Extended range of 155mm projectile using an improved Base Bleed unit. Simulations and Evaluation

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Introduction

- The ballistics of artillery shells is, among other factors, dependent on the aerodynamic drag
- Aerodynamic drag is again dependent on the shape of the projectile and the flight conditions, i.e. the two well-known aerodynamic parameters Mach number and Reynolds number
- The shape of a modern projectile is a compromise between aerodynamics and structural concerns, especially during the initial blast
- Usually the drag, C_{D0} of a blunt body is divided into forebody drag, C_{Dpv} and base drag, C_{Db0}

$$C_{D0} = C_{Dpv} + C_{Db0}$$

  - Forebody drag – skin friction and pressure drag
  - Base drag – pressure in base area lower than ambient pressure
  - The base drag is approximately 50% of the total drag.

Base drag reduction

- Base drag reduction achieved by
  - Afterbody boat tailing
  - Base bleed
  - Vortex supression devices
  - Combination of above devices
- Active or passive flow control techniques basically manipulate or alter the near-wake flowfield for an increase in base pressure and consequently reduce base drag

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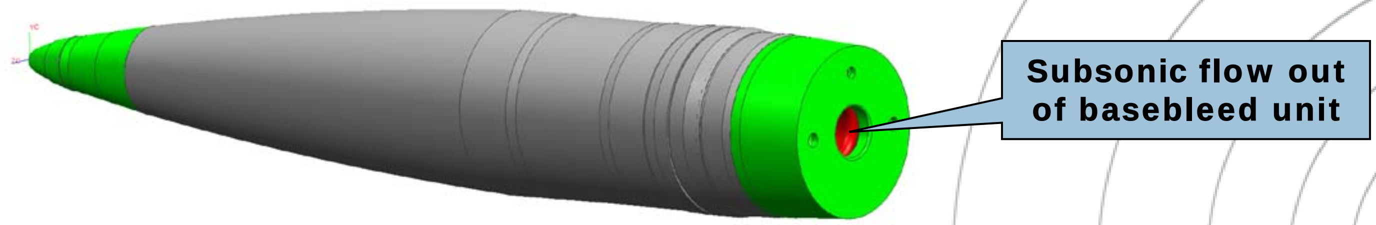
Base Bleed

