Challenges in the Use of Alternative Fuels: Solutions to handle Boil-Off Gas in Agricultural Machines

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Abstract

To meet the climate targets, it is necessary to reduce greenhouse gas emissions from all areas. Liquefied Natural Gas (LNG), which consists largely of methane, can be produced sustainably and it is suitable for mobile machines due to its high energy density. When storing LNG at ambient temperatures, evaporation creates boil-off gas. Methane is a climate-damaging greenhouse gas that must not be released into the environment. Therefore, in this paper, concepts are developed and evaluated that enable the use of LNG in mobile machines without blowing off gas during dormant periods. Using a simulation model, the components of the most suitable concept for a combine harvester are selected and dimensioned.

Introduction and Agricultural Background

Slowing down climate change and achieving the 1.5-degree-target by decarbonising mobility and the economy are some of the most important challenges of our near future. Mobile machines and especially agricultural machines face special challenges since a high energetic autonomy [1] and minimal axle loads are required. Alternatives to fossil fuel drivetrains are necessary which still fulfil the same performance demands.

Among these alternatives, LNG has one of the highest gravimetric and volumetric energy densities (see Table 1) and therefore has a high potential for agricultural applications. Studies on heavy diesel trucks have shown that CO_2 emissions can be reduced by up to 20% by using LNG [2]. If produced from renewable sources Bio-LNG can reduce CO_2 emissions by up to 77 % [3]. The process chain from production of Bio-LNG to refuelling and use in agricultural machines is investigated in the ProBioLNG project [4].

LNG consists of natural gas or, as in the ProBioLNG project, biogas. It is liquefied by cooling it to cryogenic temperatures at atmospheric pressure to -160°C depending on the composition [5]. Despite being stored in double-walled tanks with near-vacuum in between, heating of the cryogenic LNG occurs leading to a change in the aggregate state at the surface. The resulting gas is called boil-off gas (BOG) [5], which causes the volume to increase by a factor of 600 and the pressure in the tank to rise sharply. Economizers are used in the operation of LNG-fueled vehicles to allow BOG to flow from the tank into the fuel line [6]. Agricultural machines are often used seasonal and therefore are dormant for long periods (Table 2). This contrasts with the holding times of the insulated tanks of 5-10 days [7].

At an overpressure, in large industrial plants or trucks at standstill it is state of the art to blow off the excess BOG into the atmosphere. Because methane is about 25 times more harmful to the climate than CO_2 [8], it is burned to reduce the climate damaging effect. This is not suitable for agricultural machines because their environment contains easily flammable elements. Thus, a solution must be found to avoid BOG in tanks or to keep it under control during dormant periods. This paper therefore develops concepts and selects the best ones using a combine harvester as an example.

Table 1: Comparison of different fuels according to [9] [10] [11]

		Diesel	H_2 at 700 bar	liquid H_2	LNG	battery
Temp.	$^\circ C$	15	0	-253	-162	N/A
density	kg/m^3	820	41.7	70.8	423	N/A
gravimetric density	MJ/kg	42.9	120	120	50.0	0.7
volumetric density	MJ/l	35.2	5.0	8.5	21.2	1.4

Table 2: Agricultural machine's utilisation and dormant periods according to [12] [13]

	machine utilisation	dormant periods
combine harvester	daily 10-12 hours nonstop heavy duty during harvest time	completely in winter, between crop rotations in summer 2-4 weeks
tractor	daily, light to heavy duty	in winter up to 3 months possible
telehandler	daily, light duty	max 1 day

Development and Evaluation of Concepts

The two basic approaches to reduce the pressure in the tank caused by the BOG are either active cooling of the tank or withdrawing of BOG. This enables multiple implementation options. If BOG is taken from a tank it can be stored in an additional tank or it can be converted into mechanical and electrical energy using a gas engine connected to an alternator, e.g. the alternator of the vehicle. For the gas engine the main engine of the vehicle can be used or an additional engine optimized for the smaller loads. The generated electrical energy can either be stored in a battery or used to run the cooling system. In addition, the components can be located on the vehicle or externally to reduce weight and installation space. Suitable cooling systems consist of a cold head in the tank where the coolant absorbs heat and a compressor where it releases the heat again. All the different components and possible combinations are shown in Fig. 1. Due to the many possibilities the following concepts are conceivable:

Concept 1: Assuming an every day operation of the machine, the main engine operates with BOG supplied via the economizer. No critical pressure is reached.

Concept 2: A cooling system with a compressor and a cold head extends concept 1. The externally located compressor is operated via the external power grid.

Concept 3: In addition to concept 2, an alternator driven by the main engine can supply a battery, which powers the cooling system. The battery is charged only by the main engine, creating a grid-independent BOG handling system (BHS). This removes BOG from the tank to run the cooling system self-sufficiently.

Concept 4: A second smaller engine operates the alternator which is adapted to the resulting mass flow of the BOG and the power requirement of the cooling system and therefore operates more efficiently.

