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(2-28) Zero Emission Engine — A Novel Steam Engine for Automotive Applications

Stephan Mößbauer [a], *Franz Durst [a], Dimosthenis Trimis [a] and Tobias Haas [b]
[a]: *Institute of Fluid Mechanics, University of Erlangen-Nuremberg, Cauerstr. 4, 91058 Erlangen, Germany*
[b]: *IAV GmbH, Carnotstr. 1, 10587 Berlin, Germany*

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ABSTRACT

Taking advantage of several of the most modern research and development achievements in combustion technology, material science, control engineering, together with some unconventional thoughts on thermodynamics, a novel concept of a steam engine is presented, which is especially suitable for automotive engine applications. The paper starts by describing the general concept of the so-called Zero Emission Steam Engine, which includes supercritical thermodynamic states and high-pressure steam injection, and further focuses on the **porous burner technology** as the actual heat source of the process. Following a brief description of the principle of operation, the unique advantages of this novel heat source for the steam engine are outlined. These advantages include a wide, infinite variable power turndown ratio of about 1:20, which is roughly a factor of 5 greater than the modulation range of competitive burner technologies. Additionally, the porous burner excels by very low combustion emissions that are independent of the actual thermal load of the burner and are — at any state of operation — clearly below the most stringent Super Ultra Low Emission Vehicle (SULEV) standards. Another advantage of immense importance in mobile applications is the compactness of the porous burner units. Using superior heat transport properties, the porous burner allows power densities of about 3.000 kW/m^2, which is about a factor of 10 greater than the value of other premixed, low emission burner technologies, resulting in very small burner units. Finally, the porous burner technology allows complex combustion chamber geometries to be realized, which may be of special interest in applications where space is limited. Using these advantages, several porous burners for different concepts of ZEE-engines have been developed and are currently undergoing testing from which the results are presented in this paper. Although the presented prototypes are far from being mass-produced, the experimental results obtained from the prototypes clearly indicate that porous medium burners together with a modern steam engine concept can indeed be successfully applied to car engines and offer significant advantages compared to conventional state-of-the-art engines.

INTRODUCTION

Recent development activities throughout all fields of combustion engines have been characterized by an effort to reduce fuel consumption and to mainly reduce the NO_x emissions. The Berlin/Germany based company IAV GmbH has contributed to this challenge with a unique approach:
Instead of optimizing the common yet highly transient internal combustion in conventional spark-ignition or diesel engines, IAV has developed novel ideas to apply the well-known steam engine concept to automotive power trains. This so-called **Zero Emission Engine** (ZEE) is an innovative steam engine that uses an external high performance combustion process as the main heat source. One of the major advantages of this novel porous burner technology, which has been developed at the Institute of Fluid Mechanics of the University of Erlangen-Nuremberg, is its low pollutant emission behavior. With NO_x emissions below 10 ppm and CO and CH concentrations at the limit of detection, an engine prototype could be realized, which complies by far with the stringent Californian SULEV (Super Ultra Low Emission Vehicle) standard even without a catalyst. In this context, it is interesting to know that the burner operates with different fuels. Although this paper concentrates on the actual porous burner, the general idea and the most important outlines of the developed power train are also briefly described.