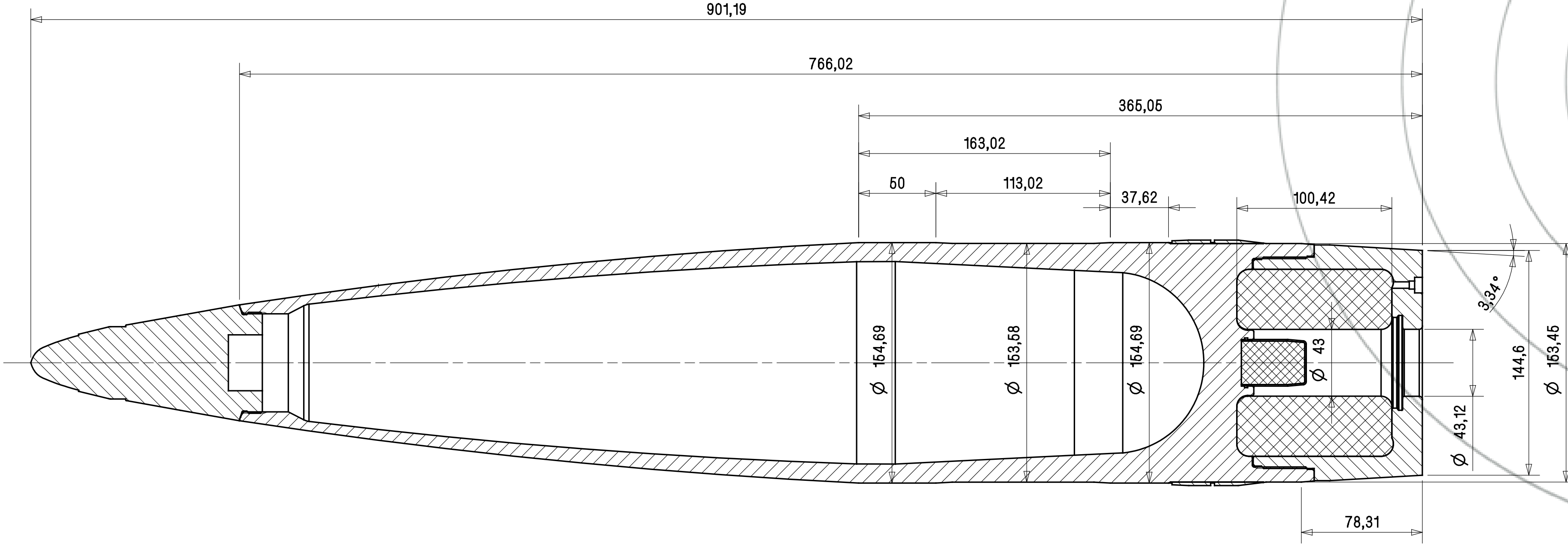


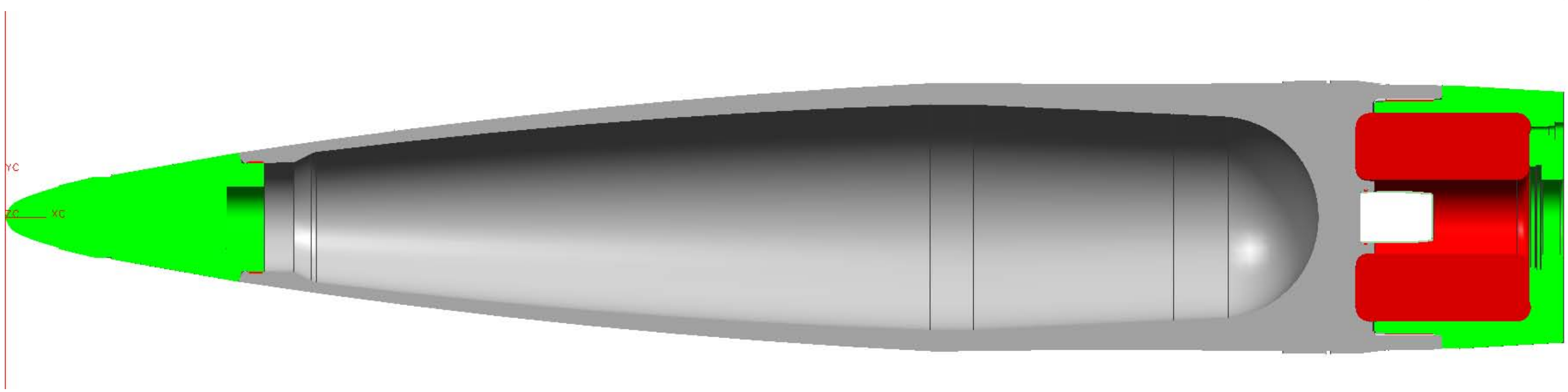
- Base bleed is a gas generator producing hot gas in the aft end of the projectile
- The aim of the base bleed is to fill up the wake zone behind the projectile and thus increase the base pressure. Increased base pressure reduces the base drag and gives increased shooting distance for the projectile
- For projectiles in service, the shooting distance can be increased by 20-30% due to reduced base drag
- Flow out of base bleed unit is subsonic
  - Internal ballistics coupled to external base pressure
  - Base pressure controls base drag
  - Coupling between base drag and internal ballistics often given through empirical expressions due to a lack of understanding of viscous-inviscid flow interactions between a near-wake flow and a freestream

Physical modeling

- Established a physical model for the coupling between base drag and base bleed internal ballistics
  - CFD computations using various turbulence models in the wake zone have been performed
- The first objective was to use computational fluid dynamics (CFD) to establish a numerical model capable of accurately predicting the drag in the supersonic range for the inert shell and yield a proper response to the increasing base bleed flow rates
  - For the verification of the CFD model, radar measurements were available for the 155 mm Heer Mk 2 artillery shell
- The second objective was to investigate the combined effect of afterbody shape and gas vent design on the net drag
  - The nozzle area, the length and diameter of the projectile were kept constant
  - Shape and location of the gas vents were modified

Heer Mk2 projectile





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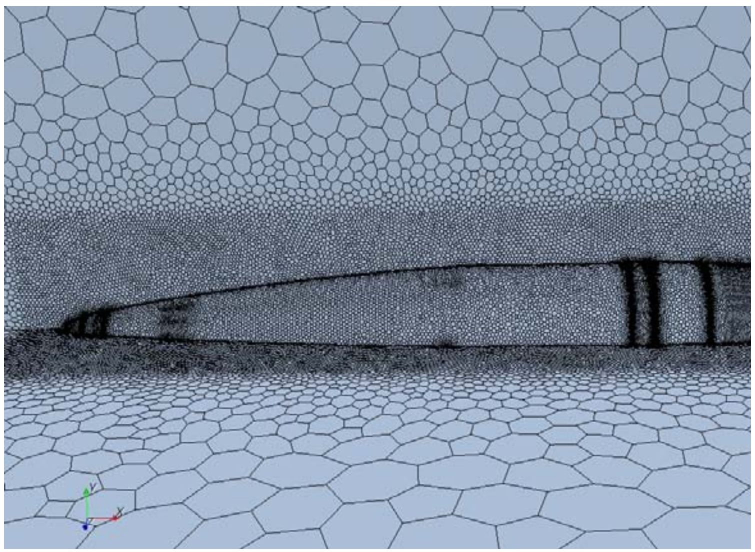
CFD modeling

