Range-Extender in electric vehicles – a revival of (highly optimized) two-stroke engines on a small scale

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Abstract

The limited accumulator capacity of modern electric vehicles, which are driven by accumulator powered electric motors, is one reason why these systems do not prevail. To increase the range and the attractiveness of electric powered vehicles, the research project "MIHY - **Mi**niatur **Hy**brid" is handling the development of a modern range extender by using two-stroke engines (mechanical power: ~ 3 kW) on a small scale. To increase the over-all efficiency, thermal energy in the exhaust system has to be converted into kinetic energy. Therefore a laval nozzle accelerates the exhaust gas to supersonic speed, which is driving a subsequent, for the exhaust conditions specialized, turbine generator. Furthermore the whole exhaust system, including the turbine and the laval nozzle, is optimized for the resonance of sound waves in order to minimize the loss of fresh gas during the gas exchange in the two-stroke engine. So the sound waves, which are caused by the combustion, must reflect at the nozzle to a certain time to assure an optimal charge of the combustion chamber. Therefore the length of the exhaust system and the propagation delay are synchronized. At the piston outlet they provoke a local pressure increase, which forces unburned gases back to the piston. All relevant conditions like pressures and temperatures at different points, the crankshaft speed and angle, the flow speed, the generated electrical power are recorded by using high speed analyzing equipment and simulated by using CFD (Computational Fluid Dynamics). In this paper relevant calculations and the dimensioning of a revolutionary exhaust system for increasing the efficiency of a light weight two-stroke range extender are presented for the first time.

Keywords: MIT&SLIM2013, e-mobility, two-stroke engine, range-extender, hybrid vehicle, exhaust turbine, waste heat, CFD, simulation, high efficiency.

1 Introduction

E-mobility is deemed to be a big challenge of the automotive industry in the next few years. Advantages like the CO_2-savings and the noiseless driving emerge obviously. Based on the high acquisition costs und the limited range of those cars the potential customers are not willing to buy them. Because of the limited range of e-cars with an average range of 100-150 km only few customers are disposed to pay an additional price compared to the price of a conventional car. The technology of the lithium-ion-accumulators shows great potential according to the store capacity and a thereby related increased range of e-cars. The price of those accumulators will certainly fall over time to a competitive level [1]. Up till then Range-Extender will be a method of choice to configure e-mobility more competitive. For that reason the Bayreuth University develops a high efficient Range-Extender in the context of the research project "**Mi**niatur **Hy**brid" (MIHY).

2 Initial situation

To realize the research intense tasks within two and a half year (project duration of MIHY) an experienced partner is needed. The industrial partner in this project is "Webra Feinmechanik GmbH" (in the following WEBRA). WEBRA produces high performance model combustion engines for a reasonable price since 50 years. For this reason amongst others, it was decided that the following developments will be realized in a small scale. Advantages of this proceeding are the fast and cost effective development as well as the less difficult technology of model engines compared to the large scaled engines in modern vehicles. Afterwards the achieved results can be transferred to the big scaled engines and Range-Extender.

2.1 State of the art

Range-Extender are available in many different variants on the market. Especially, according to the mode of use, the classification of the operation mode (serial or parallel hybrid) of electric driven cars is relevant (cf. Figure 1).

The parallel hybrid operation mode provides the possibility to drive by electric motor and/or by combustion engine. Whereas the serial operation solely uses the combustions engine to charge the connected accumulator.

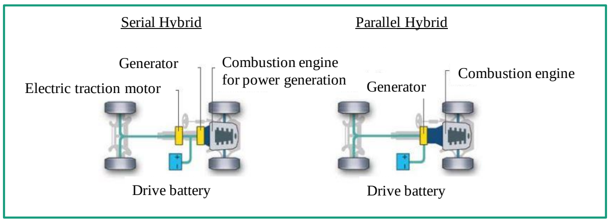

Figure 1 Hybrid drive modes [2]

This allows the use of significant smaller, lighter and load point optimised combustion engines. The Range-Extender of the MIHY-project is applied for this purpose. Furthermore the Range-Extender of this project is supposed to be more efficient than comparable systems by efficiency increasing developments.

