FINAL TECHNICAL REPORT

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Centro Ricerche Fiat ScpA - CRF
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1 EXECUTIVE PUBLISHABLE SUMMARY 3

2 OBJECTIVES AND STRATEGIC ASPECTS 6

3 SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS 8

3.1 Introduction 8

3.2 WP 1: Fundamental experimental analysis of cavitation erosion 8

3.3 WP 2: Engine related experimental analysis of cavitation erosion 11

3.4 WP 3: Modeling of cavitation erosion 17

3.5 WP 4: Model implementation into CFD code and verification 20

3.6 WP 5: Model validation / application 20

3.7 WP 6: Consolidation of database and assessment regarding experiments and simulation 27

3.8 WP 7: Project management 27

4 ASSESSMENT OF RESULTS AND CONCLUSIONS 27

5 ACKNOWLEDGEMENTS 28

6 REFERENCES 29

1 EXECUTIVE PUBLISHABLE SUMMARY

During the course of the PREVERO project the main objective was to learn about the erosion caused by cavitation and to develop a CFD tool applicable in the industrial environment for prediction of cavitation erosion damage. In order to numerically predict the damage due to bubble collapse it is very important to evaluate and quantify the number of collapsing bubbles. For this reason an advanced cavitation model was implemented into the CFD program AVL FIRE. Cavitation erosion in several test bodies has been investigated. The damaged specimens were studied and the materials' parameters were entered into the erosion model, which was implemented in FIRE along with the advanced cavitation model. The numerical results were compared against the experiments in terms of cavitating flow quantities as well as erosion effects.

Cavitation bubbles collapsing on the material's surface cause long-term damage if the collapses occur repeatedly at the same location. The main goal of AVL was to apply the experimental findings provided by other partners to validate the improved CFD tool AVL FIRE used for prediction of cavitation and consequent erosion damage. In order to predict the damage due to cavitation bubble collapse it is very important to quantify the number of collapsing bubbles. For this reason an advanced cavitation model was implemented into FIRE. The tool is able to quantitatively predict the amount of removed material as well as the incubation time, which is the time needed before any erosion damage will be observed. The CFD tool should also be applicable for systems other than injection components, every process undergoing cavitation can be considered. It was found that RANS is the numerical approach providing the results within time acceptable for industrial application.

The objective of BOSCH was to understand the complex procedures of cavitation erosion in injection systems, the impact to the hydraulic properties of the system and the identification of suitable measures to avoid erosion at critical positions. Several cavitation erosion tests were done, a data basis was created containing results of different project partners. It allows to get detailed information of the experiments as wells as of simulation results. Different experimental techniques were applied, such as interferometry, visualizations with high-speed camera, and acoustic measurements on throttle flow, free liquid jet and stagnation point flow with cavitation. Such flow regimes can be found in diesel injection systems. The dependence of erosion on temperature and pressure difference was analyzed by several experiments. Further, selected test cases were investigated by simulation. The results can be recapitulated as follows: Common turbulence models (k-epsilon or improved models such as k-omega-SST by CFX) can neither predict cavitation nor erosion in complicated geometries. The simulation technique does not resolve the cavitating flow structure. Only, the improved models, such as the hybrid method DES, SAS (Scale Adaptive Simulation, which closes the gap between DES and URANS) or the k-zeta-f model in AVL FIRE lead to more reliable results. The influence of the fluid properties could not be studied comprehensively. Too many single effects such as air release, nucleation and properties of multi component fluids (Diesel) play an important role in cavitating flow regimes. Here, additional work is necessary.

The aim of LFDT has been to slow down the cavitation process and to expand bubbles to the size to be able to obtain experimental data on meso- (bubble clouds) as well as on micro-scale (single bubbles). The experimental results showed strong evolutionary characteristics of water flow cavitation, which served for implementation of FIRE code V8.3405 into V8.5 that will be capable to cope with multi-scale nature of cavitation process. Two principle experiments were carried out to study cavitation in a confined geometry similar to valve cavitation. The first one has been designed to study a single bubble-induced cavitation, while the second experiment enabled to study massive cavitation in the slot region. The following flow regimes were observed and analyzed in terms of structural function, void fraction and bubble number density:

1. So called detachment region, where bubble breakup was observed in case of gas cavitation
2. Large scale cavitation region, where macroscopic bubbles formed clusters
3. Bubble collapse region, where individual bubbles collapsed due to the sub-cooled conditions

The experimental data bank served with input data as well as for benchmark validation of cavitation-erosion process simulation.

A new facility has been built by LEGI to support the development of the erosion model via pitting and mass loss tests. Prediction of incubation time and erosion rate proved to be in satisfactory agreement with experiments.

Different materials undergone various testing conditions (at TU Graz, BOSCH, LEGI, CRF) have been characterized at LTPCM using complementary techniques (optical microscopy, SEM, TEM, RX, surface roughness) providing new evidence for fundamental understanding of the erosion phenomena. The erosion model has been upgraded taking into account low cycle fatigue. Specimens were provided by the above mentioned partners and studied for the effects of cavitation erosion, especially those of LEGI.

An experimental facility at CRF has been set-up for studying the effects of cavitation erosion on the valve seat area of the common rail injector servo-valve. Numerical simulations of the experimentally tested geometry have been performed with AVL FIRE code for validation purpose.

The workflow of the experimental work at TU Graz can be summarized as follows:

1. Creation of flow conditions close to those in engines (flow geometry, high pressures, temperatures, operating fluid - diesel);
2. Optical access to the investigated flow area;
3. Optical measurements of cavitation distributions (volume fraction), determination of relations between geometrical and hydraulic flow parameters and cavitation onset;
4. Optical measurements of main physical flow parameters (velocity profiles and fluctuations, local temperature and pressure distributions and fluctuations), which are responsible for cavitation onset and used in a theoretical model for flow simulations;
5. Optical measurements of surface erosion at different geometrical and hydraulic flow conditions and determination of relations between erosion rates and flow conditions (flow temperatures, pressures, inlet channel shape, target angle, cavitation distribution).

The applied experimental methods provided data for a high accuracy database. Strong dependence of cavitation distributions on inlet channel shape, target shape, inlet- and outlet-pressure and temperature was established. Erosion measurements on aluminum models were performed. Local diesel density distributions were measured using interferometry, corresponding pressure and temperature distributions were evaluated. Velocity profiles were measured using LIF at different cross-sections. The velocity measurement technique was improved for extraction of flow velocity fluctuations.

The following set of experimental data is available: cavitation probability distribution (vapor volume fraction - mean value) and phase transition probability (RMS - data, i.e. gas/liquid fluctuations), mean flow velocity profiles and velocity fluctuations (RMS - data) for stream-wise velocity component, density distributions (mean value) and local density (pressure and temperature) fluctuations (RMS - data). The obtained experimental data shows the direct relation between areas of density (pressure and temperature) and velocity gradients and fluctuations and the following cavitation onset. Relation between cavitation distribution and local erosion was proved. TU Graz and AVL worked closely together during the entire project to discuss different aspects of measurements and simulation techniques.

2 OBJECTIVES AND STRATEGIC ASPECTS

The main objective of **AVL** was to develop a CFD tool for prediction cavitation erosion damage. The goal was to apply the fundamental experimental results to validate the advanced cavitation model. Implementation of the advanced cavitation model was the focus of the first phase of the project and accurate validation thereof was a prerequisite for the second phase of the project. In the second phase of the project AVL implemented the erosion model provided by LEGI. Implemented model had to be validated and the experimental findings of other partners were the basis for the comparison. It was also important that AVL offered support regarding CFD simulations for those partners who needed assistance.

BOSCH was active in two main areas of the project; experiments dealing with cavitating flows and CFD simulations. It is a known fact that phenomenon of cavitation is used in control valve (A-throttle) to get a mass flow, which is independent of the back flow pressure. This permits to guarantee an accurate injection of mass during the pre and main injection. Since cavitation erosion plays an important role in the lifetime in such control valves, it is essential to understand and predict the erosion process.

The main objectives of the work performed at BOSCH were:

- Comprehension of the erosion process depending on the boundary conditions.
- The influence of small changes of the geometry with respect to the erosion position.
- Dependence of test oil quality with respect to the cavitation erosion.

Collaboration with TU Graz, CRF, LEGI was important in terms of experimental information exchange, collaboration with LTPCM was related to the consequences of cavitation erosion on the material. Collaboration with AVL was related to numerical modeling and code validation

LFDT‘s experiment represented the fundamental validation case for the advanced cavitation model implemented in the AVL FIRE code. Despite of extensive literature on cavitation, the details that describe a particular cavitating flow pattern, like cloud cavitation, are not sufficient to provide information that is indispensable for multi-scale numerical simulation. Bubbles that eventually cluster into a cloud are usually unknown neither by size nor by number density. Also the clouds that bubbles are forming are not known by their transient characteristics. Impact rates are usually calculated based on postulated Raileigh-Plesset equation that has been derived for a single spherical bubble because there is simply not enough data obtained from high-speed flows. The aim of the LFDT part of the project had been to slow down the cavitation process and to expand bubbles to the size to be able to obtain experimental data on meso- as well as on micro-scale. This data were supposed to serve as input data as well as validation data for CMFD (computational multiphase fluid dynamics) simulation of cavitation-erosion process [1]. LFDT worked closely together with AVL in areas of cavitation modeling and validation of the code.

LEGI objective was to build the experimental facility, to perform cavitation erosion runs and to develop the erosion model. The test samples were thereafter studied with LTPCM to determine the material properties entering the erosion model. The model was provided to AVL for implementation into the CFD code.