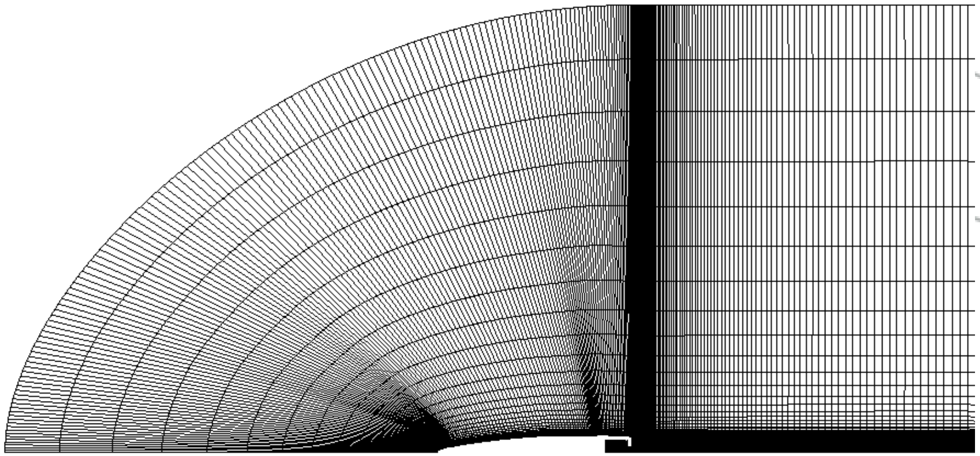
- The analyses were carried out with two CFD codes
  - Commercial available STAR-CCM+
  - In-house developed code CFDnFlow for compressible flows on structured, multi-block, body-fitted grids
  - Both codes have the option of using the Reynolds Averaged Navier-Stokes (RANS) or the detached eddy formulation (DES)
- Various turbulence models were applied to the base flow problem, from k-epsilon to Reynolds stress models based on the Reynolds-Averaged Navier-Stokes (RANS) equations to the instantaneous Navier-Stokes equations with DES

Grid - model

- To obtain grid- independent results, several grids of different size and resolution were used during the project



polyhedral volume grid from STAR-CCM+



CFDnFlow axisymmetric grid

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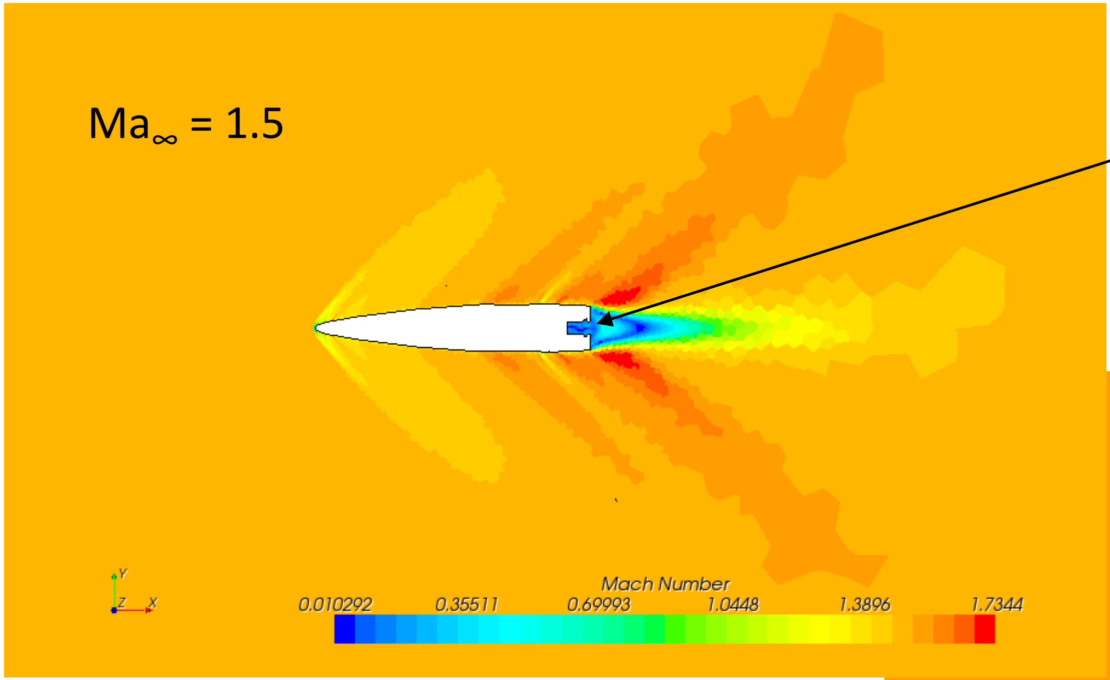
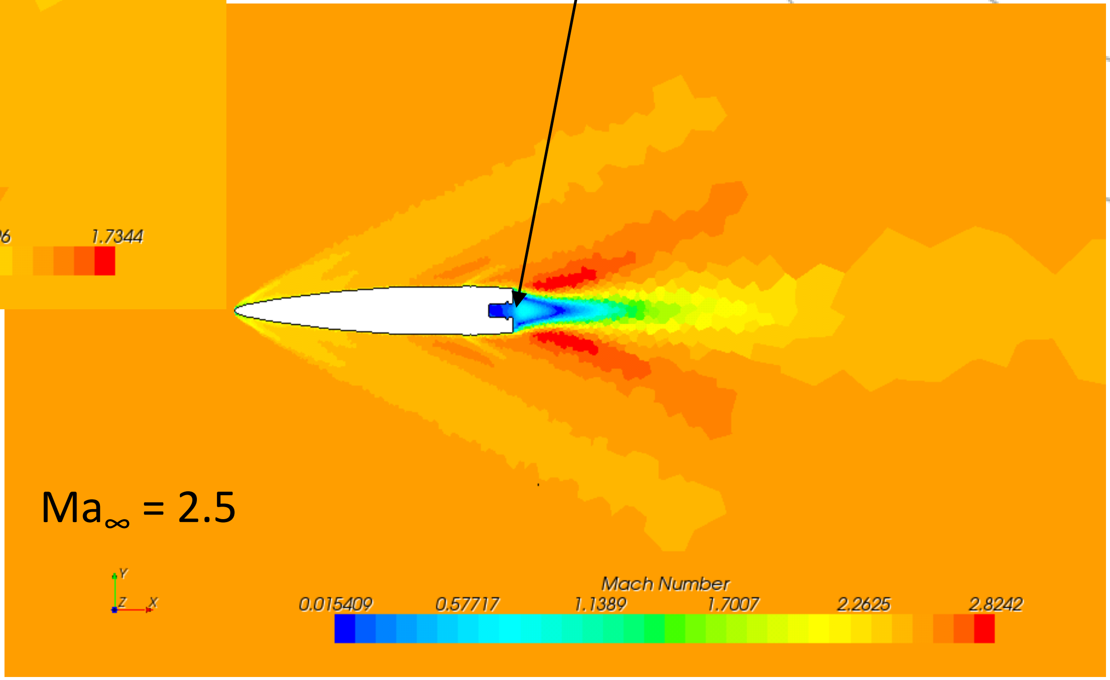
CFD analysis of projectile without base bleed