Usually combustion engines are deployed for this purpose and are indicated by an average efficiency of approximately 40%. This value characterizes the available mechanical drive power. The remaining 60% of the deployed chemical energy of the fuel get lost by the cooling of the engine and by thermal energy of the exhaust gas [3]. The previous approach of the development of load point optimised combustion engines was limited to the improvement of the efficiency of the mechanical drive power. The concept of the MIHY Range-Extender however allows the partly usage of the remaining 60% energy losses, additionally.

2.2 Procedure

Starting point of the development is the two-stroke engine “Speed 150i” from the company and project partner WEBRA. The model combustion engine has a cylinder capacity of 25 ccm³ and a performance of 2.8 kW with 11,000 rpm. The engine runs with a fuel-oil-mixture. The engine modification to propane/butane gas operation is optional to ensure a flexible and comprehensive supply with fuel. An additional advantage of the gas-fuelled operation mode is the improvement of the emission levels (pollutant emissions and noise level) as well as the increase of the efficiency. This is the way to increase the efficiency of 40 % beside other arrangements e.g. the use of the energy losses in the cooling system and of the exhaust system. Consequently the following tasks have to be completed:

- modification of the engine to gas-fuelled operation
- utilization of the thermal and kinetic energy in the exhaust gas
- utilization of the energy losses of the cooling system

Figure 2 shows the schema of the above described concept of the MIHY Range-Extender to maximize the range of an e-car. The mechanical energy converted out of the combustion engine is used to drive a first generator which is connected to the crank shaft. To use the energy contained in the exhaust gas it is necessary to lead the exhausts primarily through a so called exhaust-power turbine which is linked to a second generator. The energy losses of the cooling system are processed in another way, but also those ones will finally be converted by a third generator into electric energy. With the help of an electronic control system the electric energy of the three mentioned generators are used to charge the drive accumulator of an e-car.

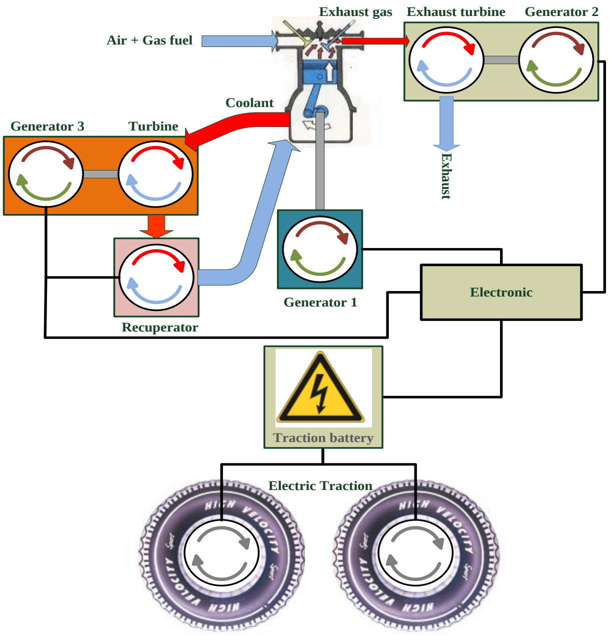

Figure 2 MIHY-concept

To accomplish the aimed targets, a step by step realization is intended. Initially the gas turbine and all necessary attachment parts will be dimensioned and constructed. These will replace the previous commonly used exhaust system (normally a silencer resp. tuned pipe). The utilization of the wasted energy of the cooling system and the conversion from petrol to gas operation will be implemented in a later state.

3 Overview of selected results

To use the exhaust energy, a range of preliminaries and calculations are necessary. Those are described in the following sections.