LTPCM: the objective was to study the test samples of all partners performing erosion tests and to provide the material properties needed in the applied numerical models.

Different materials undergoing various conditions have been investigated using complementary techniques. New evidence for fundamental understanding the erosion phenomena was documented. The erosion model has been upgraded taking into account low cycle fatigue.

CRF: The goal of CRF was to carry out experimental tests and CFD simulations on the throttling area of the common rail injector servo-valve. Experimental facility has been set-up to study the effects of cavitation erosion on the valve seat area of the servo-valve and numerical simulations of the experimentally tested geometry have been performed for validation purpose. CRF worked together with BOSCH in the phase of preparation of A-throttle specimen, which was prone to cavitation erosion. CRF and AVL collaborated during the simulation and validation phase.

The research objective of **TU Graz** was an experimental study of the material erosion effects under the influence of cavitation at conditions of high pressure cavitating diesel flows and optical measurements and precise documentation of the physical local flow parameters, which are responsible for cavitation onset and consequent erosion. The obtained experimental erosion database was used for model verification and comparison with simulation results at conditions similar to those in real common rail diesel engines. Due to the adopted measurement techniques TU Graz collaborated closely with AVL and BOSCH. TU Graz also provided specimens to LTPCM for material related investigations of eroded materials.

3 SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

3.1 Introduction

The project work was subdivided in 6 separate work packages (WP), all of them subdivided into sub-tasks. Additionally, a WP for project management was included in the project.

3.2 WP 1: Fundamental experimental analysis of cavitation erosion

The objective of this work-package was to provide experimental support for physical analysis of the cavitation erosion process on different cavitating flows and materials and to improve the understanding of the basic mechanisms to be modeled and implemented in the prediction tool. This was an important task of the project.

A new experimental facility has been designed and built at LEGI to support the development of the erosion model. The objective was to provide basic experimental data for the validation of the modeling of both the hydrodynamic and material aspects. The data was obtained and processed as a joint work of LEGI and LTPCM.

As mentioned the entire facility was designed and built by LEGI. It is a cavitation tunnel whose design pressure is 40 bar. Such a high pressure allows to reach high velocities in the test section and consequently to generate cavitating flows of high erosive potential. This was a major design criterion while looking for significant mass loss after reasonable exposure times on materials like stainless steel 316L, being not especially soft.

In practice erosion tests have been conducted between 60 and 80 m/s inlet velocity. The incubation time was in the order of a few tens of hours and steady state erosion could be achieved in less than 100 hrs with a depth of penetration in the order of 0.1 mm on SS 316L.

The facility includes a centrifugal pump driven by a 79 kW electric motor, 80 kW heat exchanger, downstream tank for pressurization and appropriate transducers for the control of operating conditions.

The test section is made of a 16 mm nozzle followed by a radial divergent of 2.5 mm in thickness. A cavity remains attached to the nozzle exit and its length can be adjusted by changing the cavitation number. The target to be eroded is facing the nozzle exit. Erosion appears in the form of a ring centered on cavity closure, where erosive potential is the highest.

LTPCM dealt with material related aspects of the eroded specimens provided by LEGI, BOSCH, TU Graz, and CRF. To allow specific characterization of the eroded surface of materials, a mechanical profilometer was acquired. Different functional parts were purchased to complete full characterization of specimens: a new anode for X-ray measurements, AFM and nano-indentation tips. Special technique for TEM sample preparation was developed to prepare cross section of surfaces.

Pitting tests have been performed to measure the aggressiveness of the cavitating flow. Pits formed after a relatively short exposure time are considered as the signature of bubble collapses.

A special procedure was developed to analyze pitted surfaces. First, the surface is scanned using a profilometer. Then, pits are identified individually and their main characteristics (diameter, volume and depth) are determined. The analysis was focused on pits in the range 20 µm to 200 µm in diameter, which proved to contribute mostly to damage.

Long duration tests allowed for determination of the evolution of mass loss with exposure time. Depth of penetration was still measured using a profilometer. As expected, an incubation period without significant mass loss was observed, followed by an acceleration period and finally a steady state erosion stage. Two types of important information were determined from mass loss tests: the duration of the incubation period and the steady state erosion rate. Both are used in WP3 for the validation of the erosion model.

The experimental facility used by LEGI and LTPCM to support the development of the cavitation erosion model is an original hydrodynamic tunnel designed by LEGI. The tunnel was mounted at the beginning of year 2 and first tests were satisfactorily conducted in June 2004. Two different kinds of testing facilities are traditionally used for cavitation erosion investigations: hydrodynamic or vibratory devices. The choice of a hydrodynamic tunnel is justified by the application to diesel engine injectors where cavitation is actually induced by the flow.

Major design criteria was to produce a cavitating flow of high erosive potential. The objective was to get significant mass loss within reasonable exposure times, typically of a few tens of hours, on materials not especially soft but still comparable to those used in injection equipment. Because of the strong influence of flow velocity on erosive potential, it was decided to design the facility for high velocities. Empirically the maximum velocity and the maximum operating pressure were defined.

Specimens provided by different partners have been characterized at LTPCM. Aluminum alloys tested at TU Graz and by BOSCH; stainless steel at LEGI and rubber replicas at provided by Fiat. The influence on mass loss and mass loss rate of initial specimens' roughness has been studied. Specific deformation features near the eroded surface have been investigated. Phase and structural transformations have been observed after erosion. Finally, eroded surfaces have been observed to determine fracture mechanisms. Specimens were also characterized in terms of hardness, and hardness evolution to provide data for WP3.

Two principle experiments were carried out at LFDT of University of Ljubljana to study cavitation in a confined geometry similar to valve cavitation. The first one has been designed to study a single bubble induced cavitation when the water pressure was reduced bellow the atmospheric pressure, but still high enough that no saturated pressure was reached in the slot region. This enabled to study the influence of shear rates on a suspended bubble that breaks up into a number of smaller bubbles. It is apparent that these bubbles form nuclei for cavitation process. This process, however, lasts more than the survival time observed for a single bubble in a collapsing region. The experiments clearly showed that the incipience of new bubble clusters does not correspond to the region of lowest pressure. This raises the question (not known from the literature) on objective local indicator of bubble cavitation. The second experiment was undertaken at a reference pressure, which was sufficient to produce massive cavitation in the slot region. The following flow regimes were observed and analyzed in details: so called detachment region where bubble breakup was observed in case of gas cavitation, large scale cavitation region where macroscopic bubbles clustered in clouds and bubble collapse region where bubble collapsed due to the sub-cooled boiling conditions. The bank of experimental data that was gained served as benchmark data for numerical simulations that were running in parallel with the experiments, both at AVL as well as at LFDT within WP4 and WP5.

The following detailed experimental data on cavitation generated bellow atmospheric pressure were obtained under WP1:

Design, construction and test runs of cavitation set-up. Cavitation phenomena identification went in course with high-speed video recording. A recording rate up to 10,000 images/sec was used at electronic shutter speed 50µs, respectively. An image size format at such a speed was 512x192 pixel with a pixel size of 10µm. Recording time span was up to 4s which produced up to 20 Gbytes of data in a single experimental run. The following phenomena were considered:

- transient characteristics of bubble structures
- bubble tear-off
- bubble breakup
- bubble cluster formation
- bubble cluster collapse
- bubble cluster impact rate on solid surface
- time scale estimate of bubble and bubble cluster life span

Interfacial measurements by resistivity micro-probes [2]. In order to get local information on flow structures, a microresistivity probe of 11µm tip size was used while synchronized with a camera at the accuracy of $0.5x10^{-4}$s. A probe traversing system enabled point measurements at a minimal step of 10µm. The following measurements were performed for distilled and tap water:

- void (or volumetric) fraction
- bubble number density
- bubble cluster generation frequency
- bubble velocity
- length scale estimate of bubble clusters
- length scale estimate of bubbles

Measurements of low pressure field dynamics in liquid bulk by optical probes. Bulk liquid dynamics was detected by SAMBA 3000 optical pressure probe. The technique is based on a miniature silicone sensor of 0.42mm size located at the end of a fiber optic cable. It works on the principle of Fabry-Perot pressure interferometer that enabled recording of static as well as dynamic characteristics.

Measurements of liquid velocity field dynamics by hot film probe TSI -1276-10W, with a tip size of 25,4µm

3.3 WP 2: Engine related experimental analysis of cavitation erosion

Cavitation occurs in various components of diesel injection systems, for instance, on the low pressure side of pumps or injectors. On one hand, it is used to control the mass flow in the servo-valve, independent of the pressure in the low-pressure circulation zone. On the other hand, cavitation can lead to erosion of the material surface and in many cases, the sealing surface of valves. As a consequence of such erosion, the hydraulic properties of the system are altered. The worst possible case would be a malfunction of the injection system. The operating pressure of present injection systems is approx. 1600 - 2000 bar and as pressure increases, so does the probability for erosion.

Hydraulic equipment used at TU Graz is described first. A two-dimensional high-pressure optical model throttle with optical access into the area of investigation through sapphire windows for flow visualization was used. Two-dimensional metal models were sandwiched between these windows. Working fluid was commercially available diesel fuel. The hydraulic part was based on a common-rail high-pressure system. The system was tested at pressures up to 1400 bar rail pressure and was able to supply a diesel mass-flow up to 18 g/s at stationary flow conditions. For the stationary flow tests, the peak inlet pressure was limited to 400 bar. The system was equipped with pressure and temperature sensors and with a mass-flow meter.

A set of variable hydraulic geometries for flow and erosion studies was developed. The throttle inlet shape was made as well sharp and rounded (R=100µm). The geometries were manufactured from stainless steel for flow measurements and from aluminum for erosion tests (plate thickness 300µm). Some more details about hydraulic equipment are described in [5, 6].