GENERAL CONCEPT OF THE ZEE

The ZEE is a steam engine and uses conventional peripheral components, such as, pumps, steam generators, heat exchangers and condensers. However, the basic idea and these components of the hardware are the only things that the ZEE has in common with the well-known steam engines of the 70's [1-4]. In order to develop a modern version of the steam engine idea, IAV combined the most innovative concepts of material science, control engineering and combustion technology along with unusual thoughts on thermodynamics.
Fig. 1 schematically shows different operational cycles of steam engines. In between the common Rankine- (blue) and Carnot-cycle (yellow), the two basic thermodynamic ideas for the ZEE are shown. Starting from the common Rankine cycle (indicated with a blue line in fig. 1), as a minimum standard for a new steam engine cycle, significant potential enhancements of efficiencies are evident. Generally, an isothermal, instead of the common isentropic expansion, is favorable since it leads to a larger thermodynamic efficiency. Although it is not possible to transfer the required heat flow during the expansion phase in steam turbines, a reciprocating piston engine is applied in the ZEE. This isothermal expansion has already been realized in a 1-cylinder engine, the ZEE-02 (red curve in fig. 1). In a further development step, the IAV engineers combined the vision of an isothermal expansion with an idea of a supercritical operational cycle as plotted with a green line in fig. 1. A feed pump increases the pressure level of the feed water to 500 bar. In the "steam generator" the operation media is heated up to 500°C without having to pass the two-phase region, but is instead transformed into a supercritical state. The combination of a special injection system combined with a superheater theoretically yields the process depicted in fig. 1 with a maximum temperature of 900°C. The special design of the superheater results in an isothermal portion in the following expansion stroke to a pressure level of 1 bar resulting in additionally gained mechanical work compared to conventional isentropic expansion (grayish area in fig. 1). Provided that the excess heat of the exhaust steam at the pressure level of 1 bar is transferred to the feed water at 500 bar this described operational cycle features significant increase in cycle efficiency.

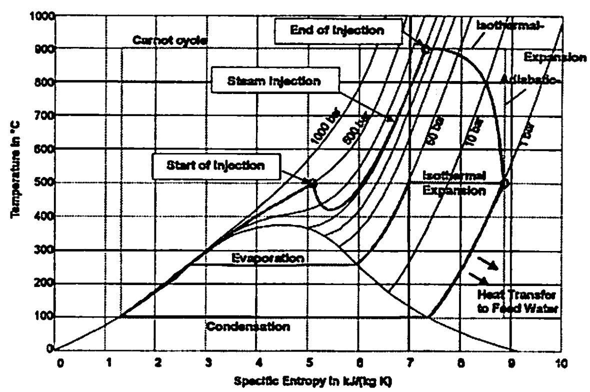

Fig. 1: Different operational cycles of steam engines

Fig. 2 shows a cutaway view of the principle design of a 3-cylinder steam engine that realizes the described operational cycle. Besides the already mentioned components like the condenser, steam generator, high-pressure steam injector, and superheater, two individual burners are shown in fig. 2. The arrangement of two burners bears the idea that one burner should cover the basic load of the engine (right hand, top burner in fig. 2) while the second burner should allow instant superheating of the live steam for peak loads (left burner in fig. 2).

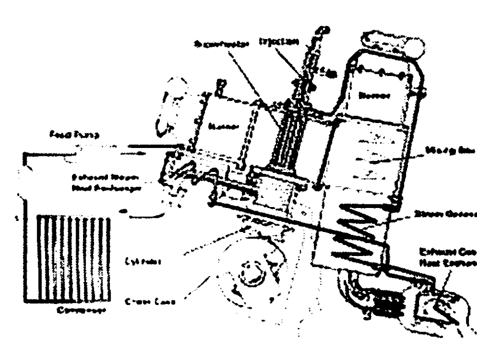

Fig. 2: General design of the ZEE

The burner located on top of the cylinder head (the left burner in fig. 2) is mainly responsible for the delivery of the heat required for superheating the process fluid. After completing the superheating process the still hot exhaust gases from this burner are combined with the exhaust gases of a second burner system in a mixing chamber. The combined gas flow heats the feed water of the closed steam cycle to supercritical temperatures in a compact steam generator. Waste heat that must be dissipated is transferred via two heat exchangers and the cooling system of the two burners into the feed water. This configuration optimally shows the efficiency potential of the isothermal steam engine concept.
Of course, all the explained principles demand high performance components along with highly developed strategies in closed loop control. Although each of the involved components deserves mentioning, this paper focuses on the main heat source of the process, the porous burner and its special requirements and advantages. More detailed pieces of information about the complete ZEE project is given in [5-7].