3.1 Range-Extender combustion engine

As already mentioned all developments are based on a 25 cm³ two-stroke engine of the company WEBRA. The reason is the extreme simple construction, modifiability high power-to-weight ratio and the low price. The achieved results during the MIHY-project can be accessed at later point in time and used to build a more powerful Range-Extender. This allows the support of the drive-accumulators of a four-person hybrid e-car with electric energy. Instead of using one large scaled Range-Extender, it is also possible to link four smaller MIHY Range-Extender to provide the needed performance. The operation method of the MIHY Range-Extender will be static at a constant rotational speed. Hereby the first thoughts about realization began. By the use of performance diagrams the possible engine power at a constant rotational speed of 5,000 rpm is determined. With an assumed efficiency of 40% the engine power is 1.3 kW [3]. Exact measurements and calculations of the efficiency take place during the project MIHY at a later point. Important for further steps is the determination of operating parameters like volume flow, pressure and temperature. By the chemical reaction equation the amount of primary energy (fuel), which is needed to achieve a performance of 1.3 kW at an engine efficiency (η_{engine}) of 40%, can be calculated (cf. Equation 3.1.1 and 3.1.2).

$$2\ C_8H_{18} + 25\ O_2 \rightarrow 16\ CO_2 + 18\ H_2O \qquad (3.1.1)$$

$$P_{chem} = \frac{P_{mech}}{\eta_{\text{engine}}} = 3.25\ kW \qquad (3.1.2)$$

With a lower heating value of $H_{\text{u}} = 40 \cdot 10^3\,\frac{\text{kJ}}{\text{kg}}$ and an air ratio of 14.7:1 the total air mass flow results to 1.27 g/s. Under normal conditions and an assumed exhaust gas density of $\rho_{\text{gas}} = 1.4\,\frac{\text{kg}}{\text{m}^3}$ this corresponds to a volume flow of approximately 0.9 l/s. Depending on the exhaust gas temperature and furthermore operating factors a volume flow of 2 l/s is achievable.

Important parameters of the exhaust gas are calculated by the help of the Otto-cycle (cf. Figure 3). Interesting are especially the conditions at point 4, which represent the pressure and temperature of the exhaust gas at this certain point. Taking the cooling losses as well as the gas-exchange cycle by the flush of fresh gas, as it occurs in two-stroke combustion engines, into consideration the conditions approx. 20mm behind the exhaust port results to:

- temperature: T = 191° C
- pressure: p = 2.8 bar

A comparison of those values with the literature shows a classification at the bottom edge of the possible. The literature refers values up to an exhaust gas temperature of 400° C and a pressure of 10 bar [3] [4].

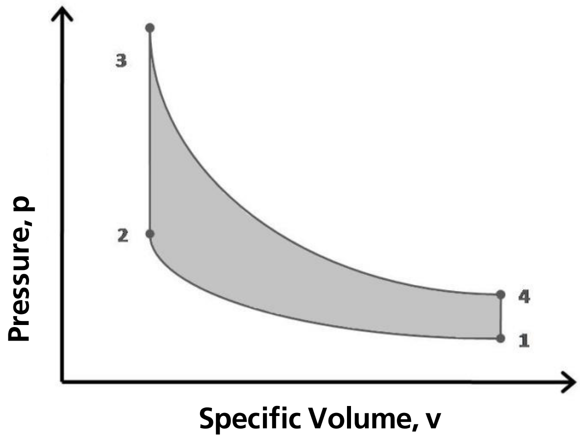

Figure 3 Otto-cycle

Important findings are the losses contained in the exhaust gas in form of thermal energy. For the considered model those are approximately 1 kW. This energy normally gets exhausted unused into the environment. In future those losses are supposed to be reduced by developing an exhaust-power turbine. Thereby the over-all efficiency of the MIHY Range-Extender is raised clearly.

3.2 Measurements at the exhaust system

The considerations and calculated values made in chapter 3.1, are verified by measurements. The used engine therefore is not the WEBRA “Speed 150i” but a related high-performance engine (product name: *Chung Yang R236*).

Temperature measurement

The temperature measurement at the exhaust port of the engine provides a maximum exhaust gas temperature of approx. 160° C (cf. Figure 4).

