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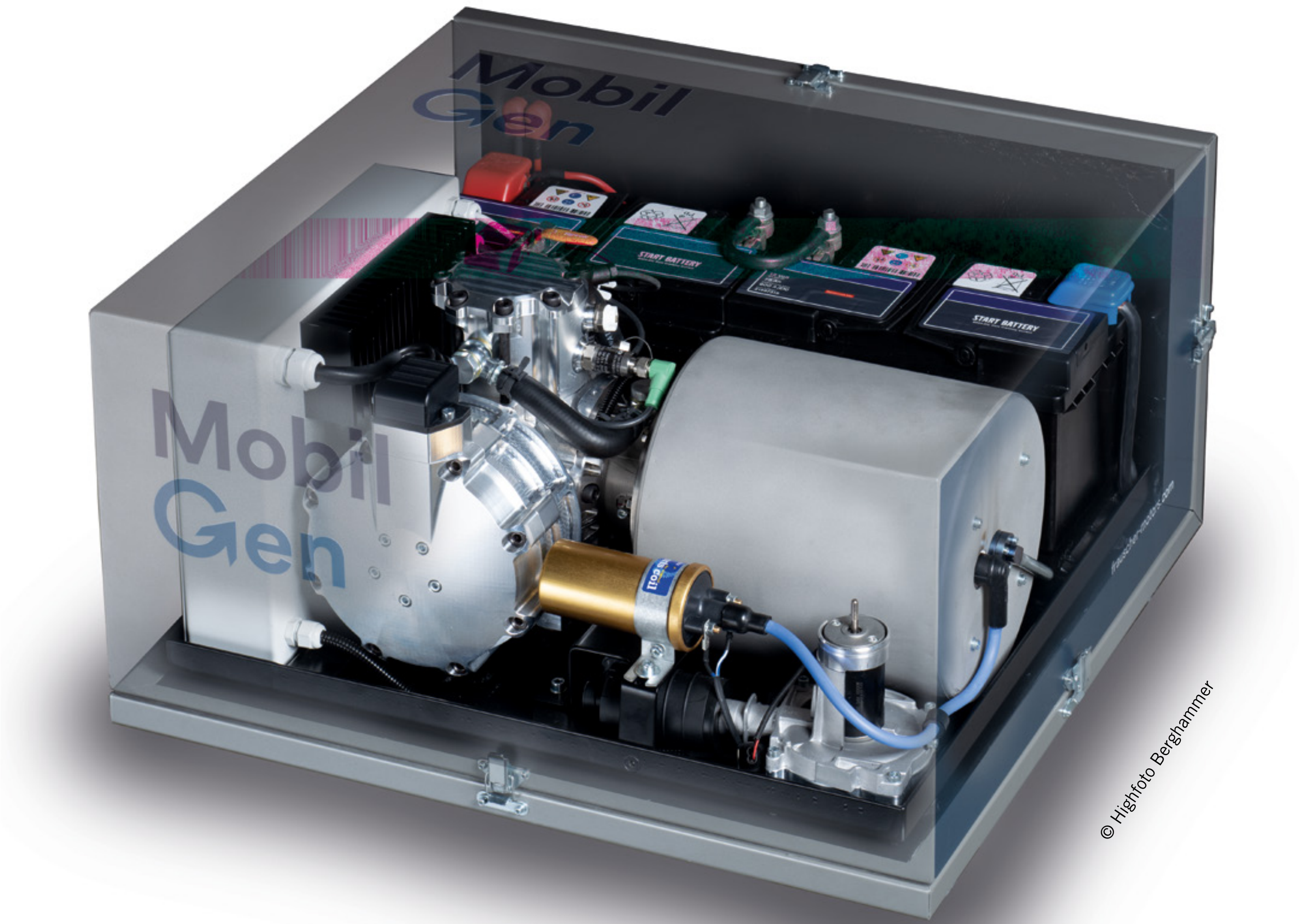
RESEARCH AND DEVELOPMENT

Stirling Engine to Air Conditioning of Trucks



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Air Conditioning for Trucks with Hotel Function

In view of rising ambient temperatures, there are more and more calls for the mandatory installation of parking coolers in trucks. For sustained cooling however, the capacity of the on-board batteries is not sufficient to supply the air conditioning system permanently. The only remedy is to start the diesel engine with all the consequences for noise, wear, wasted energy and environmental pollution. A new type of Stirling engine from Frauscher Motors could reduce the problems.