POROUS BURNER TECHNOLOGY

A completely novel concept for an automotive power train on a steam engine basis requires a very innovative burner technology as the main heat source. The applied burner has to fulfill a wide range of individual requirements at the same time:

- **Compactness.** When trying to develop an engine for automotive applications, space is limited. Therefore, the applied burner has to be very compact in size.
- **Power turndown.** The heat source has to allow the complete process to be operated in a wide range of power outputs. As a result, the burner has to show a great dynamic power turndown ratio.
- **Multi-Fuel capacity.** For automotive applications it is very important that the engine can be run with a diversity of automotive fuels, such as gasoline, natural gas, hydrogen or even rapeseed oil, industrial gas oil and rich methyl esters. It is also essential that the burner is capable of burning different gaseous and liquid fuels at a constant high performance.
- **Emission output.** As the name of the engine – **Z**ero **E**mission **E**ngine – already implies, the emission output of the burner has to be extremely low over the complete dynamic power range and for a diversity of different fuels.

The only technology that allows all of the above requirements to be met is the so-called porous burner technology, which has been developed at the Institute of Fluid Mechanics of the University of Erlangen-Nuremberg and which is described in detail throughout the rest of this paper. Along with the principles of operation and the suitable materials and shapes for porous structures, some examples of already developed ZEE-burners together with corresponding results are presented.

PRINCIPLE OF OPERATION

Unlike conventional premixed combustion processes, the porous burner technology does not operate with free flames. Rather, the combustion takes place in the three-dimensionally arranged cavities of a porous inert medium, resulting first of all in a totally different appearance of the flame itself.
The most important criterion that determines whether or not a combustion process can take place inside a porous structure is its critical pore size. If the size of the pores is smaller than this critical dimension, flame propagation is prohibited; thus, the flame is always quenched. On the other hand, if the pore size exceeds the critical dimension, flame propagation inside the porous structure is possible. Taking advantage of this fact, a combustion process may be stabilized inside a porous structure by simply combining two of those structures, one with small pores and the other with large pores [8]. Fig. 3 shows the applied flame stabilization principle in a typical porous burner with the preheating region A, where the pore size is chosen in such a way that flame propagation is prohibited, and the actual combustion region C, where the pores are large enough for combustion reactions to take place.

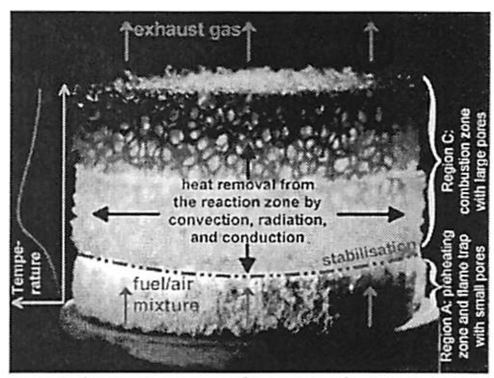

Fig. 3: Schematic setup of a porous burner

When combusting premixed fuel-air mixtures in such highly porous structures, the heat transport is enhanced by several orders of magnitude compared to conventional combustion processes with free flames. Consequently, such a reaction process leads to the following advantages, which result mostly from the very intense heat transport inside the porous structure and the stabilization principle:

- wide, infinitely variable dynamic power range of 1:20 compared to conventional state-of-the-art burners which show a power range of only 1:3,
- high power density, i. e. porous burner systems are about 10 times smaller in volume than

conventional burner units for comparable thermal loads,

- very low emissions ($C_{CO} < 7$ mg/(kWh) and $C_{NOx} < 25$ mg/(kWh)) over the complete dynamic power range,
- stable combustion for equivalence ratios of $\Phi = 0.91\text{-}0.53$ for CH_4/air mixtures (excess-air ratios: $\lambda = 1.1\text{-}1.9$),
- freedom of shape of burner with the possibility of freely adapting the burner shape to the required installation conditions.

