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Initial findings of an investigation on the removal of the cavitation erosion risk in a prototype control orifice inside a diesel injector

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Abstract

A CFD investigation is in progress to study the cavitation characteristics and potential erosion risks of a control orifice in a prototype injector. An early design of the orifice resulted in cavitation erosion after endurance testing. A design modification eliminated the erosion and subsequent prototypes were free from damage. Initial results for the two designs using different simulation methods are discussed, along with the effects of different rates of evaporating and condensing mass transfer. Preliminary findings on possible erosion risk indicators comparing the eroding with the non-eroding design are presented.

Keywords: cavitation, erosion risk, control orifice

Introduction

In some cases, the collapse of cavitation can lead to erosion of high strength metals and thereby damage system components. Being able to predict if and where such erosion is likely to occur would be beneficial to many fields, like automotive and naval. The diesel injector is a common subject in cavitation based literature as cavitation in the flow cannot be avoided, particularly so in modern systems, and so it must be understood and managed. The injector is of great importance to the performance of engines. It is an area for continued development to meet future environmental and performance standards. Hence, an understanding of the fundamental behavior of hydraulic control orifices is needed to optimize the performance and production while avoiding any potential complications due to cavitation or cavitation erosion.

The control orifice of interest in this work is a spill orifice (Fig. 1) in an automotive high-pressure fuel injector. All prototype designs are subjected to extensive testing during product development, including endurance tests. One such endurance test on a prototype component resulted in significant cavitation erosion of the orifice. Further development of the component eliminated the erosion and subsequent prototypes were free from damage.

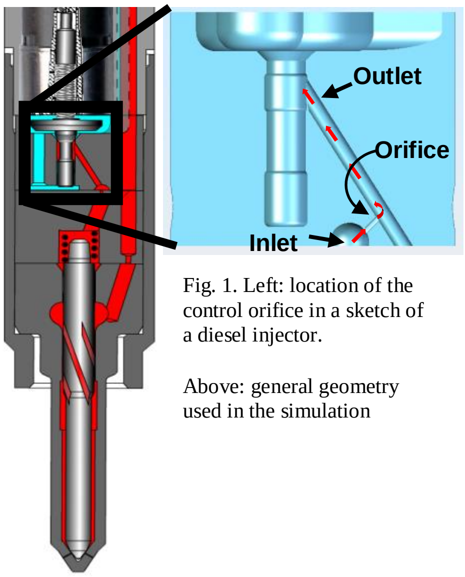

Fig. 1. Left: location of the control orifice in a sketch of a diesel injector.

Above: general geometry used in the simulation

A CFD investigation is in progress to understand the flow-field and cavitation characteristics in and around this orifice, and to explore possible indicators for cavitation erosion risk. The analyses used two design levels: the original geometry which suffered from erosion (E – eroding geometry) and a subsequent prototype design which eliminated the erosion (NE – non-eroding geometry).

The CFD study includes initial simulations using Reynolds-Averaged Navier-Stokes (RANS) turbulence modelling and the standard Zwart-Gerber-Belarmi (ZGB) cavitation model. For increased accuracy and detail, this work was then expanded upon with a hybrid LES-RANS turbulence model: Detached Eddy Simulation (DES). These types of model have shown improvement over RANS [1] [2] [3]. However, in industry the RANS method is still a useful CFD investigation tool, especially considering the heavy runtime cost of LES/DES methods. The DES simulations were first run using the standard ZGB model. Then a modified ZGB method was used, by

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means of a UDF (user-defined function) which enabled significant changes to be specified for the rates of mass transfer [4].

The paper provides some preliminary results of this on-going project, commenting on the effects of the different simulation methods and on the two different designs, all of which is backed up with photographic evidence of damage on an early prototype component. Finally, some initial findings on indicators for cavitation erosion risk are presented.

CFD Simulation

The vapor transport equation is defined as [5]:

$$\frac{\partial(\alpha\rho_v)}{\partial t} + \nabla \cdot (\alpha\rho_v U_v) = R_e - R_c \qquad \text{Eq. 1}$$

where ρ is density, α is vapor volume fraction, U is velocity, v denotes vapor and Re and Rc denote rates of evaporating and condensing mass transfer, respectively. First a standard, and then a modified form of the ZGB cavitation model was applied in the simulations. The ZGB model uses the following rates of mass transfer, first described by Zwart et al [6]:

$$R_e = F_e \frac{3\alpha_{nuc}(1-\alpha)\rho_v}{\Re_B}\sqrt{\frac{2}{3}\frac{(P_v - P)}{\rho_l}} \qquad \text{Eq. 2}$$

$$R_c = F_c \frac{3\alpha\rho_v}{\Re_B}\sqrt{\frac{2}{3}\frac{(P - P_v)}{\rho_l}} \qquad \text{Eq. 3}$$

where α_{nuc} is nucleation site volume faction, $\Re_B$ is bubble radius, ρ is density, P is pressure, F is a constant and v and l denote vapor and liquid respectively. In Fluent the default values for the ZGB model constants are 1e-6 m for $\Re_B$, α_{nuc} is 5e-4, F_c is 0.01 and F_e is 50. These constants can be grouped as follows:

$$F_{evap} = F_e \frac{3\alpha_{nuc}}{\Re_B} \qquad \text{Eq. 4}$$

$$F_{cond} = F_c \frac{3}{\Re_B} \qquad \text{Eq. 5}$$

resulting in F_{evap} equaling 75,000 m^{-1} and F_{cond} equaling 30,000 m^{-1} with the default values.

The modified cavitation method was implemented in a UDF which comes from the work of Koukouvinis et al [4]. The ZGB model is implemented with a defined mass transfer constant to create an effect closer to that of a barotropic model. A barotropic model is approached asymptotically as the mass transfer rates trend toward infinity. For this work, a large but practical value of 1e8 for both F_{evap} and F_{cond} was used.

The initial RANS CFD simulations used k-epsilon method alongside the standard ZGB cavitation model. The RANS simulations were used for the low computational costs and previously seen accuracy in predicting the Cd when implemented with due care ([7] & internal documents). Initial flow details were noted with the RANS simulations, but they were unable to display detailed transient behaviour that is likely needed in developing cavitation erosion risk assessment.

Further to that, the injector cycle experienced by the orifice was modelled in URANS (Unsteady RANS) simulations, inputting the relevant upstream and downstream pressure traces. The URANS results did show some oscillation movement in the region of cavitation, but did not add significantly to the steady state simulations. A transient injection cycle with DES would have an extremely long runtime, but may be done later when more processing

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power is available. For this paper though, steady state DES simulations are reviewed, which already take approximately two orders of magnitude longer then the RANS simulations.

The DES technique is an LES-RANS hybrid, implementing RANS at the boundaries and an LES model elsewhere [8]. This makes for a simulation that is less computationally intensive than full LES while still producing the higher level of detail at the areas of interest. The simulations were implemented in ANSYS Fluent v17 as IDDES (Improved Delayed Detached Eddy Simulation), as first proposed by Shur et al [8], which is a more recent version of DES that provides more flexibility and convenience for high Re flows. This setup was previously validated with experiment for a similar operating environment by Bush et al [1] and is also congruent with Koukouvinis et al [4].

The simulations were run with constant boundary conditions using an upstream pressure of 1380 bar and downstream pressure of 340 bar. These values provided the highest pressure difference across this orifice during a 2200 bar injection cycle. As the pressure drop is relatively high and the flow velocity was expected to also be high, a compressible fluid is used. The fluid is representative of Normafluid (ISO4113), a standard fluid used in automotive testing. The vapor is assumed incompressible for computational simplicity. The fluids are represented using a mixture model which assumes that the two fluids travel as a homogeneous multiphase flow.

For both designs, the entrance to the orifice is slightly rounded, the diameter is in the region of 0.22mm and there is a small divergent taper along the length of the hole [9]. Although highly significant in terms of design, the differences between the E and NE prototype geometries are not great, with the taper for NE geometry being slightly less, that is, closer to 0. To start with, CFD simulations were tested against pass-off criteria to ensure the CFD geometry of each design was an accurate replica of the hardware, along with a mesh study that found that further mesh refinement had little effect.

Experimental Tests

Newly proposed injector designs must all go through a rigorous testing process. One of these test is termed an endurance test. The test consists of exposing the prototype injector to a high typical load cycle (2200 bar cycle) for x-many cycles. This type of test is essential in determining if a prototype can withstand normal use and is ready for serial production. A failed example from an endurance tests can be seen in Fig. 2 The material used was automotive high strength steel with surface treatment.