Optical part consisted of the imaging system with about 10 times optical magnification in combination with digital cameras PCO SensiCam and DiCAM and a set of light sources, i.e. flash lamp, continuos wave He-Ne (633nm) and pulse KrF (248nm) excimer lasers. This system supported image size 1280x1024 pix, with spatial resolution up to 0.8 µm/pix and image recording times of 20 ns (KrF-laser and DiCAM-camera for velocity measurements), 100 ns (flash lamp and SensiCam-camera for cavitation and turbulence visualization and erosion tests) and 400 ns (He-Ne-laser and SensiCam for density distribution measurements with interferometry). A modified Mach-Zehnder interferometer was used for density measurements, UV-optics and a slit were used during velocity measurements with laser induced fluorescence (LIF).

Next, details are given on cavitation visualization technique. The liquid areas of cavitating diesel flows remained transparent, whereas gas bubbles produced a shadow. The dark regions at the images corresponded to the gas phase. The data is presented as a result of a statistical evaluation as mean bubble-density or cavitation probability distributions.

Local density distributions were measured using interferometry [7, 8], and corresponding pressure and temperature distributions were calculated using the following formula:

$$\rho(p,T)-\rho(p_0,T_0)=\frac{\partial\rho}{\partial p}(p-p_0)+\frac{\partial\rho}{\partial T}(T-T_0)$$

(WP_2_TU Graz_Equation_1)

Velocity profiles in diesel flows were measured using spatially narrow and temporally delayed LIF-signals, excited by powerful UV-radiation from KrF-laser. The measurements were performed inside the channels at different cross-sections, beyond the channel, and near to the target's surface.

Turbulence visualization of the diesel flows was performed by transmission and so called “schlieren”- method. The areas of strong gradients and turbulence appear dark in transmission images and bright in “schlieren” images.

Erosion measurements were performed using aluminum models and selection of proper pressure and temperature values. It was possible to observe the cavitating flow and to monitor the model's surface under "real-time" conditions. The erosion process lasted from 2 to 10 hours.

Results can be summarized in the following way. Cavitation distributions are discussed first. The detailed study of the stationary and transient high-pressure diesel flows displayed a strong dependence of cavitation probability distributions on inlet channel shape, target shape, inlet- and outlet-pressure and flow temperature.

Density distributions inside channels practically do not depend on the target type downstream. Channels with larger inlet radius have a thin boundary layer downstream and smaller re-circulation area. The density increase in the vicinity of the targets is connected to the static pressure recovery and flow deceleration. The density drop along the target‘s surface is connected to the static pressure drop and secondary flow acceleration.

Velocity distributions display a velocity decay close to the channel walls, a velocity maximum in the middle of the channel, and some velocity oscillations, which are reflected in density distributions. Flows show deceleration and boundary expansion due to propagation in the downstream direction. Flows are subject to the secondary acceleration along the target surfaces and to the subsequent deceleration due to friction with target surface and consequent heating.

Erosion measurements were performed and the summary is given next. Experimental conditions covered a broad range of parameters responsible for erosion, such as the inlet shape of the channel, inlet and outlet pressures and temperatures, target geometry shape and surface roughness. The sensitivity of the optical measurements to the changes of the surface shape due to erosion was 2-5 µm. Erosion was measured at the target surface area as well as inside channels. Erosion at stationary and transient (injection) flow conditions displays both similarities and differences as well. The main erosion features are listed below:

1. Location of erosion start is always related to macroscopic phase boundary (gas/liquid), i.e. to the area of cavitating bubble collapse near the surface.
2. Strong dependence of the erosion rate on the target shape, i.e. on the incoming flow angle.
3. Strong sensitivity of the erosion process to the local temperature distribution. Higher temperature corresponds to the earlier and faster erosion.
4. Higher target surface roughness causes earlier and faster surface erosion under stationary conditions.
5. Non-linear erosion dependence in time, i.e. relatively weak erosion at the beginning of the process followed by an acceleration period. Erosion always displays some temporal delay after load start at stationary flow conditions (incubation period).
6. Occasionally very fast local erosion was detected. Fast erosion results in changed flow conditions and often causes the corresponding cavitation probability decrease in the local surface area. The process is related to the local losses of relatively large material pieces of 10-20 µm size.

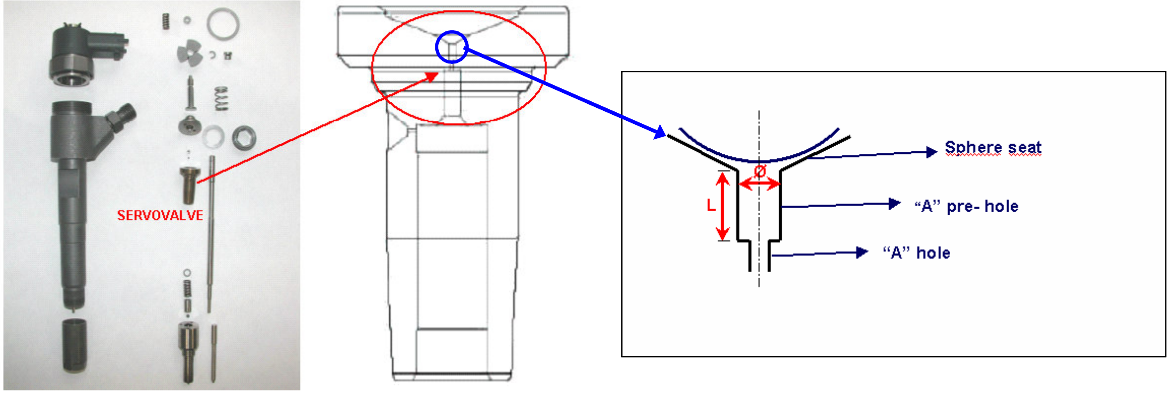
The applied experimental methods provided a high accuracy database. Strong dependence of cavitation distributions on inlet channel shape, target shape, inlet- and outlet-pressure and temperature was established. Erosion measurements on aluminum models were performed. Through selection of proper flow conditions it was possible to observe the erosion effects on a real-time scale. Local diesel density distributions were measured using interferometry, corresponding pressure and temperature distributions were evaluated. Velocity profiles were measured using LIF at different cross-sections. The velocity measurement technique was improved for extraction of flow velocity fluctuations.

The following set of experimental data is available:

1. Cavitation probability distribution (vapor volume fraction - mean value) and phase transition probability (RMS - data, i.e. gas/liquid fluctuations)
2. Mean flow velocity profiles and velocity fluctuations (RMS - data) for stream-wise velocity component
3. Density distribution (mean value) and local density (pressure and temperature) fluctuations (RMS - data)

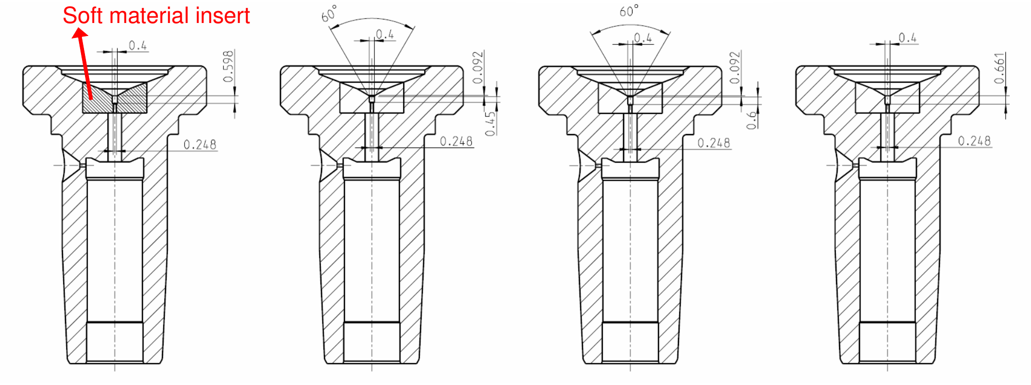
The obtained experimental data shows direct relation between areas of density (pressure and temperature) and velocity gradients and fluctuations and the consequent cavitation onset. Relation between cavitation distribution and local erosion is proved also.

CRF performed measurements on a servo valve. Throttling area of the common rail injector servo-valve represents a practical and useful case for numerical code validation (see WP_2_CRF_Figure_1).

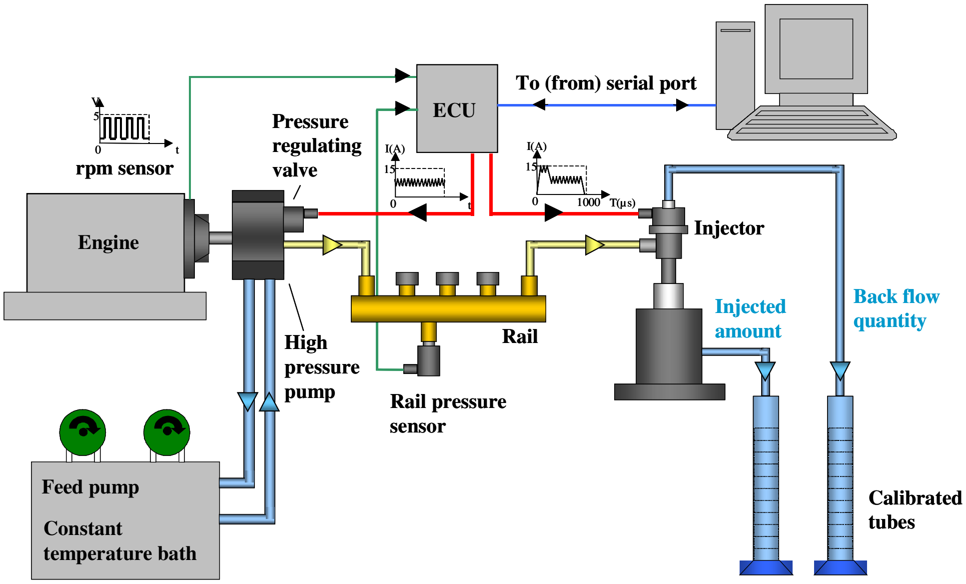


WP_2_CRF_Figure_1: Automotive common rail injector servo-valve and a zoom of the valve seat area.