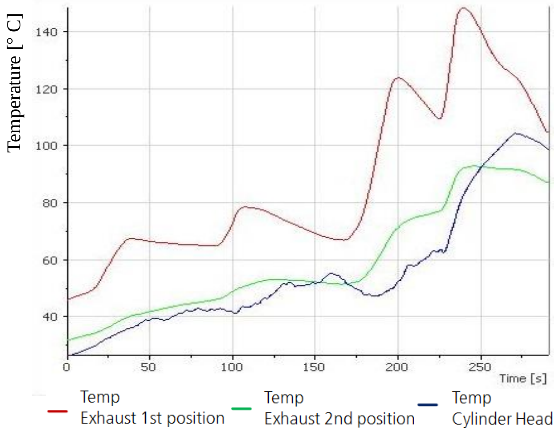

Figure 4 Temperature measurement

The undulated moving of the temperature profile is caused by rotational speed regulations during the experiment (Figure 4). From the moment t > 0 s the engine was running in idle speed. The rotational speed was raised continuously, held for 50 s and then raised stage-by-stage. The maximum rotational speed of 11,000 rpm was reached after t = 230 s with a consistent load. Therefore, it is possible to achieve the temperature of T = 190° C from the calculations of chapter 3.1.

The temperature measurement at the exhaust port and the tuned pipe outlet shows a ΔT of approx. 40° C. On the one hand this can be explained by the geometry of the tuned pipe which affects the pressure and temperature change; on the other hand, by heat losses to the immediate surroundings. For this reason a thermal insulation is applied to the resonance tube.

Low pressure measurement

When measuring the pressure ratio in the tuned pipe by a high sample rate (50 kHz) of the pressure sensor, it is possible to perform more precisely measurements compared to the slower temperature sensors. Consequently even procedures within an operating cycle can be detected by the pressure sensor. At 5,000 rpm one cycle takes 12 ms in time. With a sample rate of 50 kHz, ten measurements per cycle (every 1.2 ms) are made.

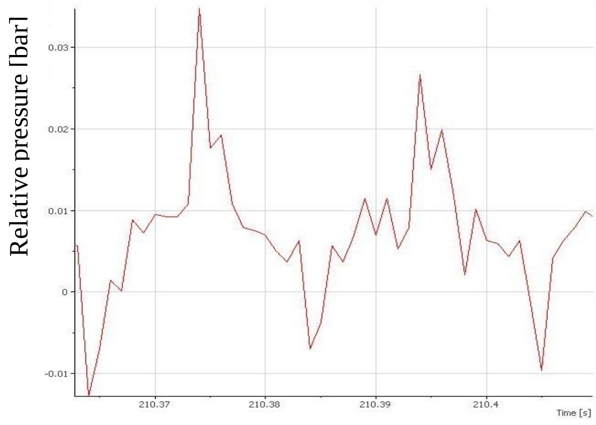

Figure 5 Pressure measurement

The relative pressure, which is measured with the pressure sensor, “DRTR-AL-10V-R10B” from *HYGROSENS*, shows periodic oscillations. An analysis of the length of the single peaks as well as a correlation by the help of the velocity of sound in the exhaust gas shows the resonance behaviour in the tuned pipe clearly. Hereby the relative pressure at the end of one stroke gets negative. This represents the exhaust back-pressure and therefore a decrease in pressure at the end of the tuned pipe (cf. Figure 5). The application of a tuned pipe at current state is essential. The maximum absolute pressure in Figure 5 is approx. 1.4 bar. The pressure measurements, the measured temperatures and the to be determined flow speed are the basis for the following laval nozzle.

3.3 Laval nozzle

By the given area of the exhaust port at the “Speed 150i” of 346 mm² and the adjusted rotational speed during first test runs, the exhaust gas velocity results to 2.7 m/s. For an effective use of the turbine this value is way too low. For this reason the flow velocity is raised by the help of a laval nozzle (cf. Figure 6). Due to their specific geometry it is possible to accelerate the exhaust far into the supersonic range. This happens by the transformation of thermal into kinetic energy.

