HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D8.8**

Study an alternative urea decomposition and mixer / SCR configuration and / or study in extended range of operation

Revision Final

Nature of the Deliverable:	Demonstrator
Due date of the Deliverable:	31.07.2018
Actual Submission Date:	25.07.2018
Dissemination Level:	Public

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Start date of Project: 01/05/2015 Duration: 42 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020

The EU Framework Programme for Research and Innovation

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1 Executive Summary

Since selective catalytic reduction (SCR) is considered to be a preferred way to comply with actual emission legislation for marine engines, tools and knowledge for designing appropriate and compact SCR systems are needed. Computational fluid dynamics (CFD) will play an important role within the engineering process. This requires validation data for the process chain of urea decomposition, which has already been studied by means of the hot gas test rig within the scope of the HERCULES-2 project. The content of the present deliverable D8.8 is an ammonia generator as one example to realize a compact unit for the urea decomposition and the subsequent SCR process.

Based on the basic layout of the ammonia generator, an optically accessible prototype was designed and built up. Experimental and numerical investigations of the initial setup were carried out to understand the flow, spray and the formation of deposits inside the generator. Based on the initial setup, two alternative concepts were designed and investigated as well. In addition, MAN tested the ammonia generator on a high-speed marine engine in order to evaluate the performance of this compact mixing device.

2 Introduction

The Institute of Technical Combustion (ITV) is part of work package group 4 “Near-Zero Emissions Engine” and is involved in sub-project 8.2 “Combined SCR and DPF”. SCR is an established method to reduce nitric oxide emissions of trucks and heavy diesel cars [1]. Also in the field of marine engines, SCR is regarded to be a promising solution to fulfil the actual IMO Tier III emission standards. However, the technology cannot be adapted without further research and development, because marine applications require special effort regarding e.g. scales, fuel flexibility and space optimized systems as well as a strong focus on numerical simulation in the engineering process. This is the reason why extensive investigations of the urea spray and decomposition have already been carried out within this work package. They are described in deliverable D8.4. Based on these results and the gained knowledge, a compact urea converter was developed and investigated for further optimization. The contribution of ITV to the present deliverable is the development of an optically accessible prototype of the urea converter and measurements to investigate the processes inside. MAN performed the respective simulations and ran tests on a marine engine test rig.

3 Objectives

The overall objectives of sub-project 8.2 which are relevant for this deliverable are:

- 80% NOx reduction with after-treatment system to reach IMO Tier III limits
- Reduce the necessary installation space for after-treatment system SCR on DPF within IMO Tier III (SCR only) system
- Adaption and integration of the after-treatment system on a marine Diesel engine

The focus of this deliverable is the compact urea converter prototype as part of a space-optimised SCR-system.

4 Demonstrator: Compact urea converter

4.1 General setup and optically accessible prototype

The ammonia synthesis from aqueous urea solution basically consists of three steps. First, water evaporates from droplets and the remaining pure urea is decomposed to ammonia and isocyanic acid (thermolysis). The isocyanic acid then reacts with water to ammonia and carbon dioxide (hydrolysis). The urea converter is designed according to this process chain. The initial and general setup can be seen in Figure 1 (left).

