionally, oxygen sensors were installed to control whether there is a layering of methane and oxygen due to diffusion processes. The oxygen sensors (Polytron 3000 from Dräger) were installed at the same height as the methane sensors. The whole construction was placed in the lab of the Institute of Mobile Machines with a continuous temperature of 21 °C.

Results from diffusion tower

Regarding to [15] a methane enrichment of 0.1 vol.-% per 10 m was expected; which means 0.03 Vol % at the highest measurement in the tower (3 m). But the results of the MethAnLand project do not prove the findings of [15]. There was no significant increasement of the methane amount due to diffusion on any measurement point. There was also no shift in the layers of oxygen and methane and the oxygen amount did not change during five days of measurement.

Figure 3 shows the measurement results of methane in % of LEL and oxygen content in vol.-% of an air-methane mixture over 4 days. The amounts of methane vary between 2.4 and 2.78 % of LEL in the different

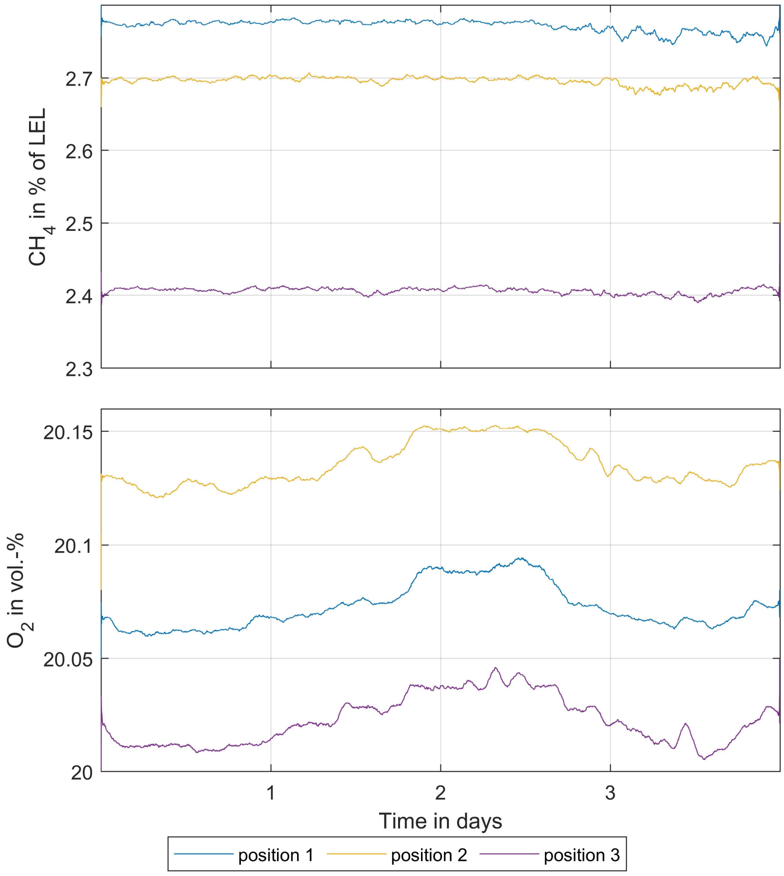

Figure 3: Development of CH_4 and O_2 amounts at 3 heights

positions; those from oxygen between 20.01 and 20.16 vol.-%. To detect an enrichment of methane, the amplitudes per position are relevant. An increase of 0.03 vol.-% (≈ 0.681 % of LEL) on the top position (position 3) was expected. The small variations during the measurement period in Figure 3 are lower and remains within the tolerance limit (≤ ± 0.5 % LEL) mentioned above. This result did not fit the theory of [1] and [15]. The upward diffusion of methane could neither be detected by measuring the amount of methane nor by displacement of oxygen downwards.

Overall Results of MethAnLand-Project

The second major part of the project focussed on separating the enriched methane from the other cowshed gas components with the greatest possible purity to use methane as liquid bio methane (LBM). For this purpose, a test stand based on cold traps had to be constructed, which guides the breathing and exhaust air through a two-stage cooler cascade. The experimental setup with two cryogenic coolers in the centre is described in [16]. Liquid nitrogen was used as coolant.

