# ORC Turbine-Generator Unit for Truck Applications

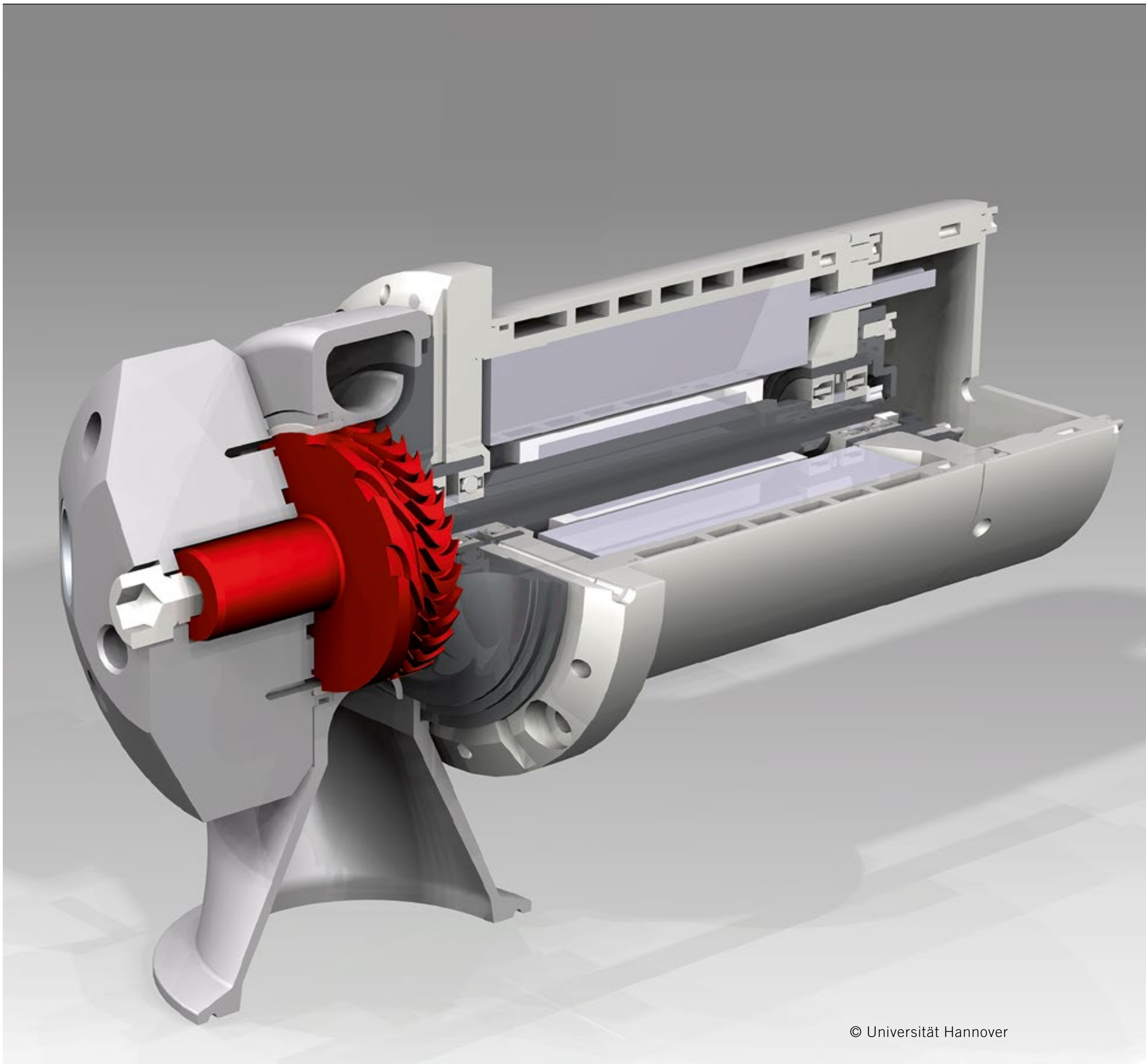
Modern internal combustion engines already utilise a large amount of exhaust gas thermal energy using turbocharger turbines and exhaust gas aftertreatment systems. Nevertheless, a large amount of thermal energy remains unused in the exhaust gas. In order to increase the waste heat recovery, an organic rankine cycle process can be used. The overall efficiency of such a process mainly depends on the efficiency of the expansion machine. For such an application, a single stage, partial admission supersonic axial impulse turbine is designed and manufactured at the Leibniz Universität Hannover.