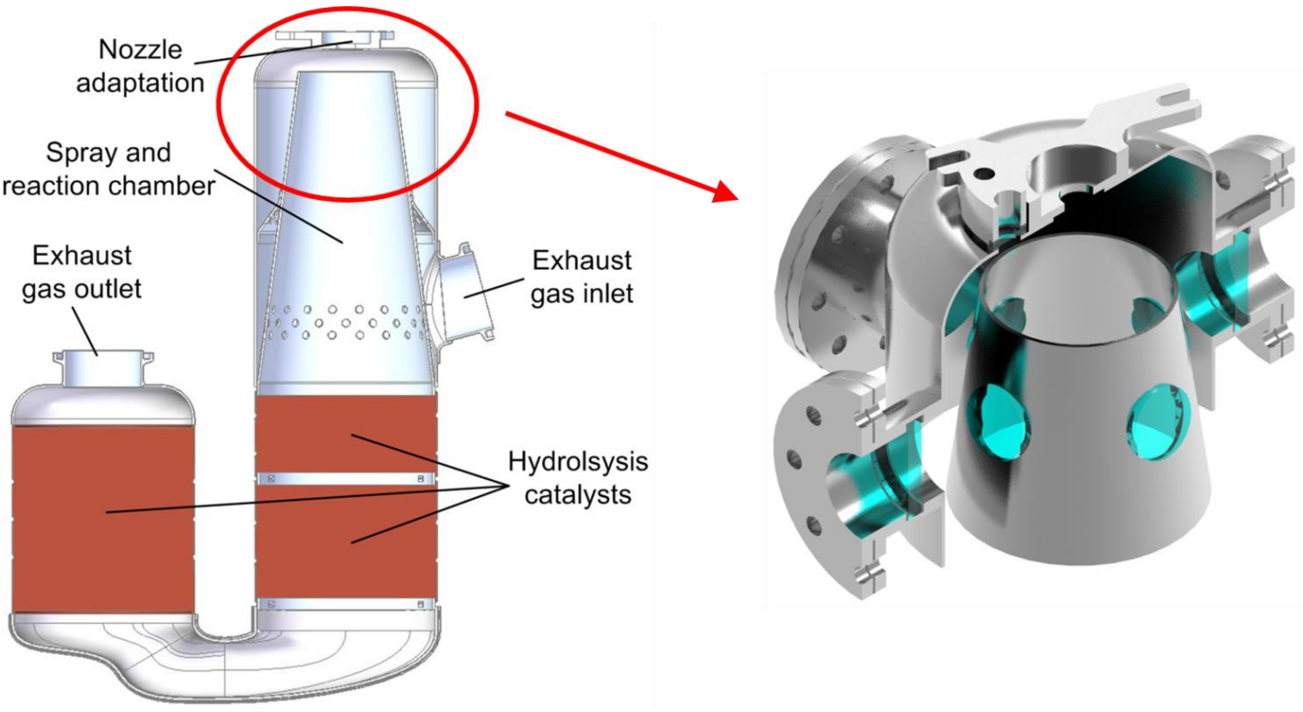

Figure 1: General setup of the compact ammonia generator and window setup of optically accessible prototype

The urea solution is sprayed into a mixing and reaction chamber formed by a cone, where the evaporation of water and the thermolysis take place. The exhaust gas flow is brought into the cone in two ways. One fraction enters through the lower part of the cone, whereas the rest is led into the cone together with the urea spray from above. After the cone, a set of catalysts supports the hydrolysis of isocyanic acid. The urea converter is placed parallel to the turbocharger and is thus provided by just a part of the exhaust gas stream. Hence, the urea converter can be as compact as possible and the concentration of ammonia in this branch is relatively high. However this approach contains the risk of deposits, which is the reason for studying the processes inside the urea converter. Therefore, an optically accessible prototype was built up.

The optical investigation of the flow inside the ammonia generator requires windows in the outer tube as well as in the inner cone. Overall, four pairs of windows are located in the upper area of the ammonia generator as seen in Figure 1 (right). The outer windows are mounted by means of flanges whereas the inner windows are directly fixed in the wall of the cone. This layout guarantees minimal disturbance of the flow due to the modifications. The window setup allows the application of particle image velocimetry (PIV) as well as phase-Doppler anemometry (PDA) (Figure 2). PIV is used to measure the velocity field of the exhaust gas as well as the velocity of the spray. The velocity of single droplets and their diameter can be measured by PDA.

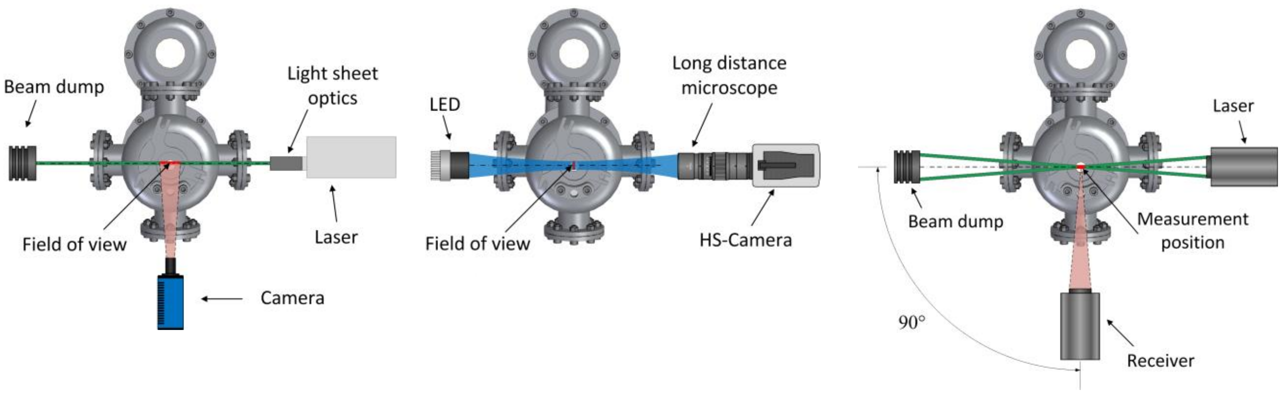

Figure 2: Measurement setups at the ammonia generator: particle image velocimetry (PIV) and planar imaging (left), high-speed shadowgraphy (middle) and phase-Doppler anemometry (PDA) (right)

4.2 Setup at the hot gas test rig

The hot gas test rig, shown in Figure 3, consists of unitized tube elements to allow maximum flexibility. The first unit contains an oil burner which offers variable thermal output in order to provide a hot gas flow according to any desired operating point.