The geometry dimensioning is achieved by the calculations of impulse and flow speed respectively, by values out of data sheets. Very relevant parameters are the area ratios inside the nozzle and at the outlet. This is ascertained by the existing pressure ratio, directly in front of the narrowest point of the laval nozzle and the external pressure [5].

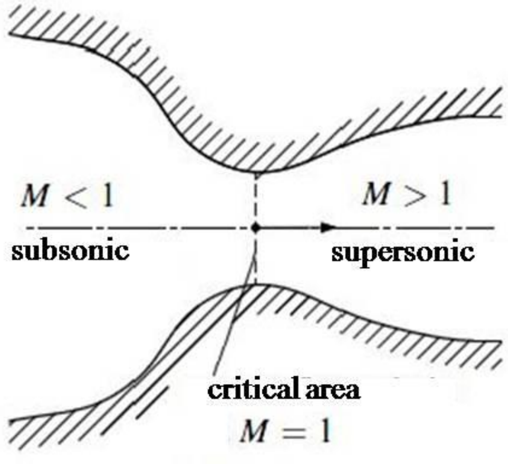

Figure 6 Principle of the laval nozzle [5]

By the temperature and pressure values from chapter 3.1 two limit cases of the nozzle geometry are picked. According to those the diameter of the tightest spot of the laval nozzle has to be between 5 and 15 mm. With those two inner diameters, (also called critical diameter) the scope for following more accurate determinations of the nozzle geometry is arranged. In this regard, exhaust gas is accelerated to Mach > 2 (approx. 700 m/s) at the nozzle outlet. This provides a very good basis for the efficient drive of the following exhaust-power turbine.

3.4 Construction

On the basis of up till now made considerations, calculations and measurements a construction of the tuned pipe, the laval nozzle and the exhaust-power turbine can be realized.

Tuned pipe

The tuned pipe for the „Speed 150i“ has to be adjusted to the present engine and its optimal operating conditions. By calculating the resonance times, most relevant dimensions of the tuned pipe are defined. In this case, the rotational speed is important. Caused by the low rotational speed of 5,000 rpm, the tuned pipe has a length of $l_r \approx 700$ mm. Further needed dimensions in Figure 7 can be calculated by formula or by empiric determined values. By dimensioning of those values the geometry of the resonance body is certain. The formula and the cone shaped geometry 12 and 14 (cf. Figure 7) apply for a range of various rotational speeds. With a fixed rotational speed as it is preset, the cone shaped courses could be omitted and a staged passage could be chosen.

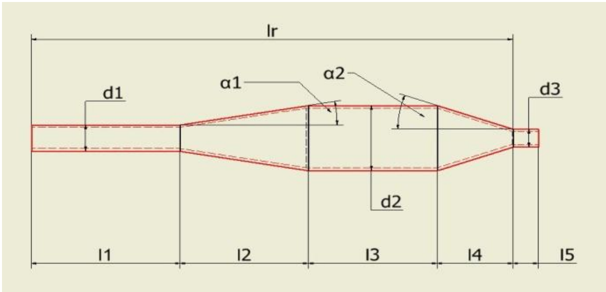

Figure 7 Dimensioning of the tuned pipe

From the previous measured values of pressure and temperature as well as the calculated values of the flow speed, exhaust pressure and exhaust temperature in front of the laval nozzle a first prototype was modelled by the help of the CAD-software *SolidWorks2013*®.

Laval nozzle

Directly to the tuned pipe, the laval nozzle is connected and represents the pre-stage of the turbine casing. The nozzle outlet is directed on the downstream located turbine wheel. As the critical inner diameter cannot be calculated exactly up till now, it is necessary to determine the value experimentally (Figure 8).