AUTHORS

**Dipl.-Ing. Ole W. Willers** is Research Associate at the Institute of Turbomachinery and Fluid Dynamics (TFD) at the Leibniz Universität Hannover (LUH) (Germany).

**Dipl.-Ing. Harald Kunte** is Former Research Associate at the Institute of Turbomachinery and Fluid Dynamics (TFD) at the Leibniz Universität Hannover (LUH) (Germany).

**Prof. Dr.-Ing. Jörg Seume** is Head of the Institute of Turbomachinery and Fluid Dynamics (TFD) at the Leibniz Universität Hannover (LUH) (Germany).



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## 1 MOTIVATION

In order to fulfill future emission limits, automotive manufactures are challenged to improve the efficiency of their combustion engines. An increase of the overall efficiency leads to a reduction of greenhouse gas emissions and fuel consumption. A possible approach to accomplish these objectives is to increase the overall engine efficiency by means of waste heat recovery. Referring to [1], up to 25 % of the unused chemical energy can be recovered from the exhaust gas. This energy can be converted into electrical energy to supply the subsystems, or into additional mechanical power, thus reducing the parasitic power consumption.

For this purpose, the organic rankine cycle (ORC) process was identified to be the most suitable system, though very high-pressure ratios are necessary to maximise the power output [2]. The general ORC process is a thermodynamic cycle based on the Rankine cycle using an organic working fluid. The efficiency of such an ORC depends on the working fluid and the expansion machine. A mixture of 95 % ethanol and 5 % water is chosen for this investigation due to estimated power output and availability [3]. The water is added to increase the resistance of the turbine material to corrosion. The operating conditions are defined by an automotive truck application of a 12.8-l diesel engine, with a power output of 375 kW. This leads to an ethanol mass flow rate of up to 0.1 kg/s, a maximum temperature of 539 K, and maximum inlet pressure of 4000 kPa for the expansion machine.

For automotive applications, turbo expanders are advantageous due to their small size, low weight and thus high specific power [4–6]. Hence a single stage, partial admission supersonic axial impulse turbine was chosen for this application [3, 7–10]. After a development of five years, the prototype of the turbine-generator unit as well as a comparison of the experimental results and the numerical simulations are presented.

## 2 PROTOTYPE DESIGN

As mentioned before, the ORC efficiency depends on the expansion machine. Due to its size, weight, speed and high pressure level, an axial impulse turbine was selected. The turbine was designed as a single stage supersonic impulse turbine for packaging reasons, and to maintain a high efficiency over a wide operating range [11, 12]. Due to the single stage design in combination with the very high pressure ratios, a supersonic turbine stage is necessary. For this reason, the flow passages of the stator are designed as trapezoidal Laval nozzles, **FIGURE 1**. The subsonic flow enters the convergent part of the stator at a pressure of up to 4000 kPa, ①, and accelerates to the speed of sound at the nozzle throat, ②. In the divergent part, the flow is further accelerated to supersonic speed, ③, before it enters the rotor passages, ④. The rotor passages have a constant cross-sectional area with zero degree of reaction. Consequently, no additional expansion takes place in the turbine rotor. To cover the required operating range (very low mass flow rates in particular), small blade heights are necessary.

In order to minimise tip gap losses a partial admission concept is chosen. At low mass flow rates, only two of the stator passages are open. With increasing mass flow rates, additional passages are opened successively. This control strategy is independent of the rotational speed because the mass flow depends only on the stator inlet conditions due to the supersonic flow at the nozzle throat. The geometrical parameters of the turbine stage are summarised in **TABLE 1** and the design is depicted in **FIGURE 2**. The turbine rotor is manufactured from a titanium alloy to achieve low weight and the required corrosion resistance. To achieve a compact design, the turbine is directly coupled to a high-speed generator. The generator magnets are attached on the rotor shaft and the turbine rotor is mounted overhung. The prototype expansion machine has an overall length of 285 mm, and a weight of less than 20 kg [13].