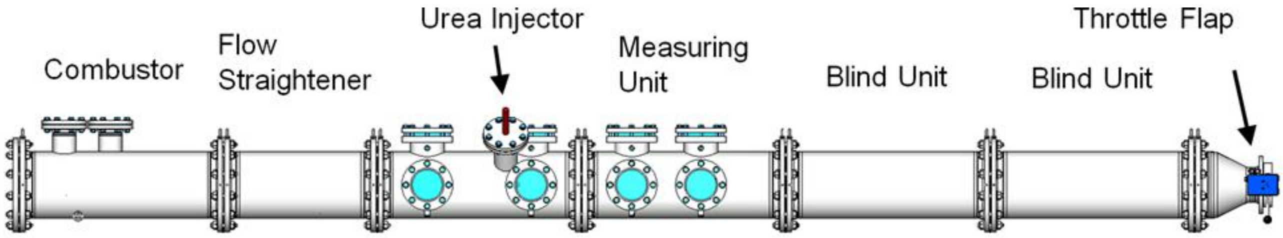

Figure 3: Hot gas test rig

The burner and the blind units of the test rig were used as peripheral devices to manage the hot gas supply and extraction. The injection and measurement unit was replaced with the ammonia generator. As the measurement setups require a position of the ammonia generator away from the axis of the hot gas test rig, the generator was equipped with tubes and flanges and mounted to the hot gas test rig using bellows and reductions. Figure 4 - Figure 5 show the completed optically accessible prototype of the ammonia generator and the setup at the hot gas test rig.