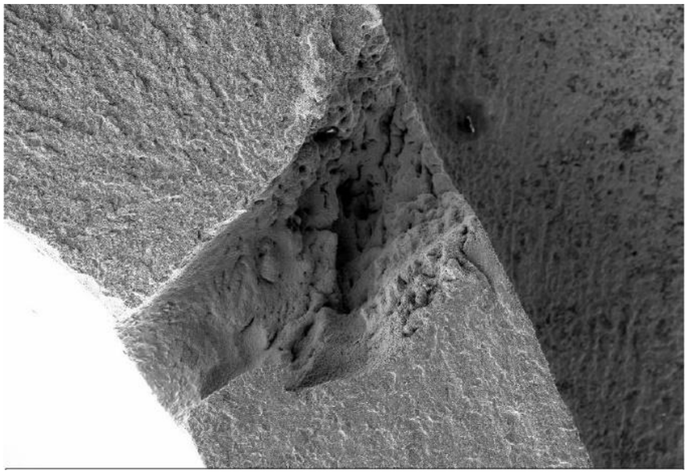

Fig. 2- Early prototype sample showing cavitation erosion after an endurance test. Subsequent design modifications eliminated the erosion

Results

Table 1- List of the different simulations sets and results overview

Case	Description	Mass transfer constants	Negative pressure (bar)	General outcome (E vs. NE)
1	RANS with standard ZGB method and default values	Default F_{cond}=3e4, F_{evap}=7.5e4	-200	Region of recirculation and backflow in E geo.
2	DES with standard ZGB and default values	Default F_{cond}=3e4, F_{evap}=7.5e4	-200	No obvious difference
3	DES with modified mass transfer UDF	UDF F_{cond}=F_{evap}=1e8	-8	NE has significantly decreased activity in max P and max DP/Dt

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Case 1- The results for the eroding geometry showed a region of recirculation and backflow at the end of the topside of the control orifice, whereas the non-eroding geometry did not (Fig. 3). This region correlated with the location of cavitation erosion seen in the failed endurance test image (Fig 2).

Case 2- Results showed no substantial differences between the E and NE geometries**.**

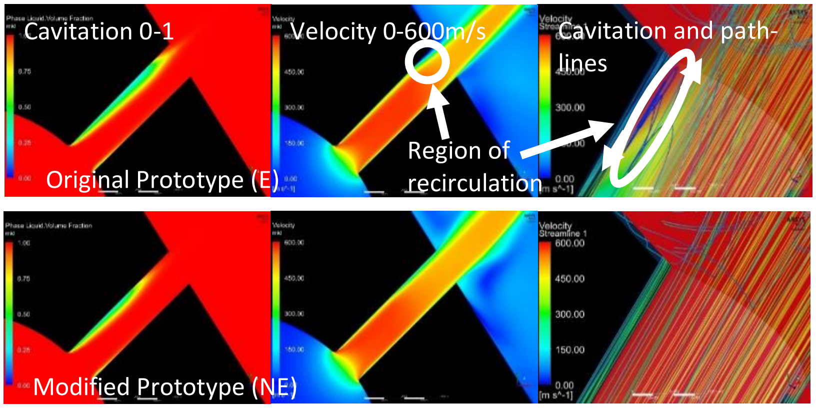

Fig. 3- Mid-plane section of the E and NE RANS simulations (Case A). Region of recirculation and backflow prominent in the E geometry.

Case 3- A key improvement using this method was the lack of negative pressure (Table 1) commonly seen in cavitating simulations which is a non-physical effect. This negative pressure is a numerical inaccuracy and is commonly capped at the vapor pressure by users during post-processing. Furthermore, the UDF enables converged solutions with the required increased mass transfer rates. However, the run time of case 3 compared to case 2 was noticeably increased.