MATERIALS AND SHAPES FOR POROUS MEDIUM COMBUSTION

It is a special feature of this technology that it is dependent on special high-temperature resistant porous components. Therefore, the presented work also provides a survey of materials and shapes of porous materials that are suitable for porous media combustion.

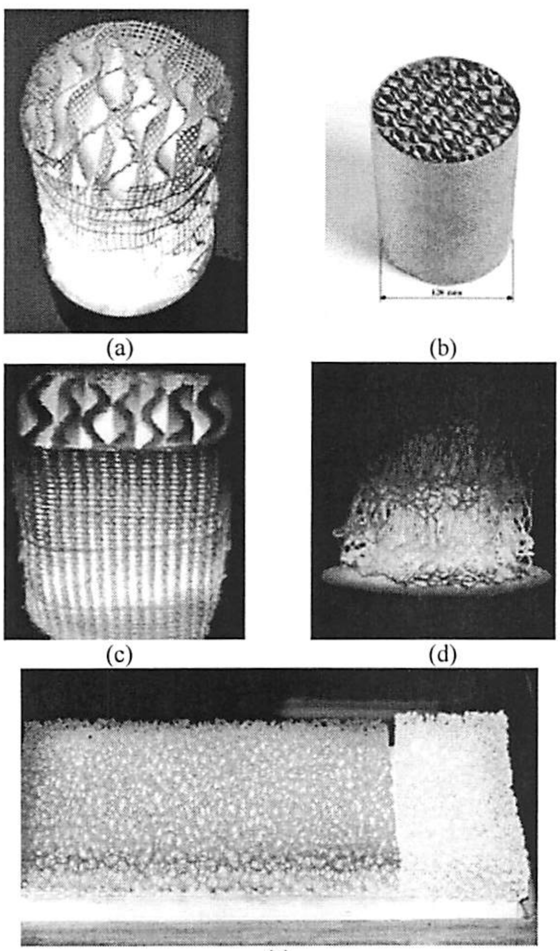

Fig. 4: Different ceramic porous materials: (a) Al_2O_3 fiber structure; (b) C/SiC structure; (c) static mixer made of micro porous zirconia foam; (d) Fe-Cr-Al-alloy wire mesh; (e) Ni-Cr-Al metal foam. left: uncoated, right: coated with ZrO_2

The overall performance of the porous body is always a combination of the base material itself and the actual porous structure. Therefore, for both the suitable materials and the shapes of porous structures the basic properties are briefly described.

The most important bodies for porous burners are SiC foams as well as mixer-like structures made of Al_2O_3 fibers, ZrO_2 foams and C/SiC structures [9]. For some applications iron-chromium-aluminum alloys and nickel-base alloys can also be used. All of the mentioned materials are substantially different with regard to manufacturing and properties. Al_2O_3 and ZrO_2 materials can be used at temperatures above 1650°C. Metals and SiC materials do not meet this qualification; however, they show outstanding characteristics with regard to thermal shock resistance, mechanical strength, and conductive heat transport. Wire meshes and mixer-like structures have a good start-up behavior and a small pressure drop whereas foam-like structures feature excellent heat transport.

With regard to mechanical and thermal shock resistance, materials which may be of special interest for automotive applications are high temperature resistant metal alloys. Whereas wire mesh (fig. 4d) has proven to be inappropriate for the current layout of the ZEE, foam structures of Ni-Cr-Al alloy (fig. 4e) show a good potential for a steam engine application. In fig. 4e such a Ni-Cr-Al-foam is shown in operation, on the left side the pure material itself and on the right side the base material has been coated with a thin layer of ZrO_2. Despite the numerous advantages of metal structures, they suffer from a limited maximum temperature resistance particularly in oxidizing atmosphere, which limits the operation range of those materials to temperatures below 1300°C. Although intensive development activities have been carried out, for the time being there are no metal structures available to be applied to the ZEE. However, great progress is achieved in enhancing both the long-term reliability and the maximum usage temperature, yet it may take another two years before metal materials can successfully be applied to the ZEE. Therefore, all of the presented ZEE burners have been equipped with mixer-like Al_2O_3 structures and special SiC foams, respectively, which show a maximum usage temperature of about 1600°C.