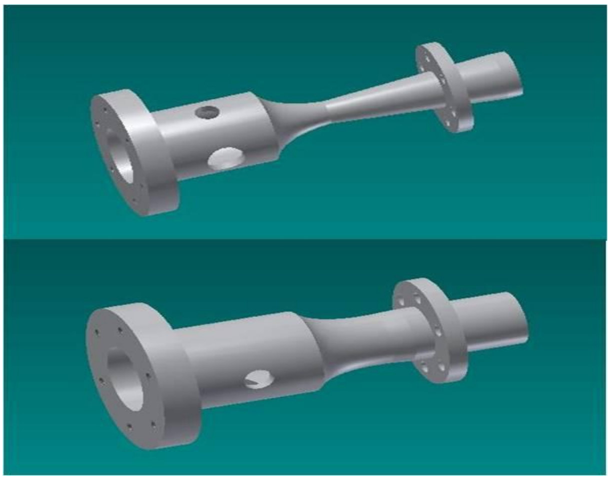

Figure 8 Laval nozzle with critical diameter of 5 and 15 mm

This process is important as the laval nozzle (a laval nozzle has six operating modes) is only working exactly with the right dimensioning. The dimensioning is dependent of the pressure ratio in front and behind of the nozzle and this, in turn, is dependent of the engine rotational speed, exhaust temperature and the pressure course of the downstream power turbine [8].

Exhaust-power turbine

The exhaust-power turbine is located directly behind the laval nozzle and is developed in several steps. After developing different possible designs, three most promising variants with the greatest potential are built in CAD-software, suitable for production and printed by the rapid prototyping method. Those can be analysed concerning their operating performance. Figure 9 shows the chosen version. The different variants are not named here.

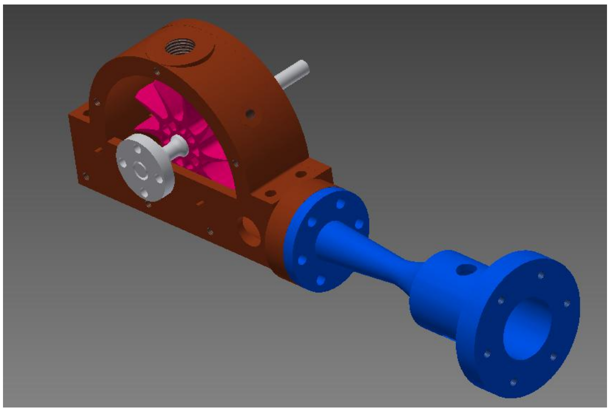

Figure 9 Exhaust-power turbine

Besides a simple and robust building technique the integration of pressure and temperature sensors as well as a flow speed sensor was also considered here. The whole construction is produced according to ISO-standards. Especially relating to screws and necessary tools, the variety of options was considered to be kept at a low level.

3.5 Simulations

According to the theoretical calculations of the laval nozzle the exhaust gas velocity should now result to 700 m/s in front of the exhaust-power turbine. To confirm the results, practical experiments and flow simulations with the help of CFD-software are executed. By different scenarios the estimation of the ideal dimensioning as well as about the actual flow velocities are possible.

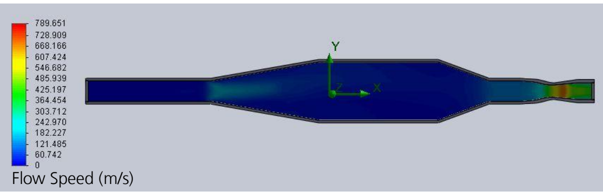

Figure 10 Flow speed in the exhaust system

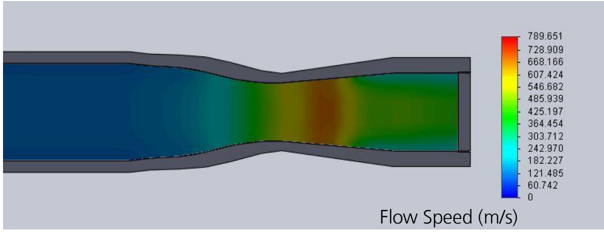

Figure 11 Flow speed in the laval nozzle

Figure 10 and 11 show the results of the simulation of the flow speed of the exhaust gas. In the area of the laval nozzle a yellow-red-coloring shows the intense sped-up. The maximum velocity of approx. 700 m/s is reached right after the narrowest section. At the narrowest section the velocity is Mach = 1. The velocity of sound c_L in the exhaust gas depends on the square root of the absolute gas temperature (cf. Equation 3.5.1) [6].