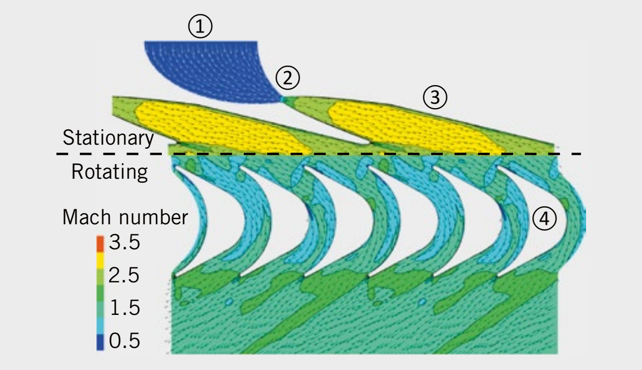

**FIGURE 1** Blade profiles and mach number distribution (at 50 % span) of the turbine stage (© Universität Hannover)

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Shroud diameter | $D_{shroud}$ | m | 0.06310 |
| Blade height | h | m | 0.00343 |
| Tip clearance | $\delta$ | m | 0.00013 |
| Rotational speed | $n_{Design}$ | rpm | 100,000 |
| Stator passages | $N_{Stator}$ | – | 8 |
| Rotor passages | $N_{Rotor}$ | – | 33 |
| Degree of partial admission | $\varepsilon$ | – | 0.2/0.4/0.6/0.8 |

**TABLE 1** Geometrical parameters of the turbine (© Universität Hannover)

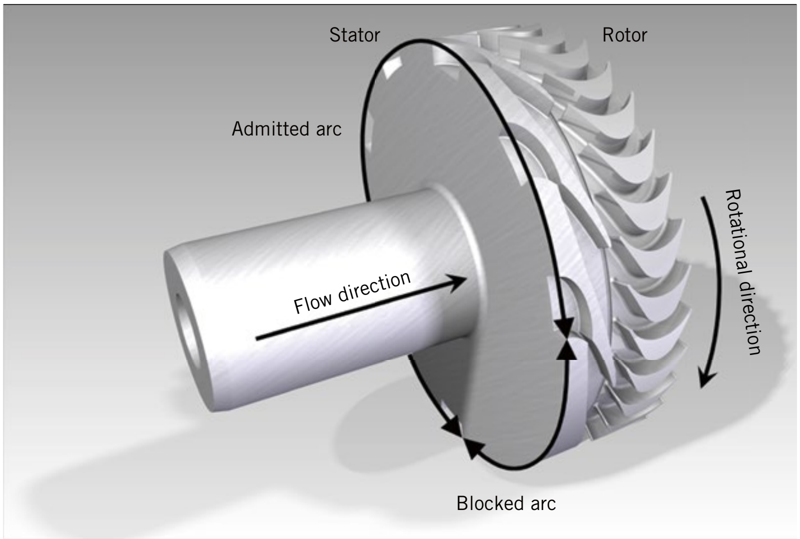

**FIGURE 2** Design of the turbine stage (© Universität Hannover)

## 3 EXPERIMENTAL AND NUMERICAL RESULTS

The experimental investigations are performed at the test bench of the TFD, located at the Energie-Forschungszentrum Niedersachsen (EFZN). The dual combustion chamber test bench can be equipped with an ORC module which belongs to the Institute of Power Plant Technology of the Leibniz Universität Hannover. The numerical simulations are performed with the commercial software Ansys CFX 14.5. The empirical approach by Aungier [14] is used subsequently to consider losses caused by partial admission.

**FIGURE 3** and **FIGURE 4** show the experimental and numerical results of the turbine with a partial admission of 20 % ($\varepsilon = 0.2$) and 40 % ($\varepsilon = 0.4$). The minimum turbine inlet pressure is 2000 kPa and is increased in steps of 500 kPa up to 4000 kPa for two passages and up to 3000 kPa for four passages. The rotational speed of the turbine is varied from 45,000 to 80,000 rpm in steps of 5000 rpm. Only the operating points with the highest power output per mass flow rate are plotted. The turbine power is determined from the electrical power of the generator, including the parasitic losses, for example generator losses and friction losses. A turbine power of 5.2 kW with an efficiency of 51.8 % is achieved at a mass flow rate of 0.03 kg/s with two open passages. With four open passages, a maximum power output of 7.6 kW is generated at a turbine inlet pressure of 3000 kPa. This peak power is achieved at a mass flow rate of 0.05 kg/s and a turbine efficiency of 57 %. The maximum deviations between experimental and numerical results are 3.8 % for $\varepsilon = 0.2$ and 4.7 % for $\varepsilon = 0.4$ [13].