PERFORMANCE OF ZEE POROUS BURNERS

As indicated in an earlier chapter, a burner for the ZEE has to satisfy a great number and diversity of requirements, as there are extremely low emission outputs, compact dimensions and a power turndown ratio as high as possible. It has also been outlined that the porous burner technology is able to meet these numerous requirements. In this chapter, a few results of different ZEE burners are presented.

Fig. 5 shows a ring-type porous burner that demonstrates the complex combustion chamber geometries that are possible. This feature may be of special interest in applications where space is limited, for instance in small engines or auxiliary power units.

This burner in fig. 5 is used in the one piston version of the ZEE. It was originally designed for gaseous fuels, but has later been adapted for combusting gasoline as well. This demonstrates one of the major advantages of the porous burner technology, its multi fuel capability. It is caused only by the previously explained applied flame stabilization principle, which is working for a variety of gaseous and liquid fuels. The design of the porous burner can be performed in such a way, that the same burner can handle a wide spectrum of combustible mixtures including hydrogen, propane, butane and all common automotive fuels. In the case of liquid fuels a separate evaporator stage is needed prior to the porous burner.

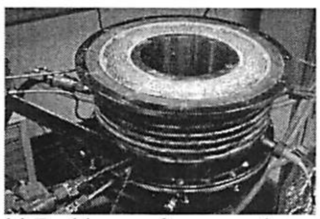

Fig. 5: Multi-Fuel burner for a one-piston ZEE

In fig. 6 typical emissions for the mentioned ring-type burner operating with natural gas and unleaded gasoline, respectively, are plotted. In the case of natural gas, there is quasi no CO emission over the entire modulation range of the burner. Also the NO_x level is clearly below 10 ppm and proves to be independent of the actual power load.

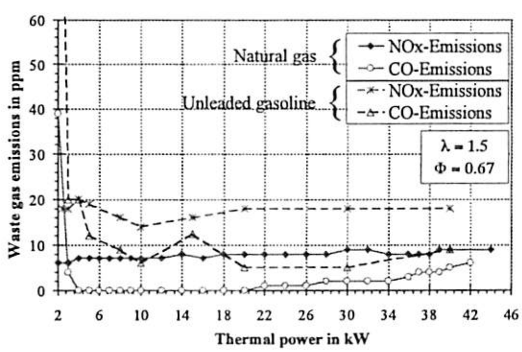

Fig. 6: Typical emissions of porous burners

The same applies to the emissions when operating the burner with unleaded gasoline. The only major difference is the emission level, which is about twice as high as for natural gas. In the case of gasoline, this increase of emissions is caused by fuel-bound nitrogen, which is fully converted into NO_x.

This emission behavior, which is typical for all porous burners and combustibles, results from a homogenous temperature field on a very low level, which is established by the outstanding heat transport properties of the applied porous structures. Fig. 6 also illustrates the immense power turndown ratio of porous burners, which is again a result of the very good heat transport inside the porous medium.

For the 3-piston version of the ZEE, the ring type burner of fig. 5 turned out to be too large in its overall dimensions. Therefore, together with some optimizations in the overall thermodynamic process a cubic porous burner was developed for the ZEE-03. This burner, shown in fig. 6, is optimized for power density and features a stunning value of 3000 kW/m². As already described, the ZEE uses two burners per cylinder resulting in a total number of 6 porous burners for the 3-piston engine that can release a total thermal power ranging from 9 kW up to 220 kW. This burner is designed for gaseous fuels, but in the case of liquid fuels, only an additional mixture preparation stage, which must not be part of the burner, is needed.