$$c_{\mathrm{L}} = \sqrt{k \cdot R \cdot T_{\mathrm{krit}}} \qquad (3.5.1)$$

Downstream the velocity decreases a little bit, but it stays above 400 m/s (cf. Figure 11, green area) and consequently in the supersonic range. This is the velocity the exhaust gas hits the wheel of the exhaust-power turbine.

The high flow velocity is reached by the transformation of the thermal into kinetic energy. Figure 12 shows this relation. In front of the laval nozzle the temperature is around 500 Kelvin. Downstream temperatures drop about approx. 200 Kelvin. The critical temperature is around 400 Kelvin.

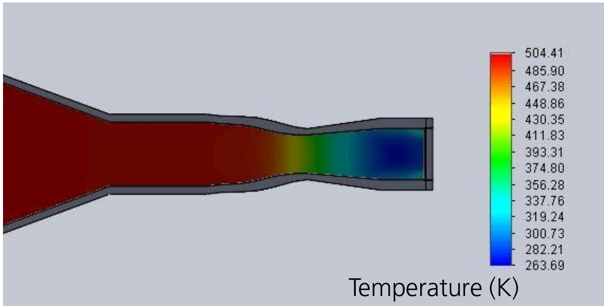

Figure 12 Temperature profile in the laval nozzle [7]

4 Current prototype

The realization of the present work from a first prototype to a complete system can be implemented in the next steps.

4.1 Complete System

All in chapter 3 specified components are shown in Figure 13. These include:

- motor flange,
- tuned pipe,
- laval nozzle,
- turbine case with turbine.

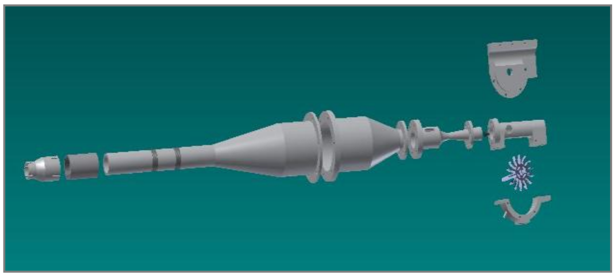

Figure 13 CAD model of the complete system

The construction is kept modular und guarantees a simple change of the components. Consequently different variants of the laval nozzle can be tested. The continuous development of single components is simplified.

The whole system, including the engine, has a maximum dimensioning of 800x100x150 mm. Later a more compact installation is planed, wich combines exhaust system, cooling circuit and engine bearer on a common square plate. The prototype is made out of steel and aluminum and is manufactured at the *Chair Manufacturing and Remanufacturing Technology* of Bayreuth University. Original pictures of the up-to-date prototype will not be published, because of patent protecting reasons.

4.2 Performance and efficiency

The most important point in dimensioning the exhaust-power turbine is the performance calculating. The determined parameters can be used to conclude on the improved over-all efficiency. The current calculating of the performance is done under following assumptions:

- lowest expected temperature before the laval nozzle (cf. Chapter 3.1)
- lowest expected pressure before the laval nozzle (cf. Chapter 3.1)
- flow speed behind the laval nozzle 400 m/s
- usage of the kinetic energy of the exhaust gas behind the laval nozzle by the exhaust-power turbine up to 60 %
- over-all efficiency of the turbine under load of 50 %

The last two headwords are assumptions to calculate the expected losses. Those decrease the value of the performance accordingly. Despite those assumptions an idling speed of the turbine wheel of n_{idle} = 88.000 rpm with a flow speed of $\upsilon_{exhaust\_gas\_in}$ = 400 m/s and a flow speed at the outlet of $\upsilon_{exhaust\_gas\_out}$ = 50 m/s of the exhaust gas could be determined (cf. Equation 4.2.1) [7].