With MobilGen, Frauscher Motors is developing a simple solution for supplying electrical energy and heat to parked trucks with hotel functions. In doing so, the considerable advances in Stirling engine research in recent years could be used, which have led to efficient, clean and quiet drives in the course of a newly developed technology. The development process up to a demonstration unit is described below.

ALPHAGAMMA STIRLING TECHNOLOGY

The basis for the MobilGen project was the success in using a new Stirling engine technology that combines the alpha principle (consists of a compression piston and an expansion piston) with the gamma principle (consists of a displacement piston and a working piston). The core element is a patented stepped piston [1], which largely keeps the compression work away from the crank mechanism. The consequence

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of this is a strong reduction in the piston forces compared to the known principles [2]. The reduced piston normal forces allow maintenance-free operation with dry-running piston guides, as are known, for example, from dry-running compressors. Thanks to a first-order mass balance, the unit consists of just five moving parts, namely two pistons, two connecting rods and the crankshaft. In a previous project regarding the oxidation of lean gas, alphagamma engines of the 7.5 kW class, equipped with asynchronous generators achieved overall electrical efficiencies (lower calorific value of the fuel to electrical output power) of more than 30 % [3]. This was the starting point for investigating the application of combined heat and power in a mobile operating environment.

CHALLENGING REQUIREMENT SPECIFICATIONS

Discussions with representatives of the truck industry brought a range of requirements for a corresponding aggregate, which can be summarized as follows:

- no increase in vehicle mass
- installation space approximately within the volume of conventional battery boxes
- no time limit for the electricity supply of commercial parking air conditioners
- heat supply to the extent of standard parking heaters
- fuel efficiency equal to or better than previous systems
- exhaust emissions in compliance with Euro Stage V limits
- continuous operation without distracting vibration and noise emissions
- suitable for different fuels: diesel, LNG, CNG, synthetic fuels
- maintenance free
- automotive test and approval conditions.

These specifications are maximum requirements. During the interviews, the urgent need for such solutions could be heard, which is also expressed in various truck-driver internet blogs.

First, it had to be proven whether there was a general prospect of meeting the requirements according to "no increase in vehicle mass" and "installation space approximately within the volume of conventional battery boxes." The on-board power supply of heavy commercial vehicles with hotel functions usually consists of two series-connected lead-acid batteries, each with 12 V and a capacity of 225 Ah, in order to ensure both the starter function and the supply of consumers when the vehicle is parked. Such a battery pack, according to DIN EN-50342-4 has a mass of about 120 kg and takes up at least a volume of about 558 × 518 × 250 mm. Assuming that a separate power source covers all electrical consumers of the parked vehicle, the required battery capacity is reduced to a battery set with 75 Ah, which is sufficient to start the diesel engine when fully charged [4]. This creates free space for the installation of an appropriately dimensioned generator, **FIGURE 1**. The saving in battery mass alone is 77 kg. In order to meet the requirement according to "no increase in vehicle mass," this mass was initially set as the upper limit for the mass of the generator including accessories.

DEFINING THE APPROPRIATE ELECTRICAL POWER

As an orientation, the power consumption of a parking air conditioner as the largest consumer was used to define the electrical power requirement. The data sheets from the manufacturers of roof air conditioning systems, for example, show currents of up to 24 A. However,