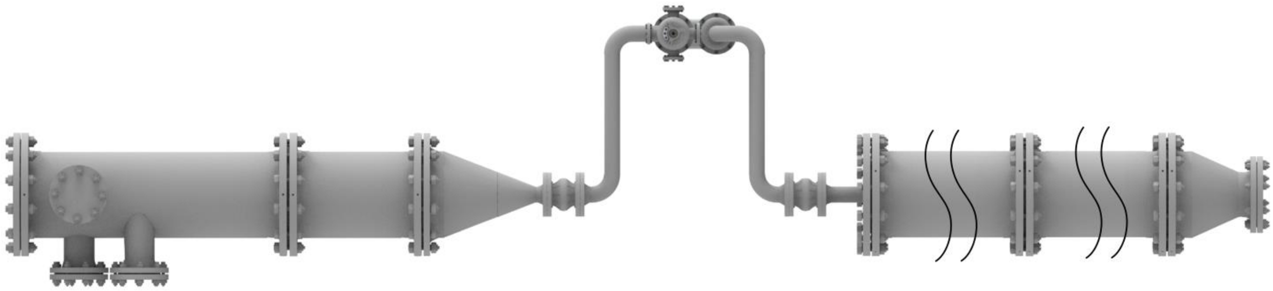

Figure 4: Setup of ammonia generator at hot gas test rig

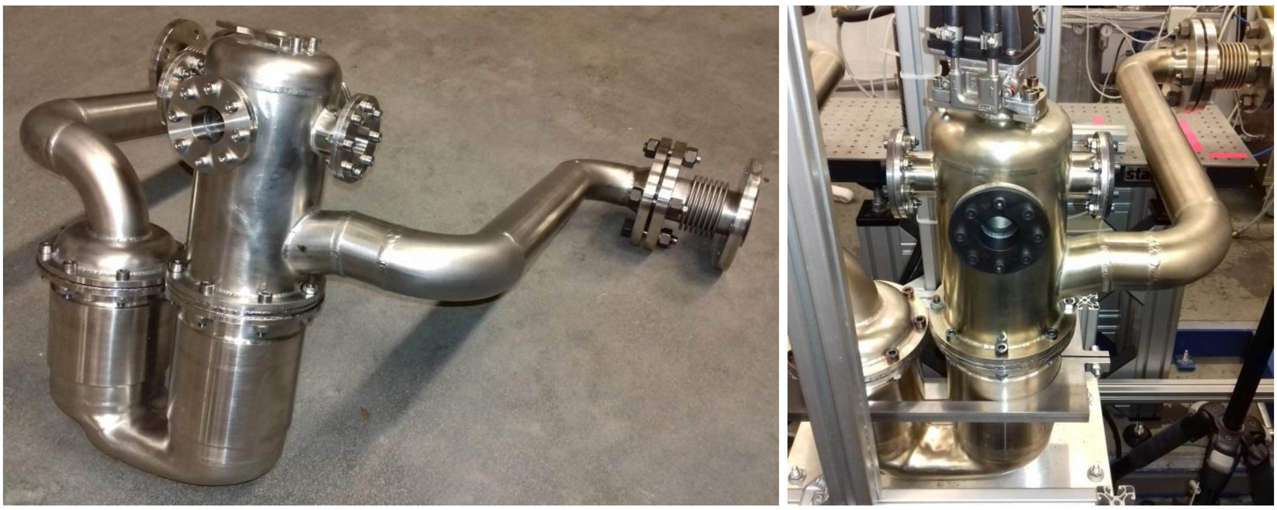

Figure 5: Optically accessible ammonia generator ready for installation (left) and installed at the test rig (right)

5 Tests and optical measurements

The previously described prototype was studied regarding flow and spray properties. Based on those results, two alternative concepts were developed and studied as well. These aspects are presented in the following two chapters.

5.1 Original configuration

The exhaust gas flow inside the ammonia generator is not symmetrical, which is caused by the single exhaust gas inlet. Numerical simulations were carried out for various configurations and Figure 6 (left) shows the flow field for the respective configuration realized here. In order to validate the simulation and test the ammonia generator experimentally, the flow field was measured by PIV (Figure 6 on the right).

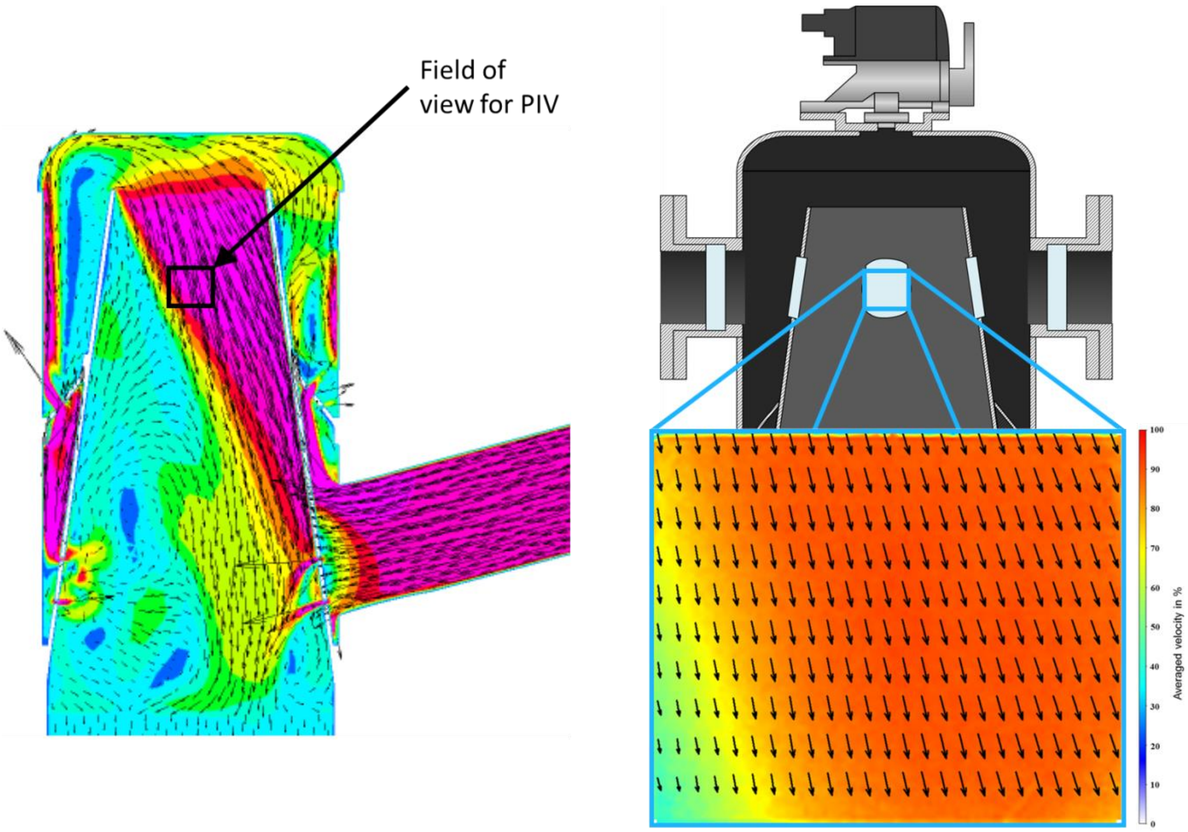

Figure 6: Simulated flow field (left) and PIV result for pointed field of view (right)