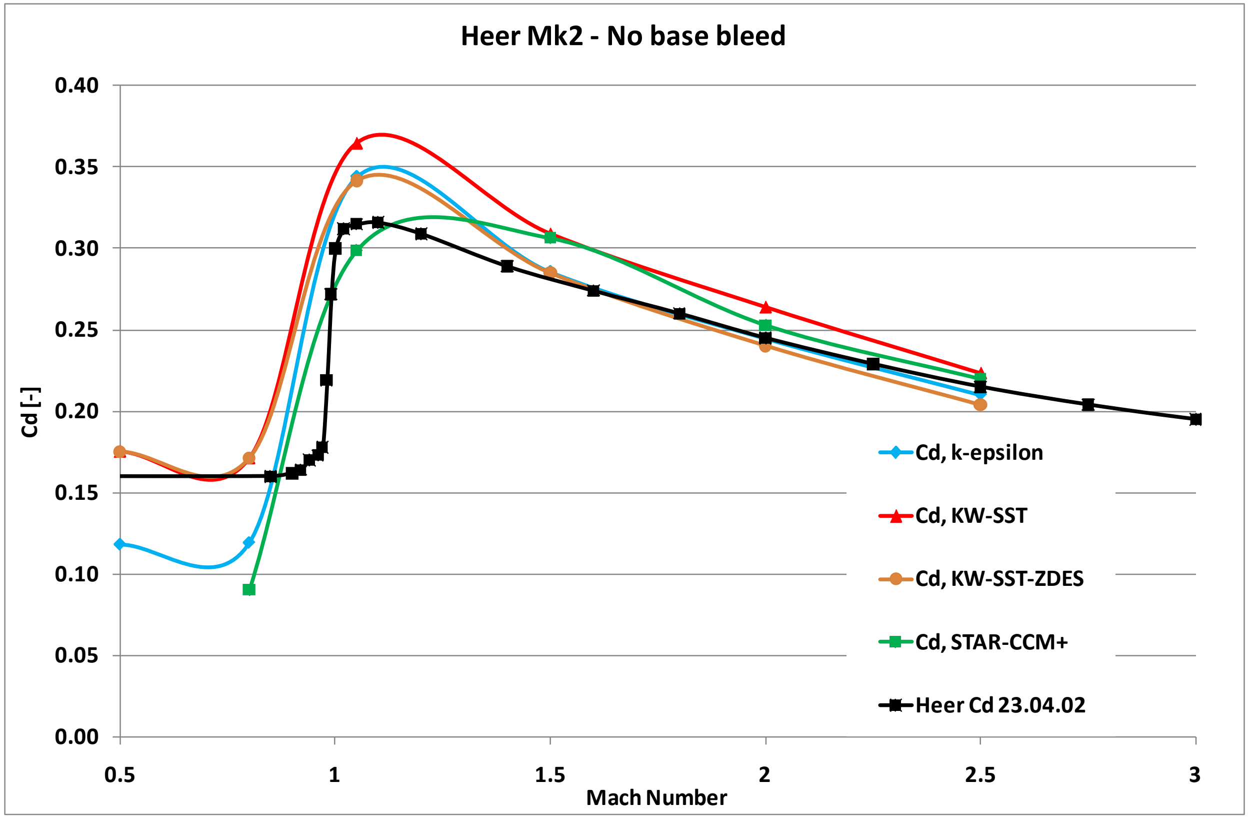
The aim of the base bleed is to fill up the wake zone behind the projectile and thus increase the base pressure