Fig. 7: Cubic porous burner for a three-piston engine

The emissions and the possible power modulation range obtained with the ZEE-03 burner are shown in fig. 8. It has to be stated that the nominal power output of the burner is 30 kW, however, overload experiments indicated a stable, reliable combustion at the same low emission level up to a maximum power of 36 kW. Also included in fig. 8 are results of experiments that were performed using **e**xhaust **g**as **r**ecirculation (EGR) as a primary means to even further decrease NO_x emissions. But also without EGR, the emission behavior is identical with the one of the ring type burner with NO_x emissions below 8 ppm. The slightly higher CO emission level of the burner owing to the extreme power density is a matter of design and is tolerated on purpose. Experiments with the complete engine showed that the temperature in the downstream region of the burner, i.e. superheater, mixing chamber, steam generator, is still high enough to allow CO to be converted to CO_2 completely resulting in quasi zero emission of CO in the exhaust pipe of the engine. Whereas the temperature profile downstream of the burner has a quite strong influence on the CO emissions, it does not affect the NOx emissions.

Although the NO_x levels of the presented burner are already very low, some special applications of the ZEE might require even lower emission values. Therefore, experiments have been carried out operating the burner with exhaust gas recirculation. As fig. 8 proves, EGR is a proper means to even further reduce NO_x emissions in porous burners without negatively affecting the overall performance of the heat source.

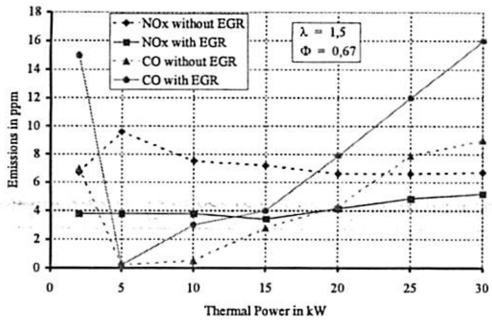

Fig. 8: Emission behavior of the ZEE-03 burner

SUMMARY AND CONCLUSION

By combining innovative concepts like supercritical steam injection and porous burner technology together with high performance materials and special closed loop control strategies, IAV has developed a modern steam engine that may be used as a power train in cars and shows emission values that are clearly below the stringent SULEV standard. Depending on the actual thermodynamic process applied to different ZEE concepts, emission values as low as indicated in fig. 9 can be obtained. All emission values plotted in fig. 9 are for a middle class passenger car in US FTP-75 test cycle.

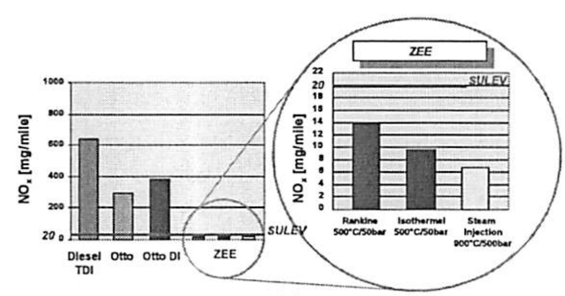

Fig. 9: Emission values of the ZEE

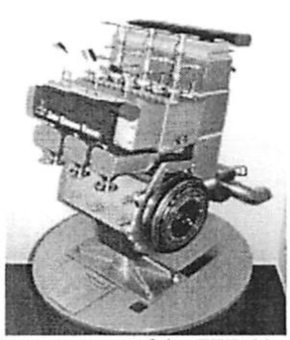

Fig. 10: Engine prototype of the ZEE-03

Fig. 10 shows a prototype of the latest ZEE engine using the described supercritical steam injection. It is a major task to further optimize this prototype for life span, weight-to-power ratio, overall installed size and potential mass production. However, IAV has successfully proven that steam engines are indeed feasible as vehicle power trains and can satisfy currently applicable requirements on power train operation.

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