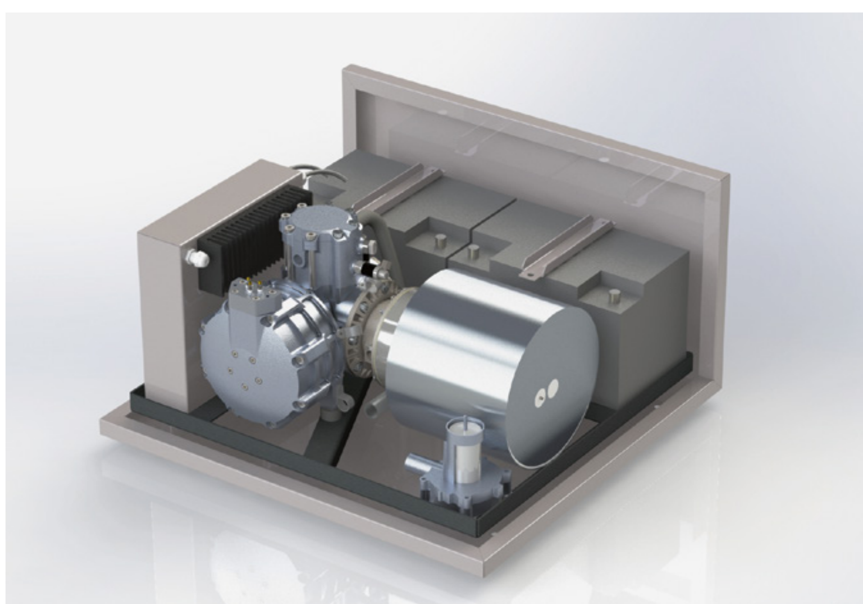


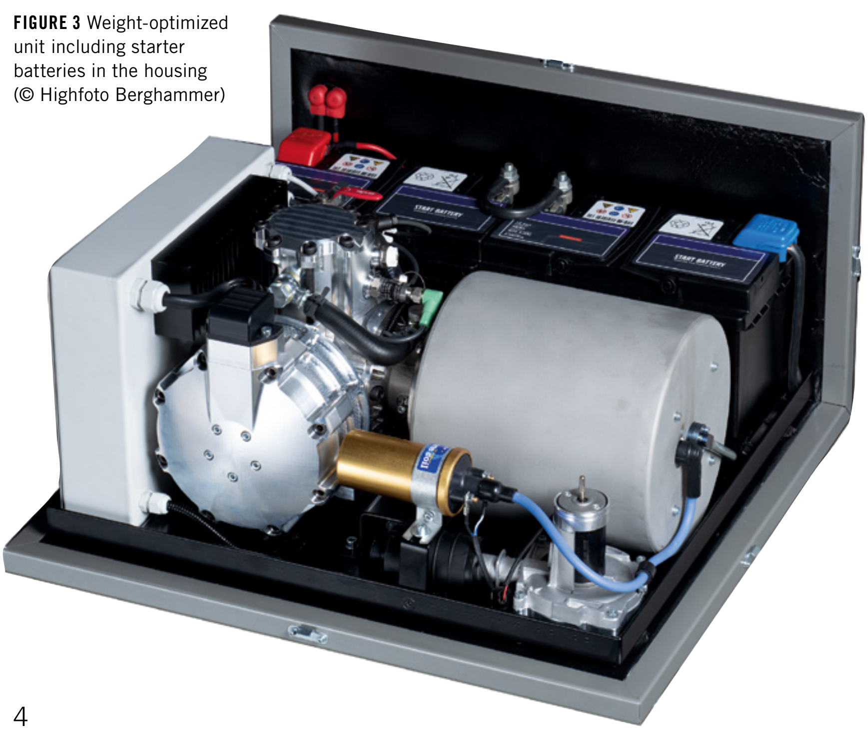
FIGURE 1 Study of positioning the aggregate in the battery box (© Frauscher)

FIGURE 2 First prototype of the unit with cooler heat exchanger (© Highfoto Berghammer)

it can be assumed that vehicle integrated electric air conditioning compressors will require significantly more power.

Finally, a power gross output of the unit of 1 kW was chosen as the basis for further calculations. This corresponds to a necessary current of around 40 A in a 24-V vehicle electrical system. It was taken into account that the starter battery, despite its limited capacity, is able to cover short-term power peaks, since it will subsequently be recharged anyway. In order to obtain a value for the required shaft power of the Stirling engine, the efficiency of the generator including rectification had to be determined. The characteristic map of permanent-magnet synchronous generators could be precisely measured on a special test stand. By using efficient Schottky rectifier bridges, it was possible to limit the generator and rectifier losses to 17 % at rated power. From this, the mechanical power output of the Stirling engine could be set to 1.2 kW and as the target value for the thermodynamic dimensioning. A polytropic simulation model was used for the thermodynamic dimensioning. It is a further development of the Stirling ideal adiabatic analysis according to Urieli and Berchowitz [5] and takes the heat transfer and pressure losses into account. The calculation

FIGURE 3 Weight-optimized unit including starter batteries in the housing (© Highfoto Berghammer)