Results – inert base bleed

- The initial axisymmetric computations served the purpose of evaluating turbulence models for the comparison of computed drag coefficient with those from radar-doppler measurements (black curve)



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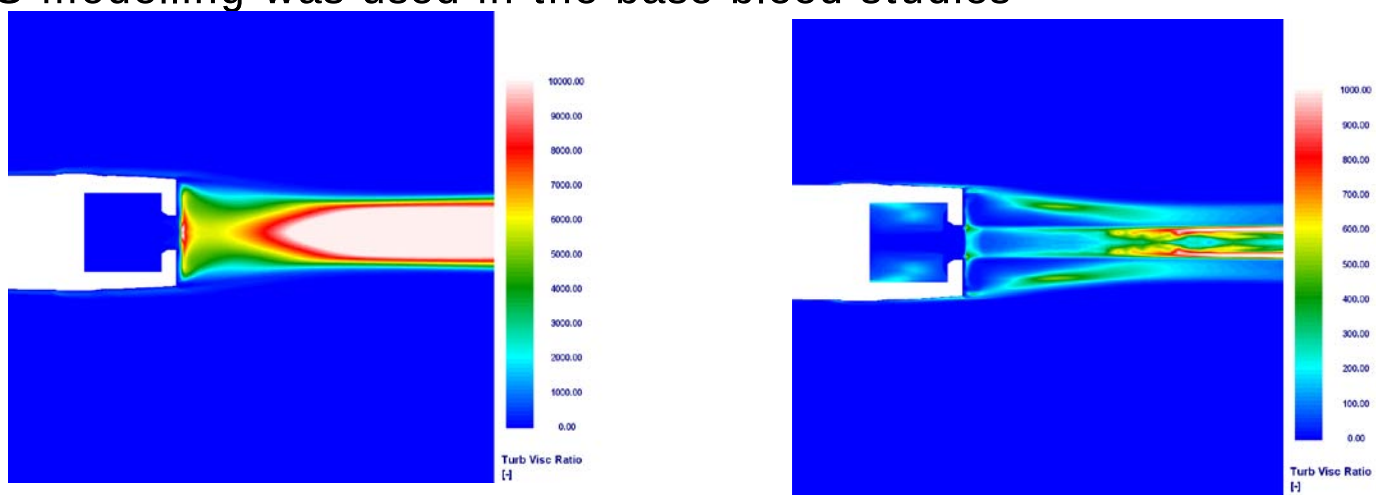
Results – inert base bleed – turbulent mixing

- From experience we suspected that the turbulent mixing in the wake might be too high, so we decided to pursue the use of detached eddy simulations (DES) in the wake
  – High level of turbulent mixing for the k-ω-SST and for the k-ε model
  – Results produced by the DES version of the k-ω-SST model showed much less turbulent mixing and more detailed resolution of the flow structures in the wake
  – DES modelling was used in the base bleed studies



Computed turbulent viscosity ratio at Mach 2.5 with the k-ω-SST model (left), and the k-ω-SST-DES model (right), without mass injection

Effect of base bleed

- The base bleed was simulated with mass injection of hot gas in the cavity at the base of the projectile
  - The mass flow injection is characterized through the injection parameter
  - The injection parameter *I* is defined as the ratio of the injected mass flow rate and the "free stream" mass flow passing through the base area of the projectile
  - Injection parameter *I*, range *I* = 0-0.01

$$I = \frac{\dot{m}_b}{\rho_\infty V_\infty A_b}$$

- Drag reduction factor, C_{red}
  - Subscript «b» denotes active base bleed
  - Subscript «b0» denotes inert base bleed

$$C_{red} = f_{dr} = 1 - \frac{C_{Db}}{C_{Db0}} = \frac{\frac{p_b}{p_\infty} - \frac{p_{b0}}{p_\infty}}{1 - \frac{p_{b0}}{p_\infty}}$$