## 4 SUMMARY

An ORC turbine-generator unit can be used to increase the overall efficiency of combustion engines and thus reducing greenhouse gas emissions and fuel consumption. The ethanol operating conditions, specified by a truck application, lead to low mass flow rates and a pressure ratio of about 49. For this purpose, a single stage, partial admission supersonic axial impulse turbine was designed. This turbine was coupled to a high-speed generator unit. This compact turbine-generator unit for ORC applications achieved

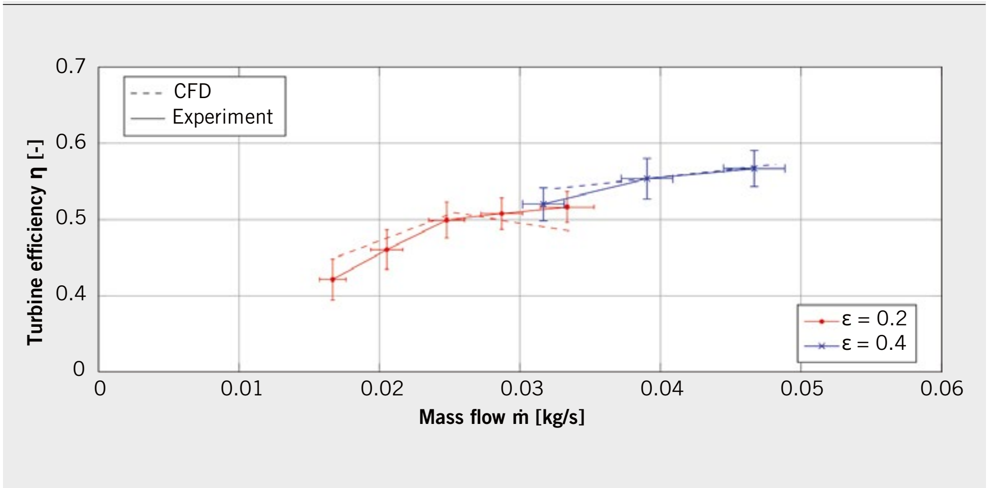

**FIGURE 3** Turbine power output map – error bars indicate the 95 % confidence intervals of the experimental results [13] (© Universität Hannover)

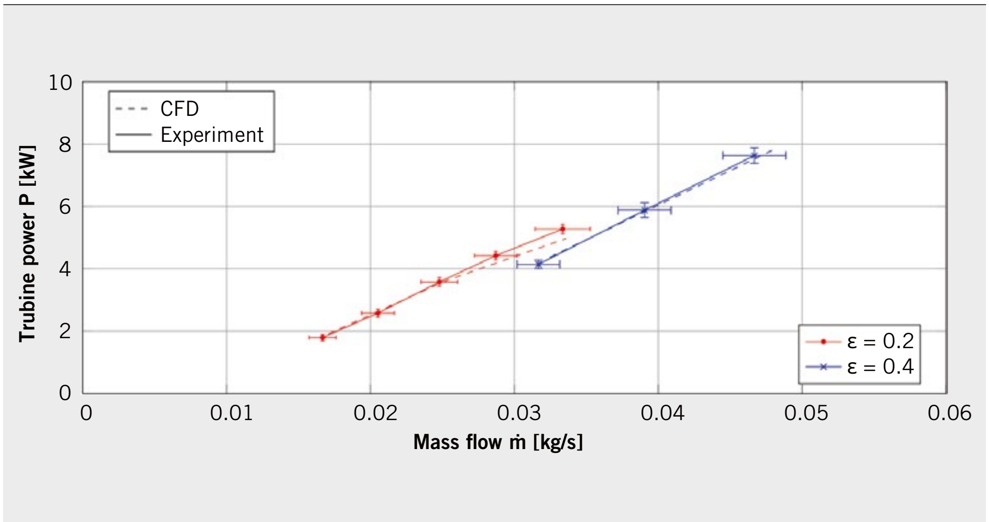

**FIGURE 4** Turbine efficiency map – error bars indicate the 95-% confidence intervals of the experimental results [13] (© Universität Hannover)

a turbine peak power of 7.6 kW and an efficiency of 57 %. This leads to a potential reduction of fuel consumption by 3 %. Due to manufacturing tolerances and a critical rotordynamic resonance case the complete operating range was not covered up to now. By managing these challenges, a maximum power output of 17 kW is achievable with this application.

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