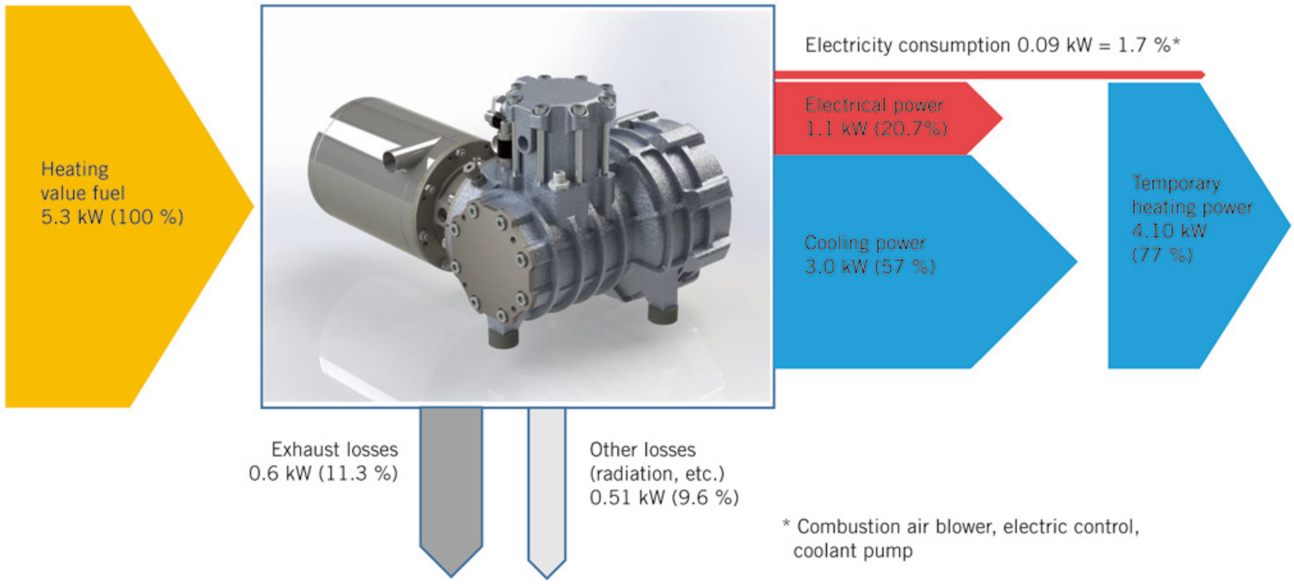


FIGURE 4 Overall energy balance (© Frauscher)

resulted in a machine with an expansion volume of 70 cm³ at a process gas temperature of 980 K and an average process pressure of 45 bar.

CHALLENGE AUXILIARY HEATING

The fact that the Stirling generator can only be considered for generating energy for the cabin heating system if a high degree of utilization and savings in vehicle components can be achieved was out of discussion from the outset. The operation of the unit is only acceptable if the noise emissions do not disturb the night's sleep either for the driver of the vehicle or for the immediate surrounding. In contrast to internal combustion engines, up to 90 % of the waste heat in Stirling engines is dissipated via the cooling circuit, due to the integrated combustion air preheating. The expense of an exhaust gas heat exchanger is therefore not useful. In this respect, the unit can initially be viewed as a water-based auxiliary heating device with the common options for using heat. In the application segment, one finds commercially available parking heaters with a thermal output in the range of 4 to 5 kW, often associated with an integration into the cooling system of the main engine. However, based on the mechanical power output of 1.25 kW, the thermodynamic calculation results revealed a cooling capacity of around 2.5 kW, which is well below the required value. In the end, the decision to start prototype production was finally made easier because a large part of the electrical output is not required in heating mode and can therefore be used to increase the heating capacity.

PROTOTYPE PHASE IN TWO STAGES

To keep the development risk manageable, the team decided on a two-stage plan for building demonstration units. In the first phase it was planned to develop a unit for tests and analysis of burner, kinematics and thermodynamics (heat exchanger) without considering the total mass. During this phase, optimized components were ultimately integrated unchanged into a lightweight housing. **FIGURE 2** shows the aggregate manufactured in the first phase. The first test bench results of the 48 kg unit were available at the beginning of 2021 with sobering results. The unit delivered only about 500 W DC power. While the components of the kinematics and the burner proved to be accurately dimensioned on the basis of previous experience, numerous optimization measures had to be carried out in the heat exchangers components cooler, heater and regenerator over the following months. In this context, the production strategy already laid down in the requirement specifications, namely largely automated production using CNC technology in connection with a high-temperature soldering process, was retained. After extensive improvement measures, the unit delivered better values in terms of performance and efficiency, until the target values were finally achieved for the first time in August 2021. Subsequently, the weight optimization and the installation of the unit in a soundproof housing together with the on-board batteries was made. **FIGURE 3** shows the resulting unit, without housing.