Standard injectors can be affected by cavitation erosion after thousands of hours of operation. In order to avoid such an expensive process, not useful for the experimental purposes, in agreement with BOSCH, CRF has used modified injectors. The servo-valves of the injectors are shown in WP_2_CRF_Figure_2; in order to accelerate the arising of cavitation erosion, a more sensitive geometry of the servo-valve has been obtained. The ratio between the length, *L*, and the diameter, ϕ, of the "A" pre-hole (see WP_2_CRF_Figure_1) has been reduced to about *1.5*, whereas the standard ratio is about *2*. Furthermore, standard servo-valve material (100Cr6) has been replaced by *copper*.



WP_2_CRF_Figure_2: Four modified servo-valves.



WP_2_CRF_Figure_3: Experimental facility lay-out.

WP_2_CRF_Figure_3 shows the layout of the experimental facility that has been set up to carry out the tests. In order to analyze the effect of cavitation erosion the following aging strategy was initially planned:

Step 1: Investigations on hydraulic rig under cavitating conditions

- internal inspection @ *0 h*;
- *50 h* of aging (4 injectors) – internal inspection;
- *50 h* of aging (4 injectors) – internal inspection.

Step 2: Aging procedure under cavitating condition

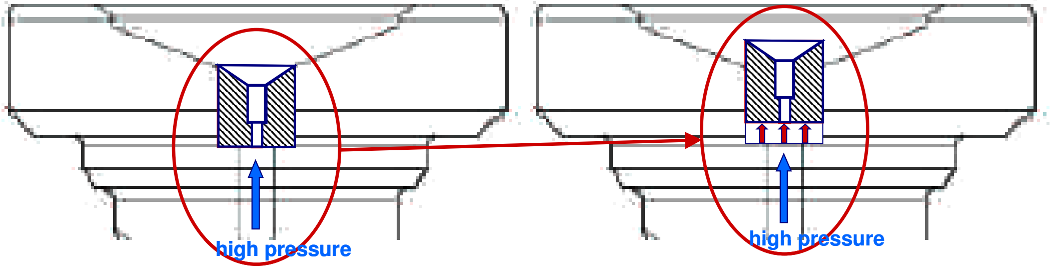
- engine tests with internal inspections every *50 h* (2 injectors);
- hydraulic tests with internal inspections every *50 h* (2 injectors).

Aging conditions defined for “Step 1” investigations are shown in WP_2_CRF_Table_1.

Rail temperature [°C]	*70*
Rail pressure [*bar*]	*1600*
Injection energizing time [*ms*]	*2*
Pump speed [*rpm*]	*2000*
Back pressure [*bar*]	*1*
Fuel return counter pressure [*bar*]	*1*
Test medium	Oil ISO 4113

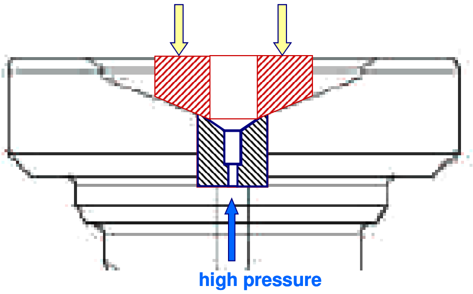
WP_2_CRF_Table_1: Aging conditions for “step 1” investigations.

Reduction of injected amount and increases of the servo-valve flow rates (back flow quantities), with respect to the initial values, have been observed in all the injectors under test after *50 h* of aging. Indeed, due to a partial lift of the soft material insert (see WP_2_CRF_Figure_4), observed during the injector disassembly, a test fluid leakage develops between the insert and the valve body.



WP_2_CRF_Figure_4: Modified servo-valve: partial lift of the soft material insert.

The inserts have been placed correctly and the injectors have been reassembled. After few hours of functioning, back-flow quantities increased because of the insert lift and the prototype injectors could not inject anymore in a stable way. One of the injectors under test has been modified at CRF laboratory to guarantee the insert stability: the insert has been clamped with a shim as shown in WP_2_CRF_Figure_5.



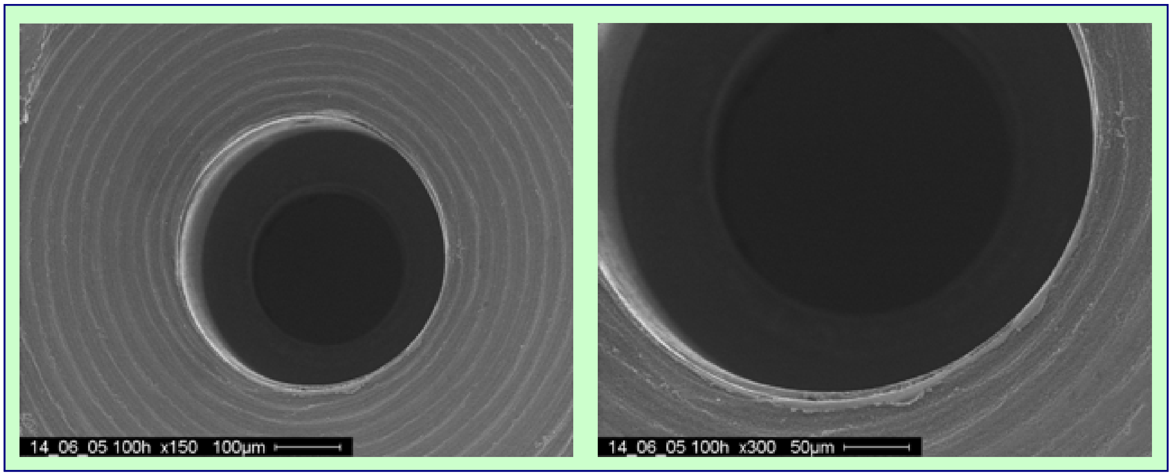
WP_2_CRF_Figure_5: Countermeasure adopted for test prosecution on hydraulic test rig.

The modified valve could operate under steady state conditions. For such a reason, in agreement with consortium partners, the new aging strategy has been defined as follows:
Step 1: Investigations on hydraulic rig under cavitation conditions (with injection)

- Internal inspection @ *0 h*;
- *50 h* of aging (4 injectors) – internal inspection.

Step 2: Aging procedure under cavitation condition with continuous flow (no injection) hydraulic tests with internal inspection.

WP_2_CRF_Figure_6 shows the top view of the throttling area of the injector servo-valve after *250 h* of operation: a moderate erosion damage is has been found in the region near the sphere seat area (see WP_2_CRF_Figure_6).



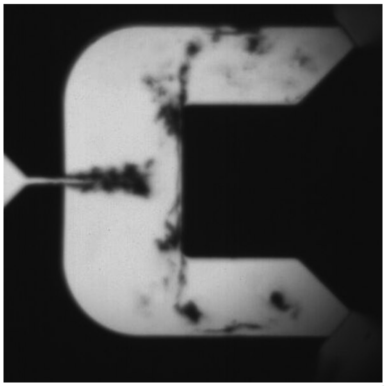
WP_2_CRF_Figure_6: Pictures of the servo-valve under test after *250 h* of aging: top view.

Experimental equipment installed at BOSCH contained the following:
- High pressure pump (CP1)
- Pressure reservoir of 60 ccm
- Test section for planar plates with vision panel
- 2 pressure transducers (inlet and outlet) and 2 temperature transducers
- A mass flow meter
- High speed camera with nano light

The test oil temperature can be kept in a range of 20°C to 60°C. A pressure range of 900 bar was used for testing the geometries. Different test geometries were defined with AVL in 2003. The objective was to investigate the cavitating flow (properties such as density fluctuation and velocity profiles on different positions) and the erosion in micro channels and deflectors, e.g. WP_2_BOSCH_Figure_1.

The essential results are summarized:
- Cavitation erosion increases with increasing inflow temperature.
- Small changes of geometry lead to a significant change of erosion location.
- Cavitation is strictly connected with the transient behavior of the flow field.
- Cavitation is coupled with local transport phenomena.

Several model experiments with cavitating flows in planar throttles in order to perform visualization have been conducted, as well as erosion tests and body acoustic measurements on aluminum specimen. Visualizations, erosion patterns and erosive mass loss and acoustic power could be correlated. The chosen geometry featured throttle flow, free liquid jet and stagnation point flow, which is a typical configuration in Diesel injectors. Mean values of cavitation appearance representing cavitation probability were calculated, so was the mean deviation. The latter one is much more convenient for comparisons with erosion patterns because erosion occurs where the vapor condenses which means there is highly transient behavior. Erosion measurements were conducted with the same geometry with systematic variations of inlet and outlet pressures so there is a reasonable database for comparisons with CFD-Simulations. Additionally the same flow conditions were observed optically. The wear was quantified by white light interferometry. Special A-throttles for Diesel injectors were built for endurance tests on a CRF test bench.



WP_2_BOSCH_Figure_1: Cavitation experiment – throttle flow combined with stagnation point flow.