The PIV results match the simulation concerning both magnitude and direction. Especially the flow direction is important, as exhaust gas flows to the wall on the side of the inlet. The simulation shows that exhaust gas also flows into the gap between cone and outer wall. Tests on the hot gas test rig showed that the spray follows this flow as well and deposits are formed at the respective positions (Figure 7 on the right). The formation of these deposits can be self-energizing because the pressure drops reinforces the flow of gas and spray to the already existing deposits.

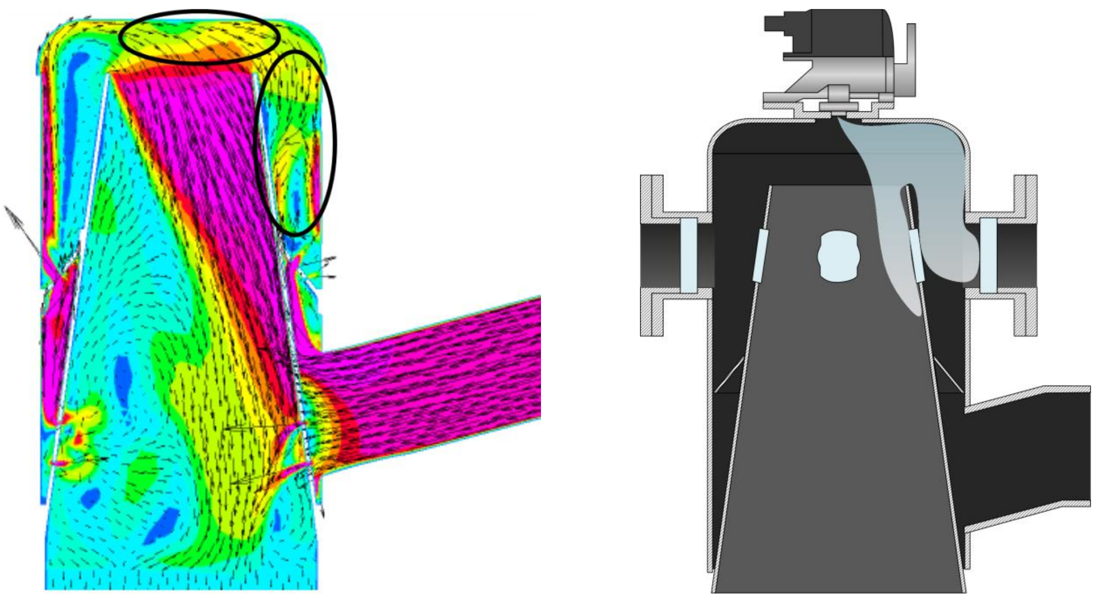

Figure 7: Flow into the gap outside the reaction cone (left) and visualization of spray propagation (right)

5.2 Alternative designs of reaction chamber

In order to prevent urea from getting outside the cone, a perforated extension was installed onto the cone and a different nozzle with a smaller spray angle was used (alternative configuration 1). The exhaust gas flow of this configuration was measured by PIV as well and the results were compared to the original configuration (Figure 8).