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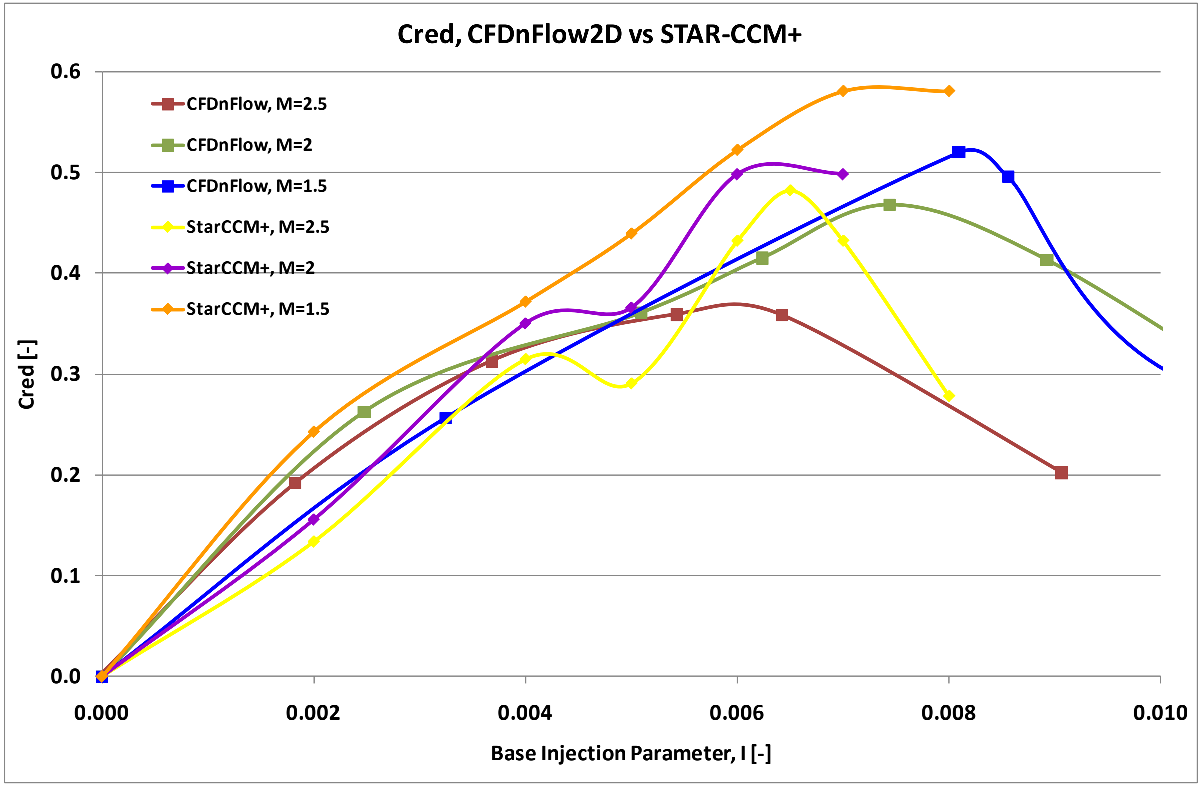
Drag reduction factor using DES turbulence modeling

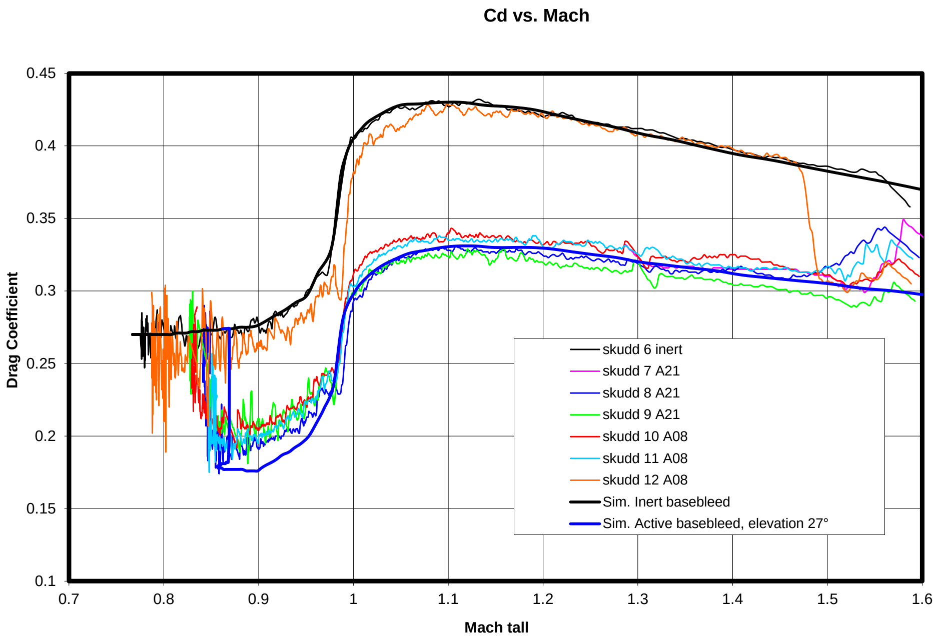
- Comparison of STAR CCM+ and the CFDnFlow results showed common trends but also some variation
  - The maximum drag reduction coefficient was found to be roughly 0.4-0.6 for base bleed rates of I=0.006-0.008