Concept 5: The holding time is further extended by discharging the BOG into a CNG tank.

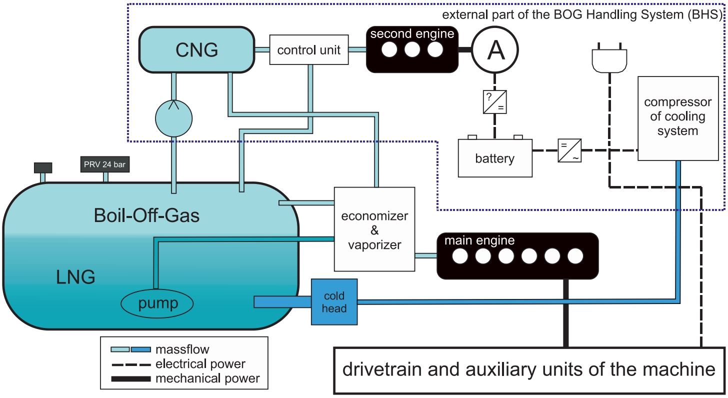

Fig. 1: Most comprehensive concept with all possible components

To narrow down the concepts using the example of a combine harvester, the premise is used that no BOG may be blown off within four weeks. This condition cannot be met by concept 1 because BOG in the tank reaches maximum pressure after at least ten days [7] without further action. The CNG tank in concept 5 does not solve the issue itself, but postpones the time of blow-off and requires a lot of space. Concepts 1 and 5 are therefore not investigated further. Concepts 2 to 4 are suitable to fulfil the above premise. Concept 2 is dependent on a power grid and therefore cannot be operated self-sufficiently in contrast to concepts 3 and 4. Because concept 3 needs less additional components it is preferred over concept 4. In order to check their suitability and to dimension the components of the chosen concepts 2 and 3, the next section simulates them using a combine harvester as an example.

Operating strategies

Depending on the concept, different operating strategies are tested. For both concepts the BOG reduction measures are starting when the pressure in the tank reaches a critical value.

With the connection to the electricity grid, the cooling system of concept 2 will cool the tank until the pressure is lowered to a defined value p_1 (strategy 1).

For concept 3, two different strategies are examined. In the first strategy, the BOG is first relieved to run the main engine and the alternator to charge the battery. After the critical pressure is reached again the energy of the battery is used for the cooling system until the battery is empty (strategy 2).

In the second strategy of concept 3 (strategy 3), a distinction must be made between two cases. In case 1 the provided power by the alternator is higher than the required power of the cooling system. Then the cooling system is first run with the battery. Once the battery is empty the main engine starts running the alternator with BOG as the fuel and simultaneously charges the battery and supplies power for the cooling system until the battery is full.

In case 2 the power of the alternator is lower than the power required by the cooling system. First the alternator operated by the main engine and the battery provide power at the same time. Once the battery is empty it is recharged by the alternator and the engine.

Simulation Model

In order to analyse the energy demand of a BHS during long dormant periods a simulation model was created. In that model battery capacity, alternator power, initial filling level, the strategies and the pressure p_1 of concept 1 were variated to find optimal configurations.

The simulation was created in MATLAB and Simulink with the structure shown in Fig. 2. The tank consists of a two-phase model of the LNG and BOG. The volume of the tank is 1863 litres which allow to store the same amount of energy as the diesel tank of a Claas Lexion [14]. At the beginning of the simulation, the tank is filled by 75 % of LNG at a common operating pressure of 10 bar [15]. The geometry is based on commercially available LNG-Tanks [16] that have a diameter of 0.65 m with various length configurations. Using the same diameter, the length of the used LNG-tank is adjusted to the volume. There is a heat flow into the tank which consists of the difference between the heat flow from the environment minus the cooling power of the cooling system. The heat flow from the environment is calculated from the temperature difference between the ambient temperature of 20 °C and the LNG temperature, the tank geometry and the heat transfer coefficient of $\alpha = 0.04 \frac{\mathrm{W}}{\mathrm{m^2 \cdot K}}$ which is determined on the basis of holding time and initial fill levels from [7] [17].

For the cooling system the characteristics of the Cryomech AL125 (for properties see Table 3) is used with a cooling power of about 120 W at -160 °C and an input power of 3.3 kW. At the beginning of the cooling process a cooling curve is considered [18].

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The tank is connected to the economizer and the gas engine. For the engine the characteristics of the 220 kW gas engine E2676 LE202 from MAN is used [19]. Based on the power demand of the alternator and the efficiency of the specific working point the BOG flow out of the tank is calculated. The cold start behaviour of the engine is neglected.

The power provided by the engine is multiplied by the efficiency of the alternator and subtracted by the power of the cooling system. The resulting power difference is integrated by the battery. For automotive alternators an efficiency between 50 % and 60 % can be estimated [21]. To be able to estimate the result of the simulation downwards, the efficiency is set to 50 %. For the battery an efficiency of lithium ion batteries of 95 % is used [22].