3.4 WP 3: Modeling of cavitation erosion

The objective was to develop a multidimensional model for cavitation erosion. It was important to develop statistical description of the bubble impact loads responsible for cavitation erosion. The procedure involved modeling of the material response taking into account its microstructure, computation of the erosion rate for the materials tested in WP1 and comparison with the measured mass-loss in order to validate the model. Finally, a CFD model was derived to simulate transient flows of bubbles that are generated at low-pressure regions and eventually collapse near the solid surface using the multi-fluid model. Predicting the probability for cavitation erosion was the main goal.

The cavitation erosion modeling had to provide the model for the cavitation and erosion process on the bubble micro-scale. The numerical model was improved to simulate the propagation of pressure waves emitted by a single collapsing bubble and its damaging effect on the material surface. The simple and the final erosion model were validated using data from the WP1 and WP2.

Impact load model is considered first. The modeling of material response was a fundamental step in the prediction procedure. Impact loads were classified according to their amplitude with respect to material yield strength and ultimate strength. For the present application and in particular for the erosion tests conducted in WP1, mean impact load generally lies between both limits. Hence, the material surface is progressively hardened by successive impacts. The work hardening process was characterized by LTPCM from micro-hardness measurements on cross sections of eroded samples. A major parameter of the model is the thickness of the hardened layer.

Using the impact load model, a relationship was derived between pit depth and impact load. It was systematically used to analyze pitting tests and determine the amplitude of the hydrodynamic load (typically in MPa) responsible for each pit. The distribution of impact loads is considered as the signature of the cavitating flow.

In practice, the information on cavitating flow aggressiveness was reduced to three integral parameters: pitting rate, mean diameter and mean amplitude of impact loads. This basic description of flow aggressiveness was used in the CFD model for cavitation erosion to estimate the mass loss.

The erosion model developed in the framework of the PREVERO project allowed for computation of incubation time and mean depth of penetration rate MDPR. An equation has been derived to predict each of them as a function of (i) flow aggressiveness as described above and (ii) material properties measured by LTPCM.

The model points out a characteristic time and a characteristic length for cavitation erosion. The characteristic time is the covering time i.e. the time required for the material surface to be entirely covered by impacts without overlapping. As for the characteristic length, it is the thickness of the hardened layer.

The erosion rate MDPR under steady state conditions (measured typically in µm/h) is scaled by the ratio of this characteristic length to this characteristic time, with a multiplication factor, which depends mainly upon the average amplitude of impact loads. The incubation time is proportional to the covering time with a coefficient which also depends upon load amplitude and which tends to unity when mean load approaches material ultimate strength. The values predicted by the model proved to be in satisfactory agreement with the experimental ones obtained from the mass loss tests conducted in WP1.

AVL was involved in developing the CFD model for cavitation erosion. The model was developed by LEGI and provided for implementation. Only minor adjustments had to be performed in order to make it ready for implementation into the finite volume CFD code FIRE. The final version of the model contains a limited number of constants, which had to be adjusted based on obtained experimental data.

The modeling of cavitation erosion required the development of an appropriate model for the material response. Bringing together the material-specific and the flow-dynamics aspects of the problem represented the major obstacle regarding modeling. The hydrodynamic loads applied to the wall because of the collapse of cavitating structures can be classified into three groups. Details are given in the second part of the report.

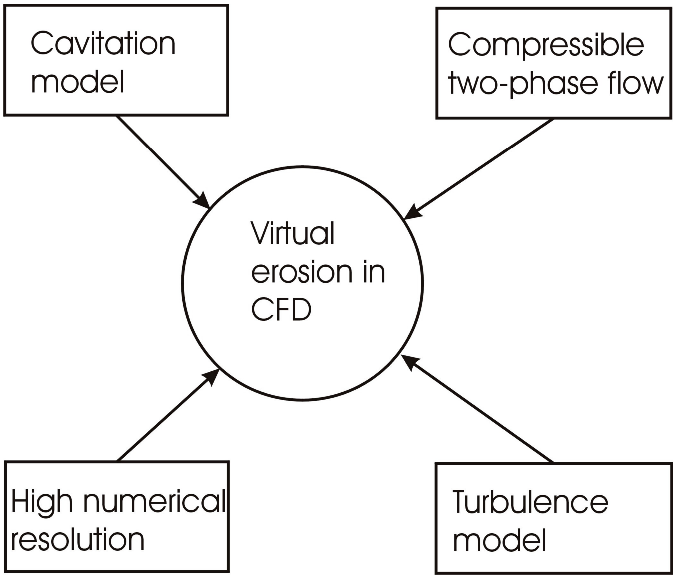
Different approaches for simulation of cavitating flows were considered. The focus of the work performed at BOSCH was on:

- Barotropic model: The two-phase mixture is considered as a one phase mixture but with a density function depending on the pressure. Thus, the speed of sound is well-defined. The entropy as well as the temperature is assumed to be constant.
- Homogeneous two phase model: it is assumed, that the velocity and the pressure of both phases are the same. This approach allows for usage of two compressible phases (liquid and steam). A continuity equation for the liquid and for the gas phase is used. The mass transfer term (which describes the evaporation and condensation) can be based on a modified Rayleigh-Plesset equation or on thermodynamic models. The turbulence model is applied to the mixture.

- Inhomogeneous two-phase models: It is assumed, that both phases have their own velocity and pressure. The exchange of mass, momentum, energy, and turbulence are described by models. In order to simplify such a complex system, it is assumed that both phase share a common pressure and common turbulence properties, which often leads to numerical instabilities.

BOSCH focused on the homogeneous two phase models. Several cavitation models were derived at BOSCH Group. The tests were done on reference volumes because of their complexities. They require a compressible approach for both phases and detailed information of evaporation / condensation properties of the fluid.

Why do we need a compressible approach? The test bodies are internal parts of a complete hydraulic system. Cavitation induces pressure waves and changes local speed of sound, which influences the hydraulic properties of the system. These pressure waves have to be considered in order to compute the time dependent mass flow as well as the transient character of the flow. In 3D simulation, the properties of the inlet as well as the outlet boundaries play an important role for the computed transient flow field. One has to guarantee, that no wave reflection provoked by cavitation or geometrical parts take place at the boundaries. WP_3_BOSCH_Figure_2 contains the dependency of the erosion process on the used models and methods. Due to lacking dρ/dP data, diesel liquid compressibility was not implemented within the presented work.



WP_3_BOSCH_Figure_2: Dependency of erosion simulation

3.5 WP 4: Model implementation into CFD code and verification

This work package was a joint effort of AVL, LFDT and LEGI. The advanced cavitation model has been implemented into the CFD code AVL FIRE. The solution method is based on a fully conservative finite volume approach with collocated variables setting used for discretization of the governing equations. The numerical solution procedure is based on the SIMPLE algorithm extended to multiphase case. An implicit inter-phase drag treatment is adopted to ensure the robustness of the multiphase algorithm (Wang *et al.* 1994). For accurate prediction of highly turbulent cavitating flows an advanced cavitation model (k-ζ-f turbulence model) was adopted for multiphase flows and implemented into FIRE. Finally, the erosion model provided by LEGI was successfully implemented into FIRE as well.

LFDT measurements enabled a new multi-scale model that has been implemented into FIRE code V8.3405 to account for bubble population balance including bubble breakup and coalescence [3], [4].

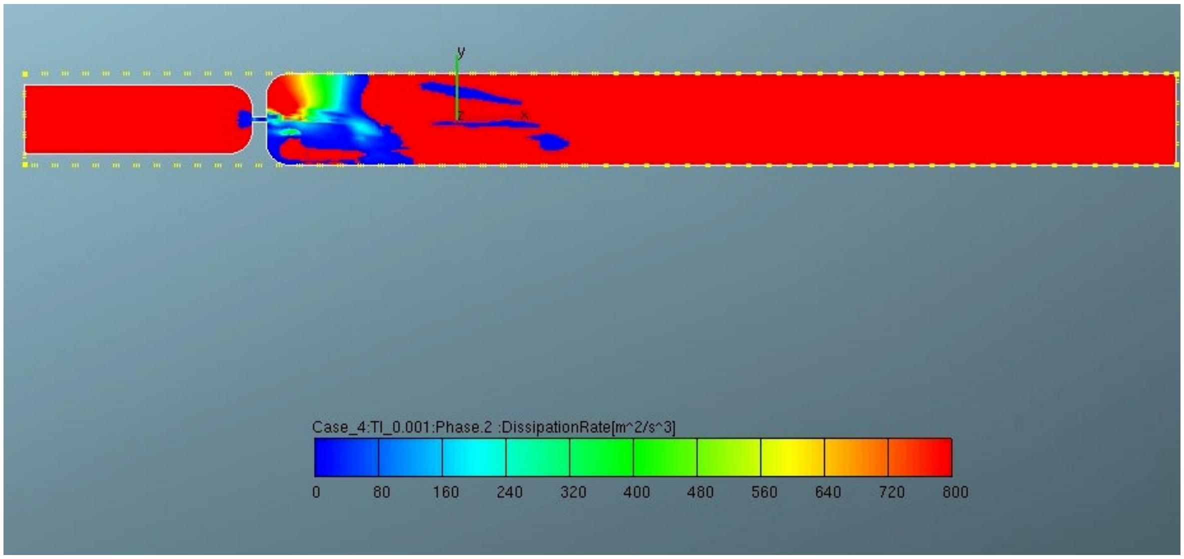
3.6 WP 5: Model validation / application

LFDT measurements from served as a benchmark reference. The following models of bulk liquid flow dynamics were tested that finally led to a new k-ζ-f model implementation into the FIRE code V8.3405:

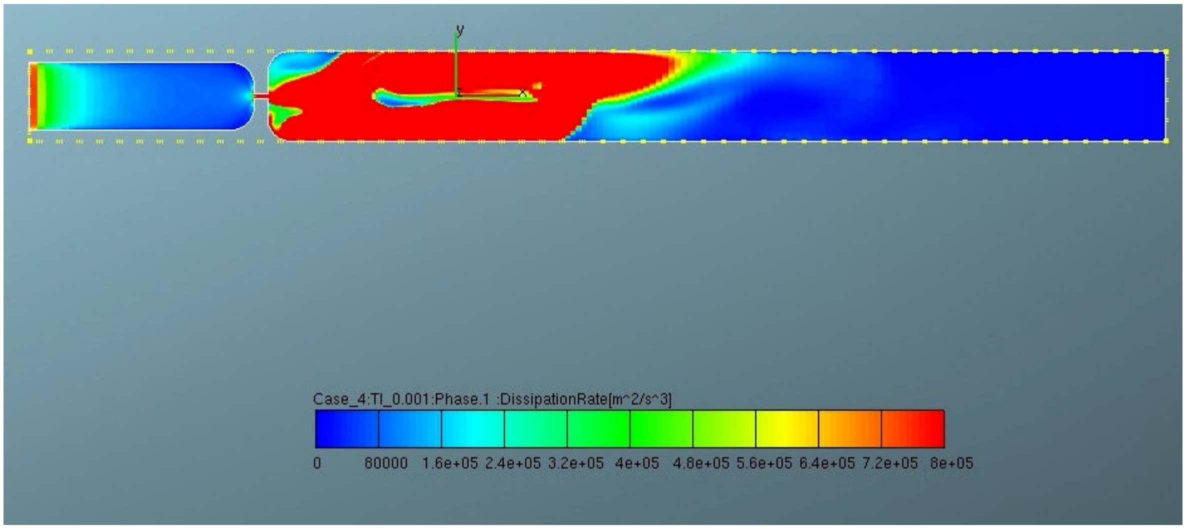
- 3D geometry laminar case (vortex shedding fades out)
- 2D geometry, turbulence model k-e (vortex shedding fades out)
- 2D geometry, turbulence model AVL HTM 2 and AVL RSM
- 3D geometry, turbulence model k-ζ-f (proved to be most efficient)

BOSCH tested 2 different CFD codes to validate the results. The results of the erosion experiments were compared with different turbulence model calculations. RANS-type simulation failed completely while URANS are capable to predict vortices at the right place but not the vortex cavitation. The reason is the large turbulent viscosity in the URANS computation, which leads to low vorticity. Since the presence of intense vorticity is necessary for the generation of vortex cavitation, prediction using URANS is not possible. In order to catch the phenomenon of vortex cavitation it is necessary to use the so called Detached Eddy Simulation (DES), which combines the advantages of URANS in regions with low grid resolution, especially near the walls, and the LES inside the shear layers and the stagnation point of the flow. The comparison between simulation and experiments showed that the predicted cavitation vortices are too small compared to the measured one. The discrepancy can be due to the grid, sub-grid model, air release model or surface roughness influences.

The following figures show the result of a calculation with the simulation program FIRE 8.4. The simulated geometry was investigated experimentally. The throttle was operated with a differential pressure of 360bar (inlet pressure 400bar and outlet pressure 40 bar). The temperature at the inlet was set to 30℃. In this experiment an isothermal flow assumption was made, thus no energy equation was solved. Next to this, it was assumed for simulation that the liquid and the gas phase are incompressible. This assumption is a strong limitation of the model. As mentioned above, lack of experimental dρ/dP data prevented AVL from implementing a liquid diesel compressibility model. Such decision was made by AVL and BOSCH.

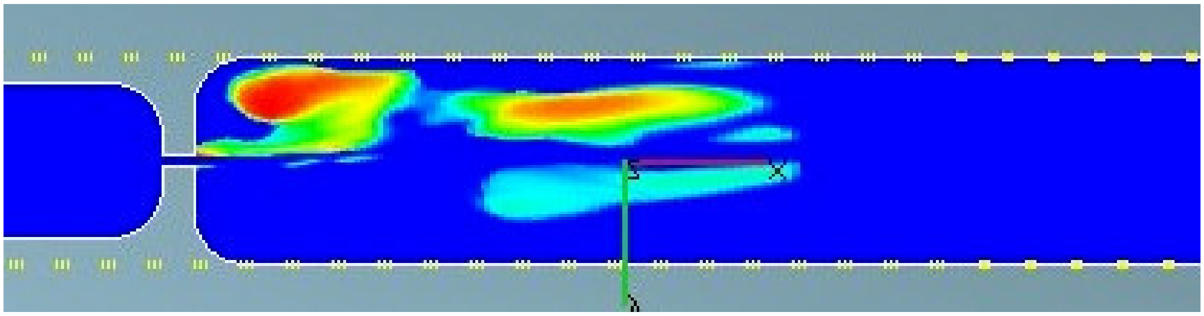


WP_5_BOSCH_Figure_1: Calculated dissipation of steam at t=0.001 s

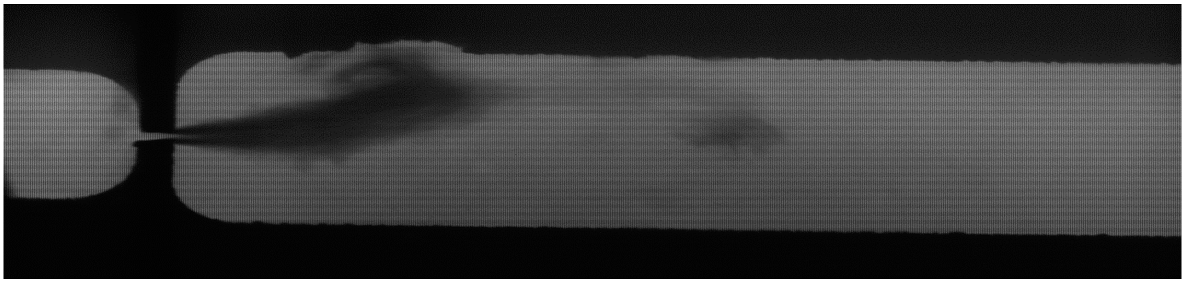


WP_5_BOSCH_Figure_2: Calculated dissipation of liquid diesel fuel at t=0.001 s

The above figures show the calculated dissipation of vapor and liquid diesel. The high dissipation of fuel at the inlet is not physical correct.



WP_5_BOSCH_Figure_3: Calculated volume fraction of steam (red) at t=0.001 s



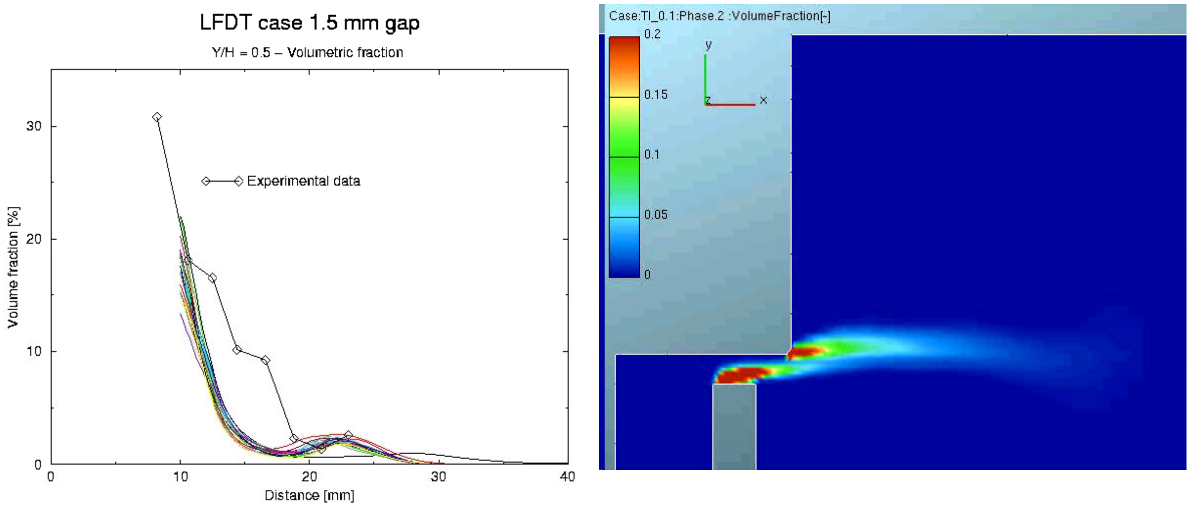
WP_5_BOSCH_Figure_4: Cavitation is black shadowed and distributed in small-scaled vortices, erosion is located on the top of the geometry

In summary:

- The experimental geometry is not perfectly symmetric, hence asymmetric flow beyond the throttle
- WP_5_BOSCH_Figure_3 shows a single layer within the geometry at a specific time-plane
- WP_5_BOSCH_Figure_4 shows a see-through experimental image
- Therefore it can be concluded that distribution and the position of the predicted and the measured volume fraction is in moderately good agreement.
- Shear layer induced cavitation behind the throttle is difficult or even impossible to catch with RANS based two-phase models.
- Small variations of the experimental geometry lead to significant changes of the flow field and can not be represented in the simulation model. In the present case, the shear layer induced cavitation behind the throttle attached always the upper side of the geometry due to a very small gap at the end of the throttle.