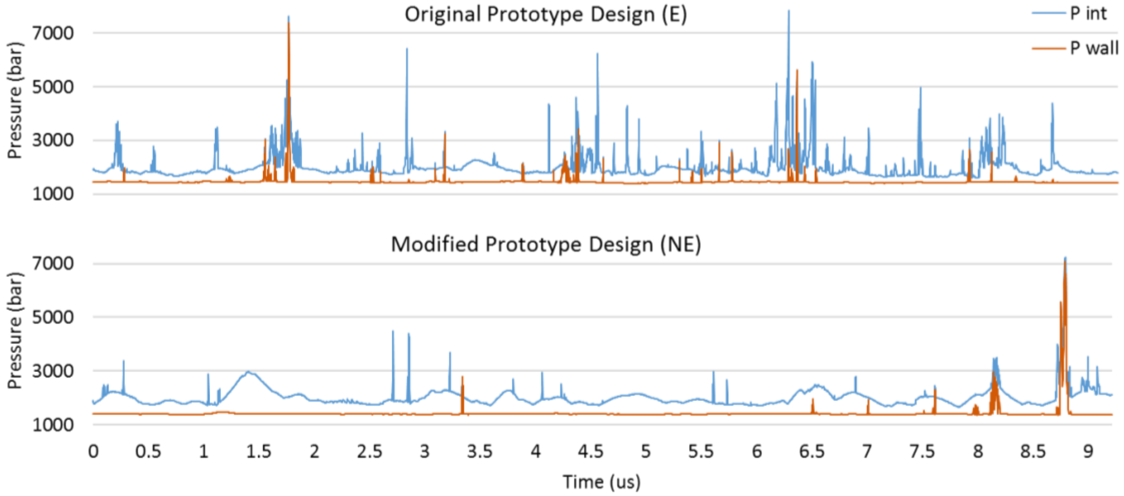

Fig. 4- Maximum pressure seen in the entire domain (P int) and on any surface (P wall) for 9 us after initialization.

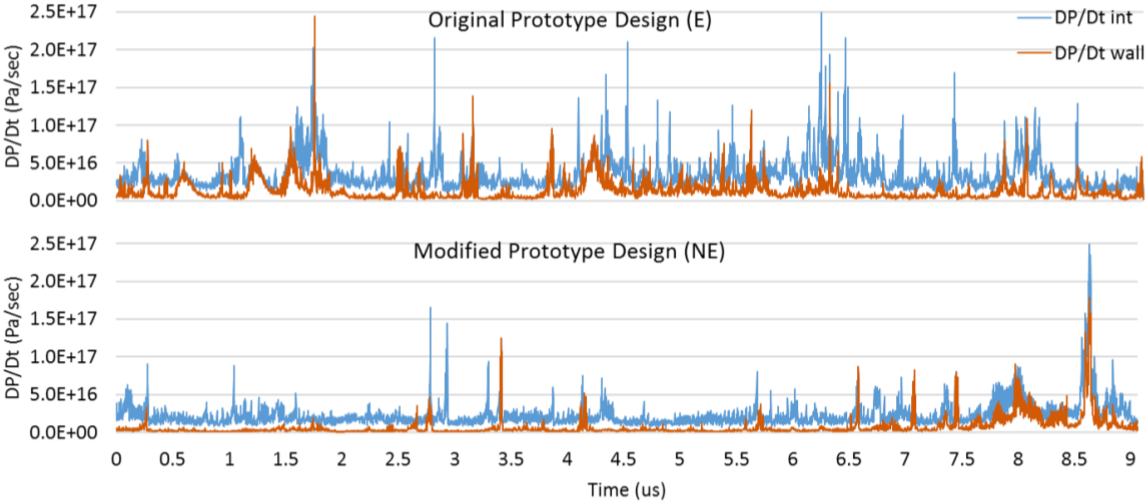

Fig. 5- Maximum total derivative of pressure seen in the entire domain (DP/Dt int) and on any surface (DP/Dt wall) for 9 us after initialization.

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Fig. 4 shows the maximum pressure computed in the entire domain and on the wall for each time-step for the E and NE geometries. Both geometries experienced pressure spikes in the 7000 bar range, and further analysis (not included here) has shown that these occur in the region of erosion. However, the E geometry experienced many more spikes above 5000 bar range. The first total derivative of pressure also shows much more activity for the E geometry, both in the interior and on the wall (Fig. 5). Again, the maxima hit similar values, but the frequency of occurrence is starkly different between the two designs.

Discussion

For much of the CFD work performed in industry, the RANS technique for modelling turbulence is still the method of choice due to its acceptable time scale compared with LES/DES techniques. Hence, it is worth noting that the RANS model results (Case 1) showed a significant difference between the E and NE geometry. It is possible this difference was only case specific. However, it is interesting that the difference was in the region of erosion and it is possible the results indicate that backflow and recirculation close to collapsing vapor structures results in an increased risk of erosion.

Employing the UDF for modified mass transfer with the DES method (Case 3) enabled a more accurate and potentially useful result than any of the DES cases without the UDF. The results showed notable differences between the original prototype design (E) and the modified design (NE). As such, they are encouraging, but further work is required before concluding the outcome. This work is in progress and includes running the simulations over longer periods of time, and further data analysis and interpretation. Future work will also include stress analyses using the actual hardware geometry to understand the effect on the metal. These stress analyses will explore the impact of pressure spike levels and associated frequencies, as well as the rate of pressure change.

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