Table 3: Properties of Cryomech AL125 [20]

Volume cool head:	9 l
Weight cool head:	13.2 kg
Volume air compressor:	151 l
Weight air compressor:	80 kg
Max. pressure:	16 bar
Costs:	approx. 28 000 €

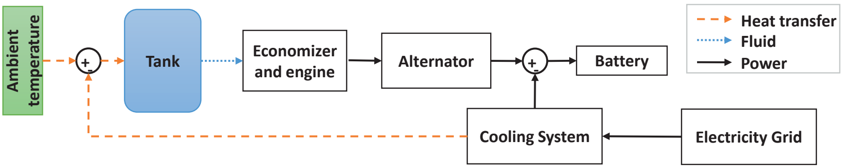

Fig. 2: Structure of the simulation

Simulation results

Two effects can be observed with concept 2 (Fig. 3): The closer the pressure p_1 gets to the critical pressure of the tank of 16 bars, the higher the electricity consumption becomes. This is due to the cooling curve at the beginning of the cooling process. At lower pressures the temperature difference of the tank to the ambient temperature and the heat flow into the tank increase, which also leads to a higher energy demand. The fluctuations at low pressures result from the situations at the end of the simulation. A high peak in electricity consumption occurs when the system cools down exactly at the end of the simulation. For the optimal pressure of p_1 of 15 bars 914 kWh over 4 weeks are necessary. This equals an average

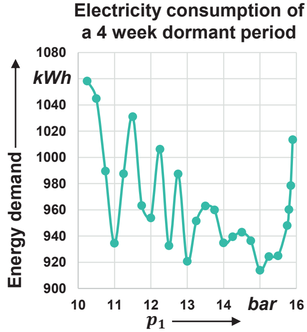

Fig. 3: Results concept 2, strategy 1

energy demand of 37.8 kWh per day after the holding time of the tank is reached. To reduce pressure from 16 to 15 bar, the cooling system runs for 12 hours on average.

For concept 3 the higher the power of the alternator the lower is the required energy (Fig. 4 and Fig. 5). This is due to the better efficiency of the main engine at higher loads. Comparing strategy 2 and 3 there is almost no difference for large battery sizes between 300 and 600 Ah, but for smaller battery sizes strategy 3 shows better results. An exception is the peak of strategy 3 at an alternator output of 3.5 kW. When the alternator power is slightly larger than the power needed from the cooling system, it takes a long time to charge the battery. Thus the tank pressure and temperature get very low and this results in a higher heat flux from the environment. On average for a battery size between 300 and 600 Ah and an alternator power between 7 and 10 kW the required energy for strategy 2 is 2980 kWh. Strategy 3 is slightly better with an energy demand of 2950 kWh, which corresponds to an average energy demand of 122 kWh per day (strategy 3) after the holding time is reached. This equals a total loss of 212.7 kg methane compared to a loss of 355.7 kg over 4 weeks if the BOG is blown off.

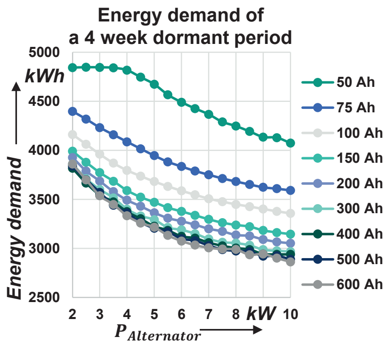

Fig. 4: Results concept 3 with strategy 2

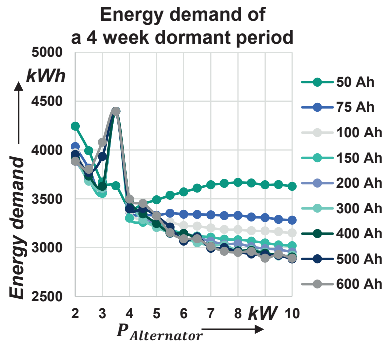

Fig. 5: Results concept 3 with strategy 3

Conclusions and Outlook

An overview over possible concepts to handle BOG in agricultural machines was given. Concept 2, requiring a connection to the electricity grid, and concept 3 as a self-sufficient solution were modelled and simulated for a dormant period of 4 weeks. After the holding time of the tank is reached on average 37.8 kWh to 123 kWh are required per day to operate a BHS. The energy demand of concept 2 can be improved if a more efficient cooling system is used. In addition, concept 3 offers optimization opportunities for the alternator and the gas engine. If an additional gas engine optimized for small loads and a more efficient alternator is used, the methane demand can be reduced by up to 30 %.

In real applications there will not be enough space to store the LNG in only one large tank. In further research concepts with multiple LNG tanks and cooling heads need to be investigated.

Acknowledgement

Many thanks to M.Sc. Daniel Sichermann for his help in creating the simulation model as part of his master's thesis. The authors would also like to thank the BMBF (Bundesministerium für Bildung und Forschung, Germany) for funding the ProBioLNG-project.

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