In the first phase of the project reference case computations (AVL) were performed with the standard cavitation model of FIRE. The objective was to get a feeling about the cavitating flows within the geometries investigated experimentally by other partners and to prepare the computational grids, which were then used throughout the project. The results showed the need for an advanced cavitation model in terms of prediction of bubble collapse zones and the need for an advanced turbulence model.

An important validation case was the geometry of University of Ljubljana. The case with the flow-rate of 800 liters/hour was simulated. The expected periodicity of the cavitating zone was predicted. The cavitation region shape looked plausible. The k-ζ-f turbulence model was applied in combination with the advanced cavitation model to accurately predict the cavitation region and pressure pulsations. WP_5_AVL_Figure_1 shows the results of volumetric fraction curves (left) and phase distribution (right). The code modifications performed along the course of the project were found to be necessary to reproduce periodic nature of the flashing region and to match simulation results with the experimental findings quantitatively.

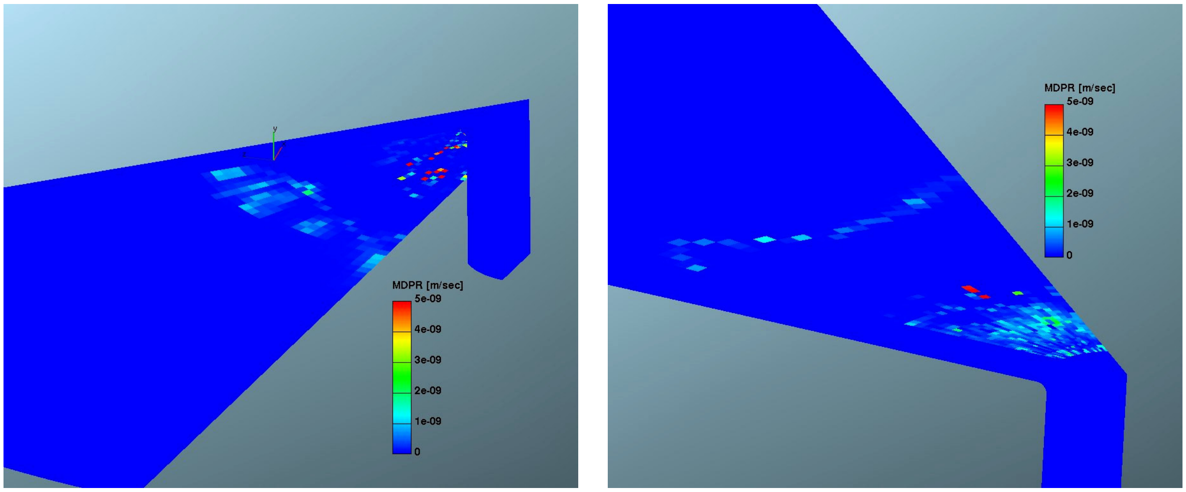


Calculated (colored lines) vs. measured volume-fraction in the middle of the gap

Vapor (red) volume-fraction

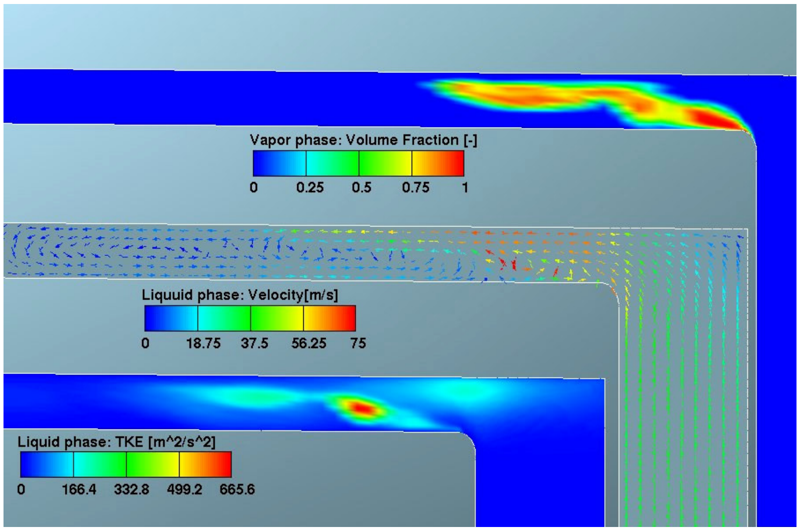
WP_5_AVL_Figure_1: Geometry of LFDT – FIRE cavitation result

Erosion model validation was performed by AVL with the LEGI geometry. The computational mesh was constructed only for a segment in order to decrease the computational complexity. The results showed that cavitation is expected to occur on the place where cavitation region ends. This was in agreement with the findings reported by LEGI, TU Graz and BOSCH. The maximum velocity around the cavitation reported by LEGI was 65 m/s, calculated velocity around the vapor region was 65 - 75 m/s. Results are shown in WP_6_AVL_Figure_3. The size of the cavitation region was fluctuating, which was observed in experiments as well. The size of the cavitation region corresponds to the erosion location, as reported previously. Erosion rates are shown in WP_6_AVL_Figure_2. The erosion is predicted in the bubble collapse region in agreement with the measurement as well. The values reported by LEGI were 3-5e-10 m/s, AVL FIRE predicted 3.33e-10 m/s material removal.



Bottom side Top side

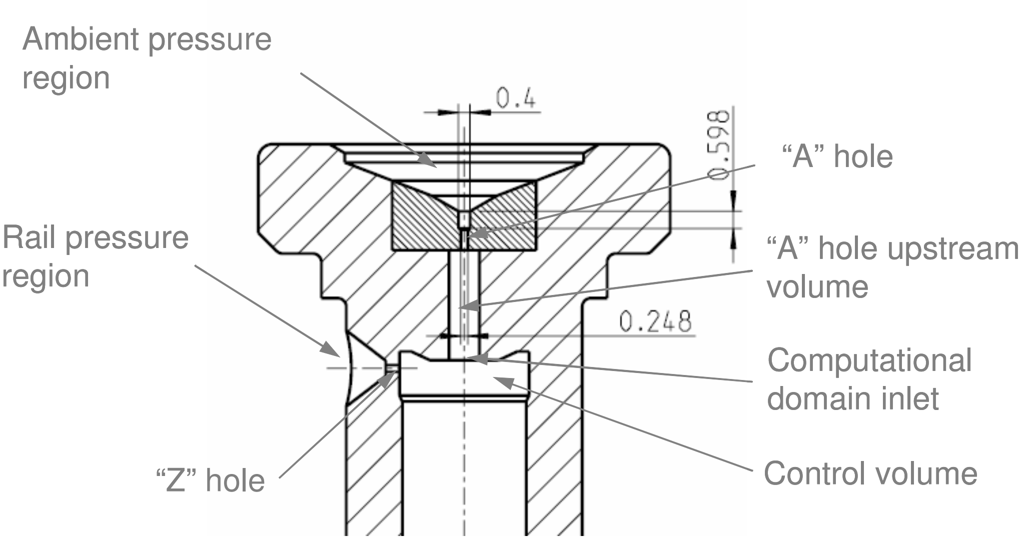
WP_6_AVL_Figure_2: Geometry of LEGI – FIRE erosion result



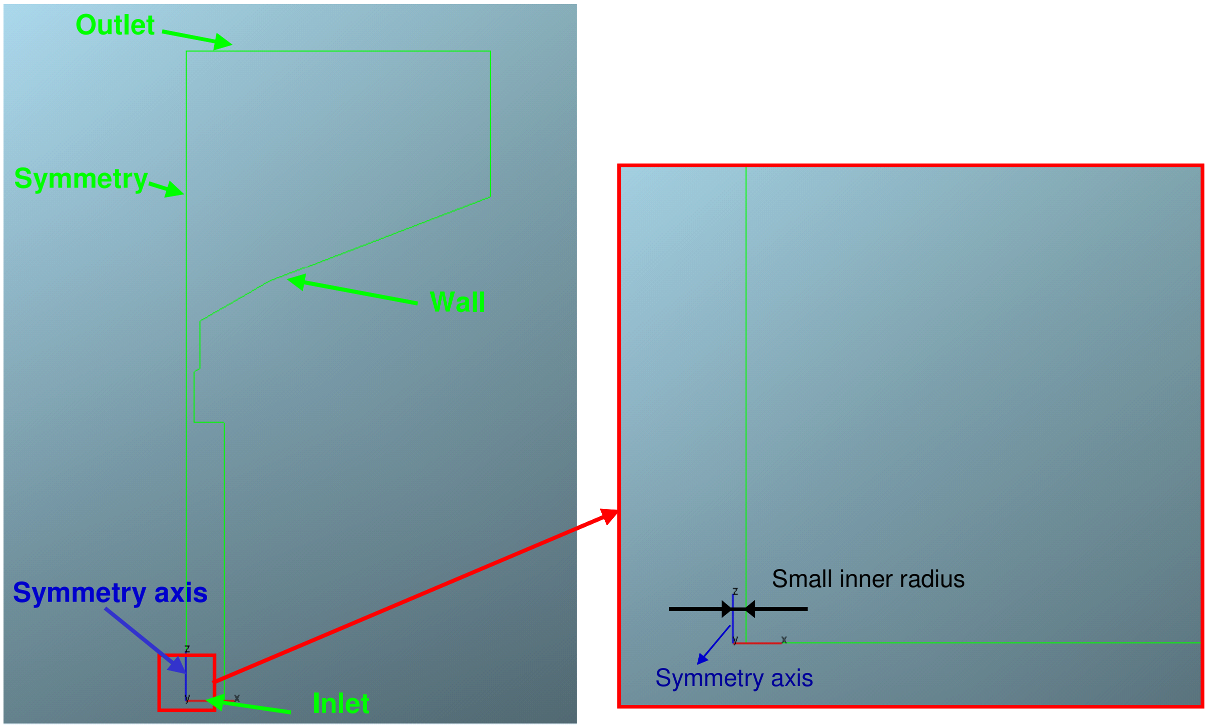
Vapor volume-fraction (top), liquid velocity (middle), and liquid TKE.