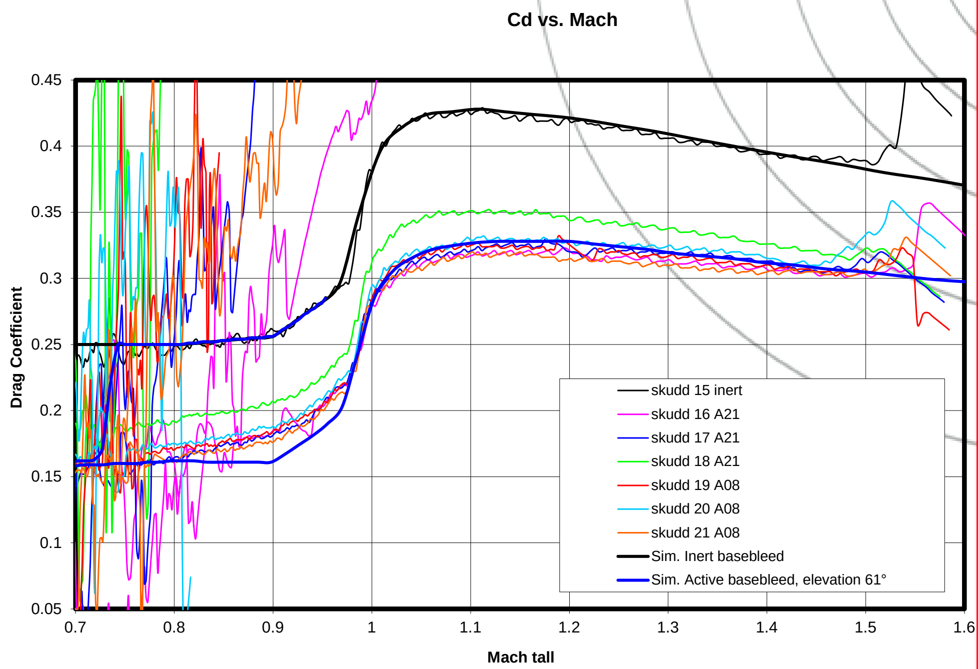
Validation of results

- The computed drag reduction factor, f_{dr} versus injection parameter and flight Mach number were introduced into an in-house developed trajectory model where the effect of the base bleed was included
  - The model uses the inert aerodynamic properties (drag versus flight Mach number) of the projectile as input
  - Once the inert aerodynamic properties have been determined, the base-bleed model which computes the gas generator influence on aerodynamics is invoked
    - This model computes the mass flow, base pressure and gas generator chamber pressure, using iteration, starting with an initial estimate of the base pressure
- Results from trajectory analyses using drag reduction factors from CFD analyses are compared with firing results at 27° and 61° elevations