The step-by-step sequestration of the cowshed gas began with CO_2 separation as dry ice in the first cooler. The residual air escaping from this cooler was then pumped into the second cooler, where O_2 and CH_4 condense. During the separation of O_2 and CH_4, alternating condensation and vaporisation of O_2 results in temperature fluctuations between -180°C and -162°C and thus a pulsating release of O_2. In the end, the CH_4 remained as a liquid in the second cooler. [16]

The energy efficiency of the cryogenic system for CH_4 separation from the respiration chamber gas was 0.15 %, which is 37 MJ/g LNG. If the CH_4 concentration fed in is increased by a factor of 5 to 10, the energy efficiency also increased fivefold to 0.75 %, which corresponds to 7.4 MJ/g LNG. The low energy efficiency of cryogenic cooling is primarily due to the high flow rate of liquid N_2 (2.5 to 3.2 kg/h) and the leakage of the coolant into atmosphere. Future projects should therefore focus on recirculation of the cooling medium and improved heat recovery, considering the counterflow principle and better insulation. The low energy efficiency of the overall process is mainly due to the extremely low initial concentration of methane and the insufficient enrichment prior to cryogenic cooling. The results of cryogenic cooling show that the cryogenic system developed can be used with optimisable efficiency but high purity. [16]

In order to be able to utilise the generated LBM on a farm at a later date, a utility value analysis was also carried out. This showed that a combined heat and power unit (CHP) performs best in terms of power consumption, costs, maintenance, environmental compatibility and several other points. [7]

Conclusion and outlook

The enrichment results of [1] and [15] could not be verified with the diffusion tower presented, even though it was 50 % higher than that in [1] and [15]. The enrichment of 0.01 vol. % per meter could not be detected, although the height of the tower was higher than required by the sensor tolerance. The separation of methane from cowshed gas using cryogenic cooling has been successfully demonstrated.

To make the enrichment and separation process more ecologically and economically efficient, it should run continuously in future. Larger coolers would also be useful. This could lead to a significant reduction in CH_4 and CO_2 emissions from cowsheds. However, the linear dependence of enrichment and separation efficiency shows that a significant increase in efficiency can be achieved by increased and faster enrichment of the cowshed gas prior to cryogenic cooling. Possibilities to achieve a higher initial concentration for the separation are the enrichment with vortex tubes [18] and the near-mouth capture of methane by head boxes [19].

Instead of the energy-intensive production of LBM, the cowshed gas enriched to around LEL could alternatively be used directly in a CHP, which is the best utilisation alternative on the farm according to the utility value analysis carried out. This is because it would be possible to operate a CHP based on flow reversal reactors: Catalytic Flow Reversal Reactors (CFRR) and Thermal Flow Reversal Reactors (TFRR) can already operate with concentrations of approx. 0.06 vol.-% and 0.19 vol.-% respectively [20]. This means that the energy source is on the farm and only CO_2 is emitted after burning the methane, which reduces the GHG.

The reduction of GHG emissions from livestock farming in agriculture through enrichment and separation is possible overall, but further research is required for efficient implementation.

Acknowledgements

The project MethAnLand was funded by the German Federal Ministry of Food and Agriculture (BMEL) under the funding indicator 28N-2-005-01.

References

[1] Wang, W.; Ren, J.; Li, X.; Li, H.; Li, D.; Li, H.; Song, Y.: Enrichment experiment of ventilation air methane (0.5%) by the mechanical tower. Scientific reports 10 (2020) H. 1, S. 7276.

[2] Lee, H. e. a.: IPCC 2023 Synthesis Report Summary for Policymakers. TSU Compiled Version, 2023, URL: https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf.

[3] Lakner, S.; Jurasinski, G.; Sommer, P.: Klima und Landwirtschaft – Auswirkungen und Politikoptionen für eine nachhaltige Transformation für mehr Klimaschutz. Bundeszentrale für politische Bildung, 2021, URL: https://www.bpb.de/themen/umwelt/landwirtschaft/343030/klima-und-landwirtschaft/, Zugriff am: 06.08.2024.

[4] Umweltbundesamt: Beitrag der Landwirtschaft zu den Treibhausgas-Emissionen. URL: https://www.umweltbundesamt.de/daten/land-forstwirtschaft/beitrag-der-landwirtschaft-zu-den-treibhausgas#klimagase-aus-der-viehhaltung, Zugriff am: 24.04.2023.