WP_6_AVL_Figure_3: Geometry of LEGI. FIRE result on a cut in stream-wise direction.

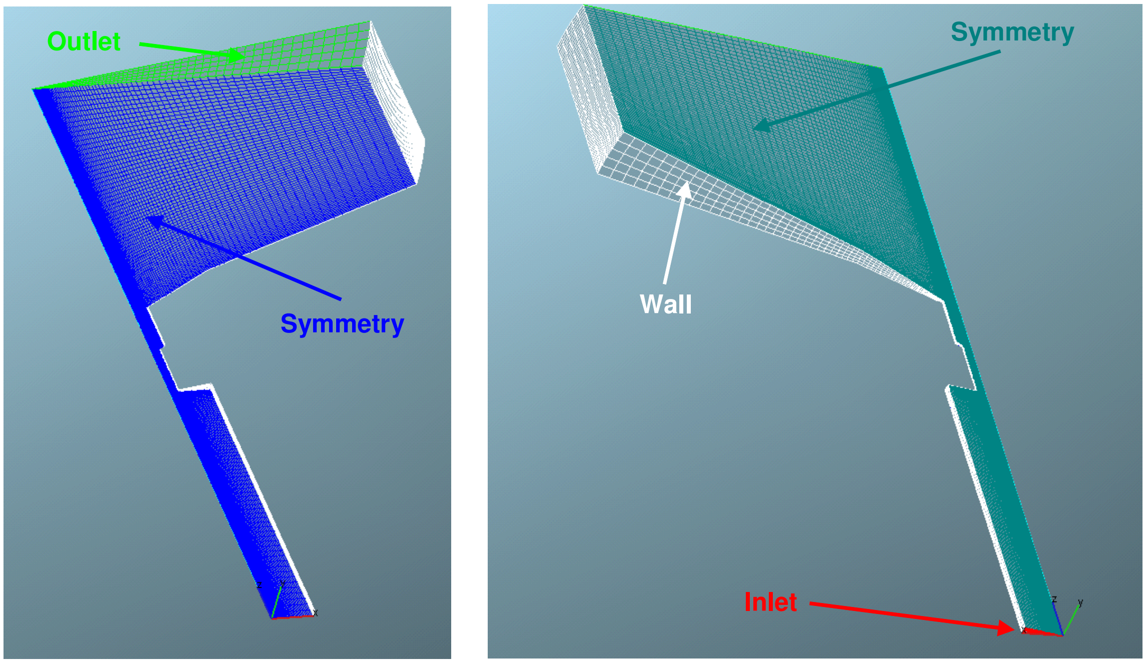
The scheme of the injector servo-valve measured by CRF is shown in WP_5_CRF_Figure_1. In order to focus on regions of interest and to reduce the computational effort, excluding the parts which do not affect the flow-dynamics, the region between the “Z” hole and “A” hole upstream volume (see WP_5_CRF_Figure_1) has not been modeled. WP_5_CRF_Figure_2 shows a section of the computational domain and the boundary types as well; furthermore a small inner radius has been arbitrarily defined in order to separate the symmetry axis from the computational domain according to suggestions of AVL.



WP_5_CRF_Figure_1: Scheme of the injector servo-valve.

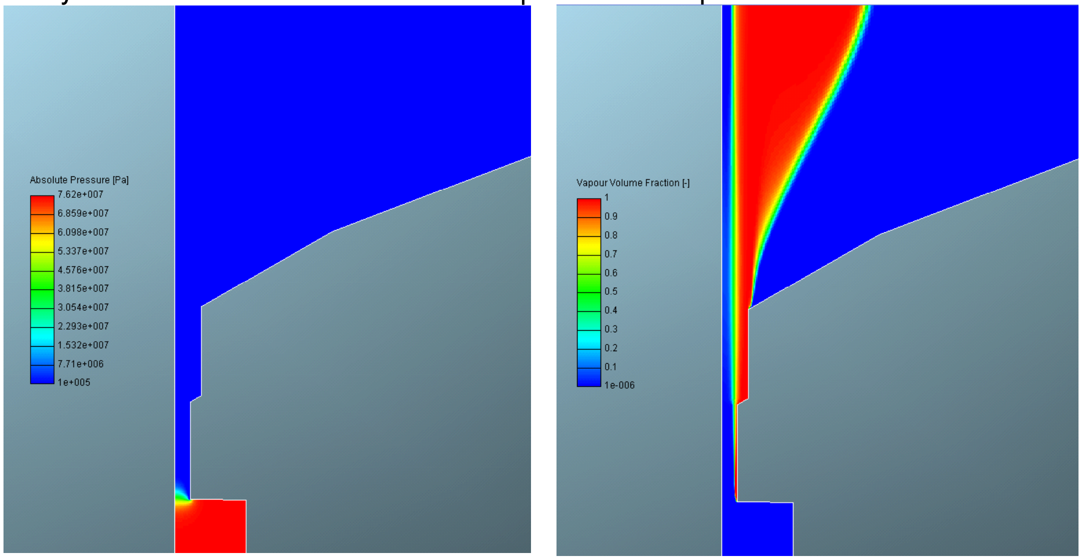


WP_5_CRF_Figure_2: Section of the computational domain and boundary types.



WP_5_CRF_Figure_3: Computational grid and boundary types.

The computational domain has been discretized using multi-block structural grids; WP_5_CRF_Figure_3 shows one of the computational grids created to carry out the numerical simulations with FIRE. Three grid levels of about *130000*, *330000* and *440000* cells have been considered in order to achieve the grid independence of the numerical solution. Isothermal, incompressible and two-phase flow models and steady state boundary conditions have been used in the problem set-up.



WP_5_CRF_Figure_4: Pressure and vapor volume fraction distributions in the region near the “A” hole area.

WP_5_CRF_Figure_4 shows the pressure and the vapor volume fraction distributions in the region near the “A” hole area; a thin liquid to vapor transition region has been found near the sphere seat area in agreement with the experimental tests results. Indeed, the erosion damage has been observed in proximity of the seat area (see WP_2_CRF_Figure_6).

3.7 WP 6: Consolidation of database and assessment regarding experiments and simulation

Results from all partners, including experiments and simulations were collected in separate databases collected by the coordinator. The collected data is organized by the geometries along with the investigated conditions.

The simulations performed at AVL, LFDT and CRF using FIRE show good agreement with the measured data using RANS approach. Successful quantitative comparison is also described in [4] on LFDT geometry and in [14] on TU Graz geometries. It is important to note that RANS provides the results within time frame acceptable for industrial usage.

Besides the AVL FIRE code BOSCH used a different CFD tool, CFX, to validate their measurements. The experiments included visualizations, cavitation probability calculations by means of averaging, erosion pattern and wear measurements by white light interferometry and body acoustic measurements. Only the DES or SAS simulations show the flow and cavitation patterns of the optical visualization and have the potential to explain the erosion pattern.

3.8 WP 7: Project management

Within WP7 detailed planning and organization of information exchange was performed. Problems and discontinuities within information exchange were solved. Tasks regarding organization of meetings also fell into this WP. Report contributions of all project partners were collected and compiled by AVL.

4 ASSESSMENT OF RESULTS AND CONCLUSIONS

Application-related criteria should be used to assess and measure the output results.

AVL reached the final objective to predict the possibility for erosion due to cavitation. Reaching this goal depended on accurate prediction of cavitating flows within injection equipment and consequently predicting the erosive effect after the collapses were estimated accurately. AVL managed to implement an entirely new cavitation model in the FIRE code, to validate it based on the experimental results provided by LFDT and TU Graz, and finally to implement and validate the erosion model provided by LEGI.

BOSCH the results are oriented for development of Diesel injection systems as well as general hydraulic systems. The dependence of temperature and surface roughness on cavitation erosion can be considered as the main results of the project. This result is underlined by many detailed tests, however, it is not straight consider the effects numerically. A temporally reaped test using aluminum targets can be used to find erosion locations in geometries of an injection system such as an A-throttle.

The detailed measurements of the velocity profiles done by LIF are very good comparisons for the numerical simulation. It shows the influence of the friction to the viscosity near the walls. These properties have to be considered in the CFD models.

UNI LJ found that the following three regions of bubbly structures play a major role in cavitation process were quantitatively identified: (i) bubble detachment region, (ii) large scale cavitation with periodic clustering and (iii) bubble collapse region. The bank of experimental data was gained for benchmark tests of the FIRE code. As a result, two major implementations in the cavitation code were realized in collaboration with AVL:

- bulk liquid flow dynamics is described now by a new k-ζ-f model which enables stable periodic vortex shedding simulation in Eulerian frame and
- a new multi-scale model to account for bubble population balance including bubble breakup and coalescence was developed

TU Graz generated an experimental database for high pressure cavitating diesel flows at stationary and transient conditions. The database covers the following parameters: channels (sharp and round inlet) and targets (with different flow angle) hydraulic geometries; stationary and transient hydraulic flow conditions; local flow density (pressure and temperature) mean distributions and fluctuations (RMS-data); mean velocity profiles and velocity fluctuations (velocity-RMS), local cavitation probability (volume fraction) distributions and volume fraction fluctuations (volume fraction - RMS); external hydraulic flow data (inlet and outlet pressures and temperatures and mass-flow); real time erosion data (erosion rates and local features) related to defined cavitation distributions and external hydraulic

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