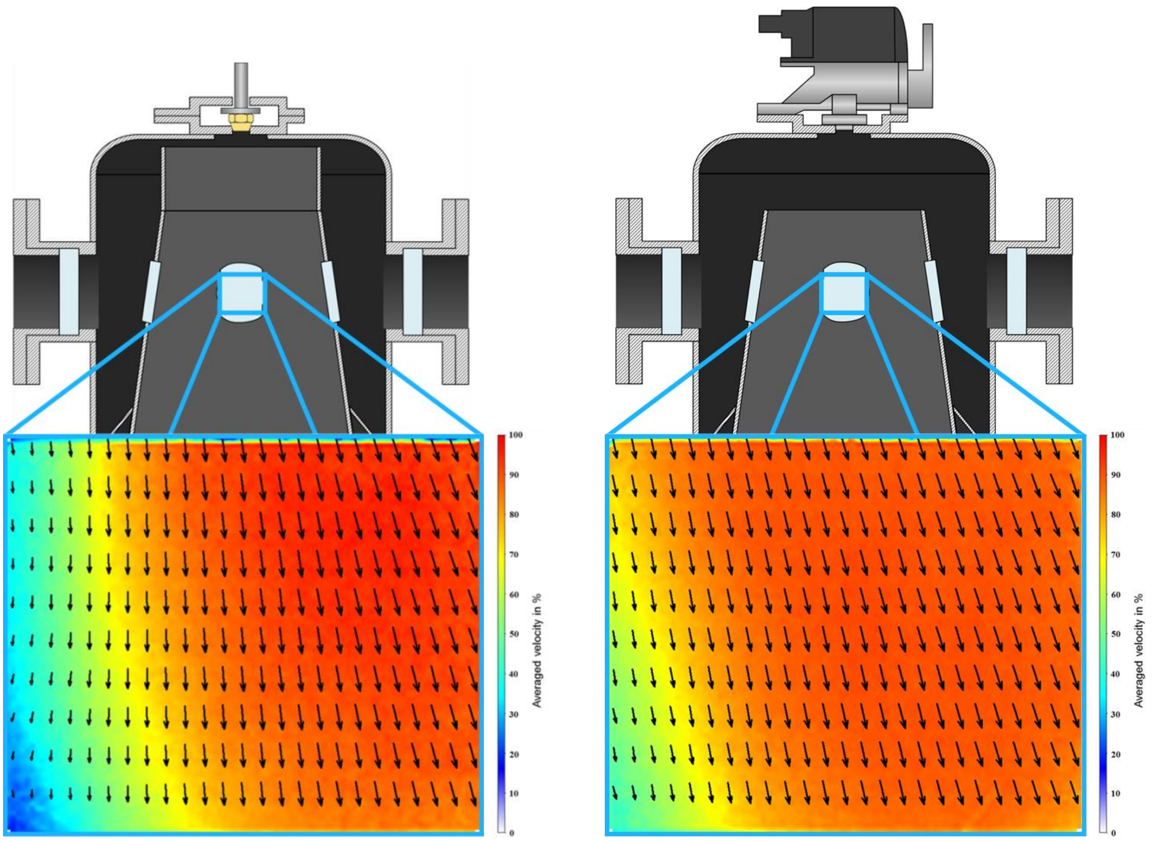

Figure 8: Measured exhaust gas flow field with extended cone (left) vs. original configuration (right)

Peak velocities are minimally higher than before but especially in the area opposite the inlet, the flow is significantly slower. The average velocity is a little lower which is explainable by the additional pressure drop due to the extension tube. The flow is still directed to the side of the inlet though the angle has decreased especially in the left and middle area of the field of view. In order to check whether the droplets follow this flow, their velocity field was measured by PIV as well. The spray follows the flow in two ways, which can be seen in Figure 9. First the spray velocity is directed in a similar way and second, the spray density is higher in the right part of the field of view.