$$n_{\text{idle}} = \frac{60 \cdot \eta_{\text{flow}} \cdot (\upsilon_{\text{exhaust\_gas\_in}} - \upsilon_{\text{exhaust\_gas\_out}})}{\frac{360°}{\alpha} \cdot l} \qquad (4.2.1)$$

n_{idle}:	idling speed
$\upsilon_{exhaust\_gas\_in}$:	speed of exhaust gas flowing to turbine blades
$\upsilon_{exhaust\_gas\_out}$:	speed of exhaust gas flowing out from turbine
η_{flow}:	efficiency of the turbine
l, α:	flow length, angle of dip of exhaust gas over turbine blades

Thereby a theoretical performance of $P_{turbine\_max}$ = 922 W could be achieved. The difference between idling cycle and operation with load is defined with above named over-all efficiency of 50 %. At load i.e. linking the turbine to the electric generator the performance is added up to $P_{electric}$ = 411W. The efficiency of the exhaust-power turbine in relation to the whole deployed (cf. Chapter 3.1) chemical energy arises to $\eta_{turbine}$=14% [7].

The efficiency of the whole system can be calculated by summing up the single efficiencies of the engine and the exhaust turbine (cf. Equation 4.2.2).

$$\eta_{total} = \frac{P_{crankshaft}}{P_{chem}} + \frac{P_{turbine}}{P_{chem}} = 54\% \qquad (4.2.2)$$

The over-all efficiency of the system is increased by the exhaust turbine from initially η_{engine} = 40% to η_{total} = 54%. This efficiency exceeds commercial available Range-Extender powered with diesel fuel.

5 Summary and forecast

The given tasks and aimed goals of the research project MIHY are very extensive.

A methodical and strict procedure is necessary to achieve them. The results published in this paper are consequently only the first step to an optimized Range-Extender.

5.1 Summary of the previous results

The up to now achieved results during the project MIHY have a high potential for future developments. A disadvantage that hasn't been handled till now is the bad emission level (pollutant emissions and noise level) of two-stroke engines. Advantageously in contrast is the usage option of the thermal energy included in the exhaust gas. By the thermodynamic calculations and the flow conditions at the outlet of the engine, as well as the necessary transformation of thermal into kinetic energy, the usage of a laval nozzle got required. With an ideal adjusted geometry the exhaust gas is accelerated into the supersonic range (currently approx. 400 m/s).

The accelerated exhaust drives the exhaust-power turbine which supplies an electric generator that dispenses an electric performance of 411 W. The over-all efficiency of the system is raised to η_{total} = 54%. This exceeds occasionally the Range-Extender which are commercially available.

The fuel resistance of the power turbine, additional efficiency improvements, practical experiments and the compliancy of the exhaust standards are to accomplish.

5.2 Forecast and further approach

The further steps which are to accomplish during the research project MIHY are related to the gas modification of the engine "Speed 150i". The results achieved here, shall help to improve the emission levels as well as a rise of the temperature of the exhaust gas. This influences the performance of the turbine positively.

Furthermore as a part of the gas modification a direct fuel injection can be tested. This would decrease the losses by the flush of fresh fuel-air-mixture during the two-stroke cycle. The replacement would also affect the geometry of the tuned pipe, which could get simplified. The laval nozzle has to be adjusted, too. In the case of an ideal adjusted laval nozzle it could approximate to the proved principle of a radial turbine.

As an additional task to increase the over-all efficiency it could be tried to use the losses of the cooling and to convert it into electric energy.

Finally the produced electric performances of the crankshaft, the exhaust-power turbine and the cooling cycle are linked together and used to charge the drive accumulators. The realization of the given tasks and aimed goals should lead to a high efficient Range-Extender in a compact configuration, which can be tested in a radio-controlled car in the scale 1:5.

6 Acknowledgments

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