[5] Haenel, H.-D.; Rösemann, C.; Dämmgen, U.: Calculations of gaseous and particulate emissions from German agriculture 1990 - 2018: Input data and emission results. Göttingen: Open Agrar Repositorium 2020, DOI: 10.3220/DATA20200312140923.

[6] Johnson, K. A.; Johnson, D. E.: Methane emissions from cattle. Journal of animal science 73 (1995) H. 8, S. 2483-2492.

[7] Gerdes, C.; Arnim, F. von; Geick, T.; Geimer, M.; Kuhla, B.: Abschlussbericht MethAnLand 2024.

[8] Derno, M.; Elsner, H.-G.; Paetow, E.-A.; Scholze, H.; Schweigel, M.: Technical note: a new facility for continuous respiration measurements in lactating cows. Journal of dairy science 92 (2009) H. 6, S. 2804-2808.

[9] Doms, M.; Bischof, B.; Kajimura, R.: Landwirtschaft und Klimaschutz – Eine Orientierungshilfe. Agentur für Erneuerbare Energien e.V. (Hrsg.), 2022, URL: https://www.unendlich-viel-energie.de/media/file/4651.AEE_Landwirtschaft_und_Klimaschutz_Mai22.pdf.

[10] Hristov, A. N.; Melgar, A.; Wasson, D.; Arndt, C.: Symposium review: Effective nutritional strategies to mitigate enteric methane in dairy cattle. Journal of dairy science 105 (2022) H. 10, S. 8543-8557.

[11] Bundestag: Bundes-Klimaschutzgesetz – KGS (2019).

[12] Bundesregierung: Klimaschutzprogramm 2023 der Bundesregierung 2023, URL: https://www.bmwk.de/Redaktion/DE/Downloads/klimaschutz/20231004-

klimaschutzprogramm-der-bundesregierung.pdf?__blob=publicationFile&v=10, Zugriff am: 06.08.2024.

[13] Ays, I.; Geimer, M.: Methane-Fuel cell-CCS-Drive: the emission-free working machine. DOI: 10.5445/IR/1000091557. 7. Fachtagung Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen, 20.02.2019, Karlsruhe. In: Geimer, M.; Synek, P.-M. (Hrsg.): 7. Fachtagung Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen, Karlsruher Schriftenreihe Fahrzeugsystemtechnik, Bd. 67, KIT Scientific Publishing 2019.

[14] GESTIS-Stoffdatenbank: Methan. Institut für Arbeitsschutz der Deutschen gesetzlichen Unfallversicherung, URL: https://gestis.dguv.de/data?name=010000, Zugriff am: 15.04.2023.

[15] Wang, W.; Wang, H.; Li, H.; Li, D.; Li, H.; Li, Z.: Experimental Enrichment of Low-Concentration Ventilation Air Methane in Free Diffusion Conditions. Energies 11 (2018) H. 2, S. 428-438.

[16] Pethani, K. B.; Geick, T.; Kuhla, B.: A pilot study to capture methane from the exhausted air of dairy cows using a cryogenic approach. Journal of environmental management 356 (2024), S. 120588.

[17] Dräger Safety AG & Co. KGaA: Dräger PIR 7000 / Dräger PIR 7200 – Gebrauchsanweisung 2022.

[18] Kulkarni, M. R.; Sardesai, C. R.: Enrichment of Methane Concentration via Separation of Gases using Vortex Tubes. Journal of Energy Engineering 128 (2002) H. 1, S. 1-12.

[19] Levrault, C. M.; Eekelder, J. T.; Groot Koerkamo, P.; Ploegaert, J.; Ogink, N.: Measurement of dairy cows‘ individual methane production rates: the Cubicle Hood Sampler, an on-barn alternative. In: AgEng-Land.Technik 2022 – International Conference on Agricultural Engineering ; November 22nd and 23rd 2022, Berlin, VDI-Bericht, Bd. 2406, Düsseldorf: VDI Verlag GmbH 2022, DOI: 10.51202/9783181024065, S. 85-91.

[20] Gosiewski, K.; Pawlaczyk, A.; Jaschik, M.: Energy recovery from ventilation air methane via reverse-flow reactors. Energy 92 (2015), S. 13-23.