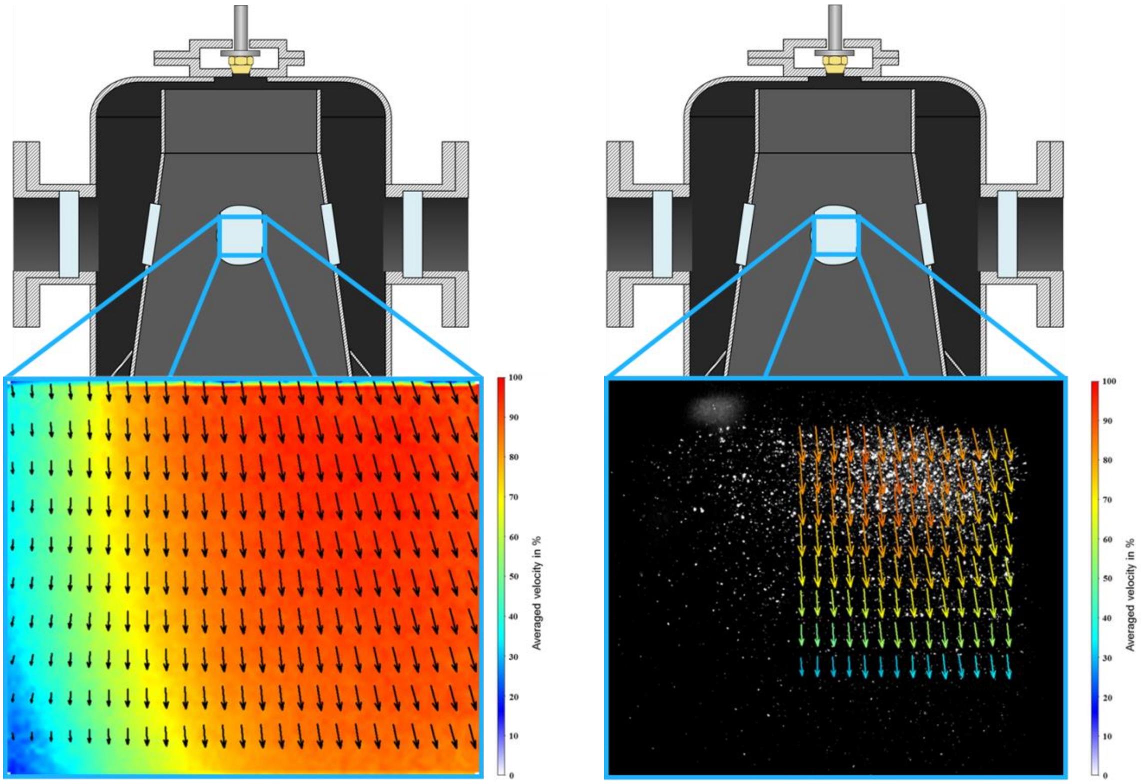

Figure 9: Exhaust gas flow field with extended cone (left) and respective spray velocity field (right)

Hence, long-term test were conducted to force and to characterize the formation of deposits. In this test, a strong liquid film was observed on the wall directed to the inlet, which matches the results of the velocity measurements. The film leads to deposits as shown in Figure 10 (left).

A second alternative (Figure 10 on the right) was set up with the aim to avoid the strong liquid film inside the cone. Therefore, the cone was perforated in the area of the liquid film to create an air cushion. Long-term test were carried out with this alternative using the same parameters as before.

The position of the resulting deposits is exactly opposite to the one from alternative 1. A liquid film like before does not occur, but deposits are formed already on the inner walls of the cone.

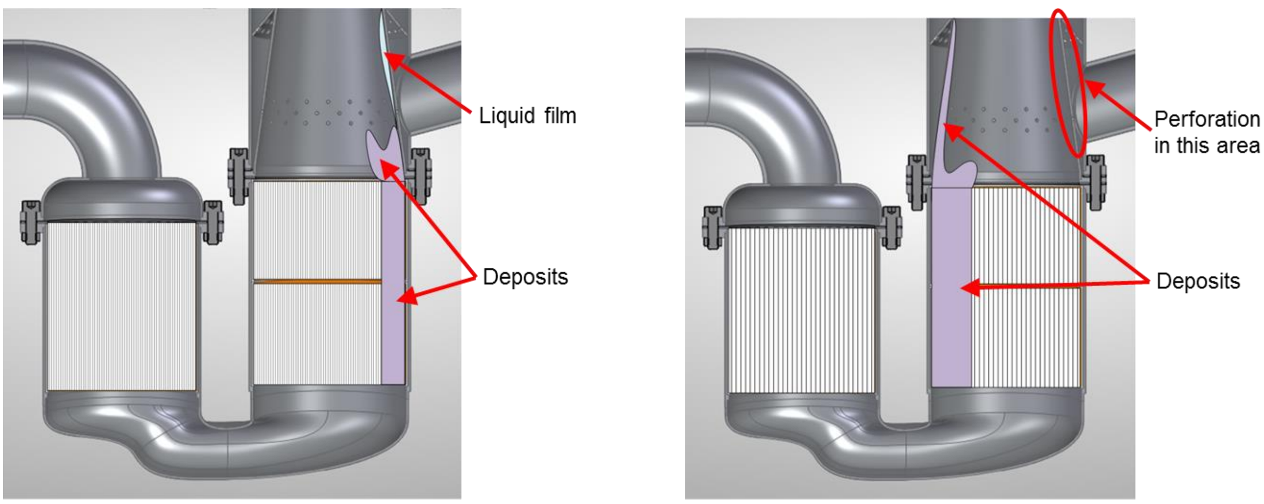

Figure 10: Position of deposits after long-term tests of alternative configuration 1 (left) and 2 (right)