RESULTS

The analyzes and measurement values are summarized in **FIGURE 4**, and in **TABLE 1**. The positive mass balance is particularly noteworthy. The weight optimization resulted in a mass saving for the unit from originally 48 to 34 kg. Taking into account the savings in battery mass, a reduction in the total mass of the vehicle of more than 40 kg can be achieved. Further weight reductions, for example by the omission of the auxiliary heating, have not been taken into account yet. Fortunately, during the optimization phase a considerable power reserve could be reached as a result of increasing the operating pressure. It was finally fixed at 56 bar, together with

Description	Value	Unit	Comment
Aggregate			
Type designation/series			MobilGen G70 No. #0100
Electrical efficiency	22.4	%	DC power to lower calorific value Propane gas
Sound pressure level according to MR 2006/427EG	59.5	dB(A)	In closed battery box
Mass aggregate	34	kg	Without electronic control and battery box
Engine			
Configuration			Alphagamma Stirling
Process gas			Helium
Hot end temperature	650	°C	
Mean process pressure	55.9	bar	
Stroke volume	70	cm³	Expansion volume
Cylinder phase angle	90	°	
Rated mechanical power	1.42	kW	At the crankshaft
Rotational speed	1987	rpm	
Cooling power	2.99	kW	Heating power for driving cab
Coolant temperature	36.3	°C	Up to 50 °C
Coolant flow rate	0.39	m³/h	0.3–0.5 m³/h
Lifetime	>5000	h	Target, in testing
Generator			
System	3-phase AC		Permanent magnet excited multipole machine
Electrical power	1.19	kW	At 27.9 V after rectifier
Burner			
System			Outlet-mixing gas burner
Maximum thermal power	5.3	kW	Lower heating value
Fuel			Propane, natural gas, CNG, LNG
Gas pressure	50	mbar	Propane
Air flow	17.4	kg/h	
Air flow pressure	30	mbar	
Exhaust gas temperature	219	°C	at 25 °C ambient temperature
Exhaust gas value O_2	5.0–8.0	%	With propane operation
Exhaust gas value CO	4.42	g/kWh	With propane operation, O_2 = 5.3 %
Exhaust gas value NO_x	1.53	g/kWh	With propane operation, O_2 = 5.3 %

TABLE 1 Technical specifications and measurement data (© Frauscher)

an increase in shaft power to 1.42 kW and a cooling capacity of 3 kW. The overall electrical efficiency of 20.7 % should definitely keep up with the values achieved in driving operation. The efficiency of the diesel engine minus the losses in the belt drive, in the generator and rectifier and in the charging and discharging losses of the lead-acid batteries must be considered. In terms of noise emissions, the measurement results are within the expected range. The housing reduces the already characteristically quiet operating noise of the Stirling engine to a pleasant level. Also worth mentioning are the exhaust emissions, which are in the lower half of the Euro Stage V limit values thanks to the atmospheric combustion with active flame cooling. The burner concept, which is suitable for natural gas, CNG and LNG, comes from the knowledge gained in the lean gas project mentioned above. The diesel burner, which is still to be developed and which is essential for broad market acceptance of the unit, will undoubtedly be a challenge.

SUMMARY AND OUTLOOK

The MobilGen project demonstrates a technical solution for the supply of heat and electricity in commercial vehicles, yachts and mobile homes. The requirements for mass, installation space, performance, efficiency and engine smoothness could be met and are verifiable. Further project steps, such as the development of a liquid burner, the electronic control and the proof of maintenance-free operation should be completed by the mid of 2023, according to the current planning status.

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Like a car battery, but with 100,000 (one hundred thousand!) ampere hours*

What sounds utopian becomes reality: the small Stirling power pack finds space in the installation space of commercially available battery boxes directly next to starter batteries and provides an unlimited supply of electrical energy to a parked vehicle.

The gain in comfort for the driver is considerable. The MobilGen not only supplies the vehicle‘s stationary air conditioning system, but also delivers enough heat for the cabin heating system, and all with just a sustained whisper.

Extremely clean exhaust gases and considerable component and weight savings round off the innovative features of the new power unit.

Get an impression of the new technology at demonstration level during a demonstration appointment. Please send enquiries to info@**frauscher-motors.com**

Mobil Gen™

by Frauscher Motors

* Charging energy at 24 volts within a carefully extrapolated maintenance cycle of 2,500 hours.