6 Engine tests

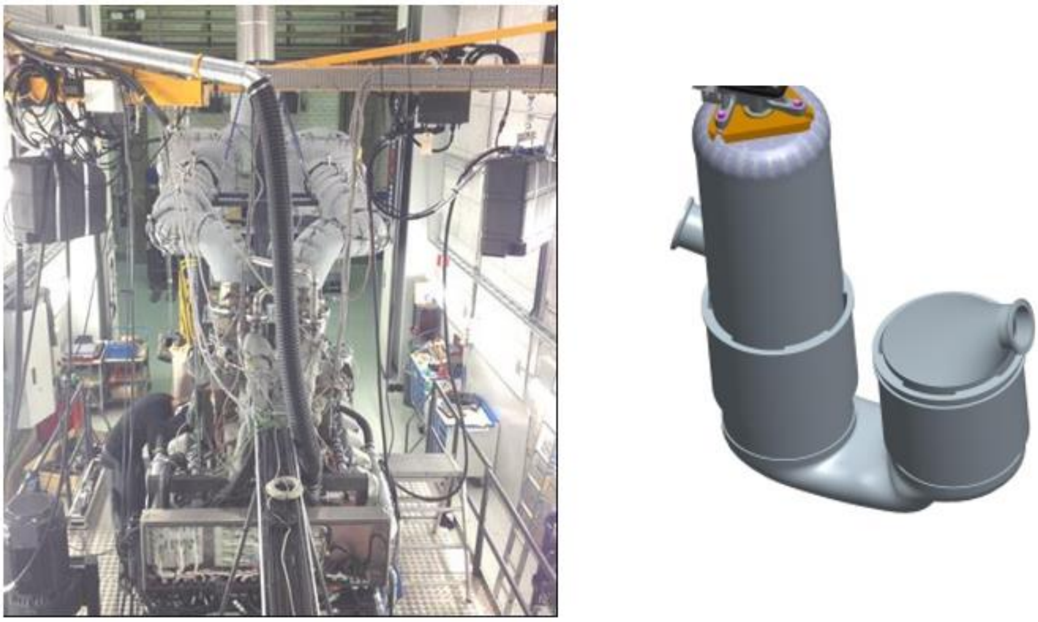

Figure 11: MAN engine test bed (left) and CAD model of the ammonia generator used at the test bed (right).

The evaluation of the ammonia generator performance took place at the MAN175D test bed (Figure 11). Equipped with a similar injector set-up as at the hot urea test rig, it was possible to reproduce deposits inside of the cone on the intake side (Figure 12). The position of the observed deposits compares well with the findings from the hot urea test rig at ITV.

Figure 12: Urea deposits in the ammonia generator for the original set-up during two individual engine test runs.

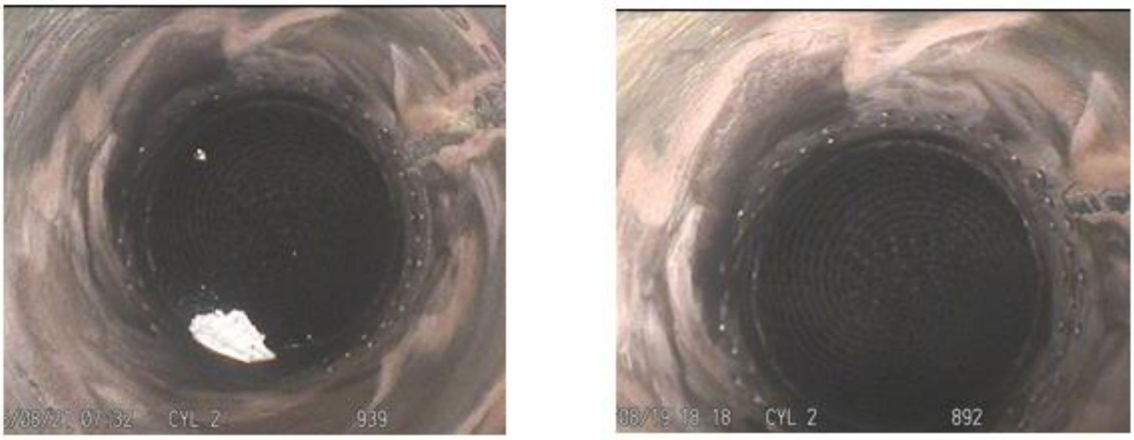

Figure 13: Urea deposits in the ammonia generator for the two optimized injector set-ups.

As geometry changes in the ammonia generator can hardly be applied at the engine test bed, it was decided to investigate modified injector set-ups by changing multiple parameters such as the spray angle or injector timings. With an optimized injector set-up, it was possible to reduce and finally fully avoid deposits at the walls (Figure 13).

7 Conclusions

The ammonia generator is a compact device for the decomposition of urea. Within the work of the Deliverable D8.8, the ammonia generator was successfully built up as optically accessible prototype. The prototype was used for investigations of the flow and spray properties inside the generator. Special attention was paid to the formation of deposits and different designs and operating conditions were studied. Appropriate geometric design parameters depend on the exhaust mass flow and thermodynamic boundary conditions, which is given by the respective engine. First investigations on a test engine showed that injection system set-up strongly affects the deposit formation.