Comparison firing results and trajectory analyses



27° elevation



61° elevation

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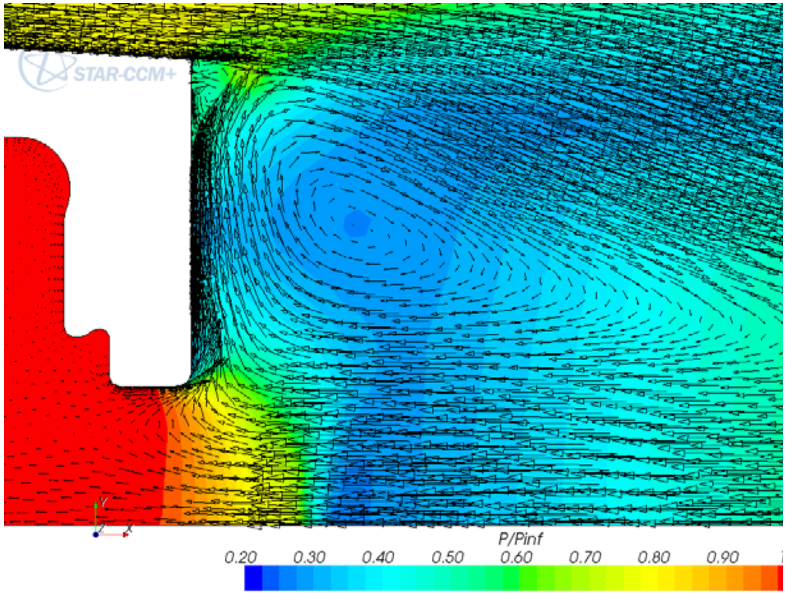
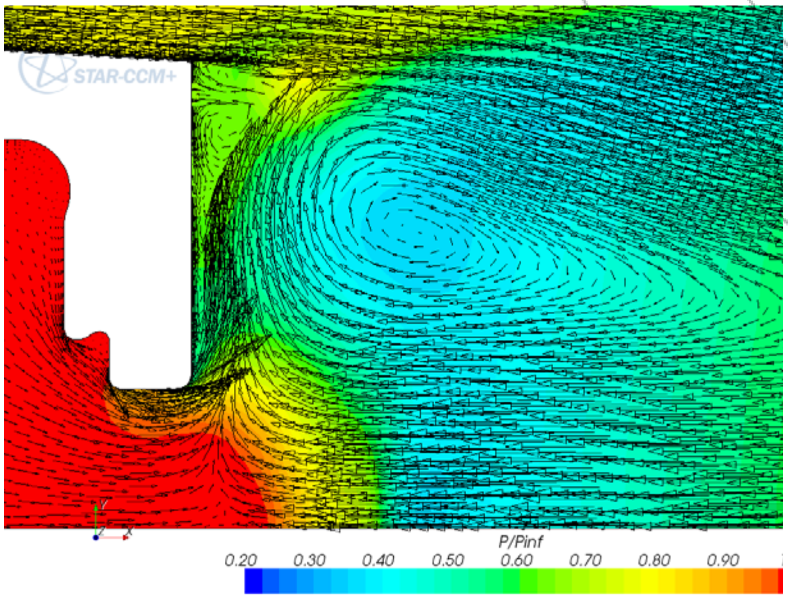
Optimization of base bleed

- Due to the high local velocity in the vortex giving rise to suction in the base, it was decided to try slowing the vortex to recover some of the dynamic pressure and, hence, reduce the base drag





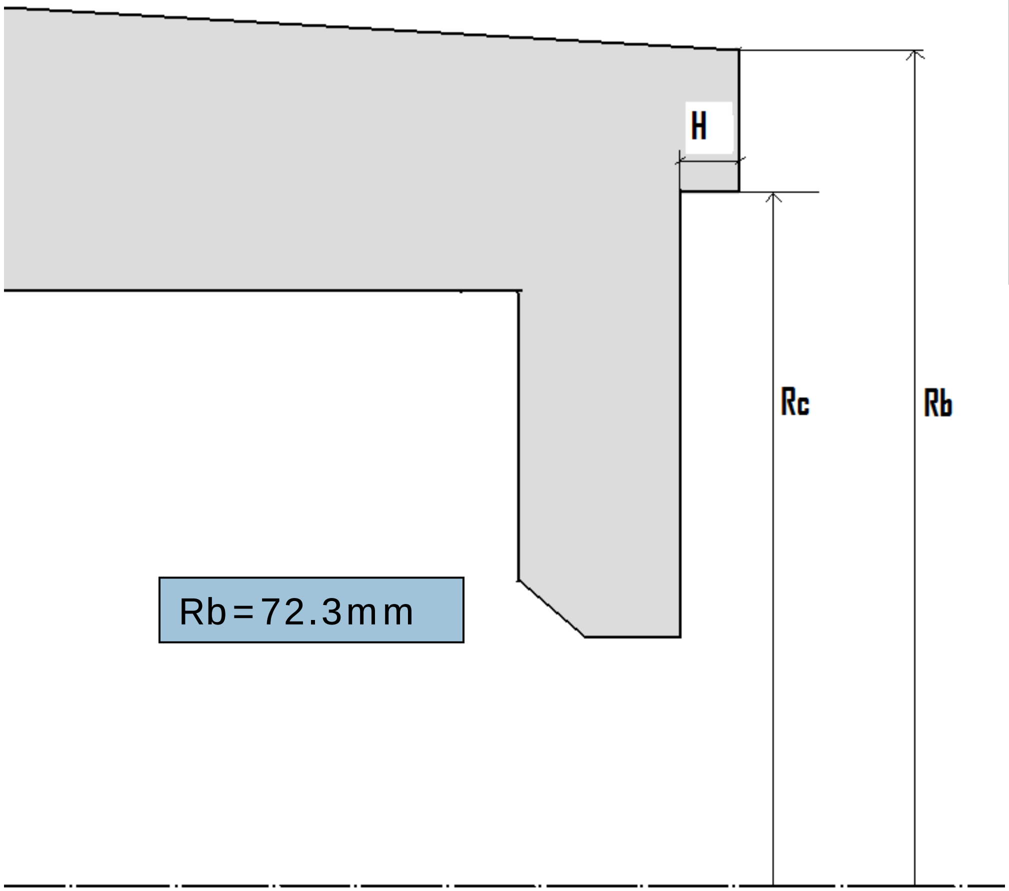
$$I = \frac{\dot{m}_b}{\rho_\infty V_\infty A_b}$$

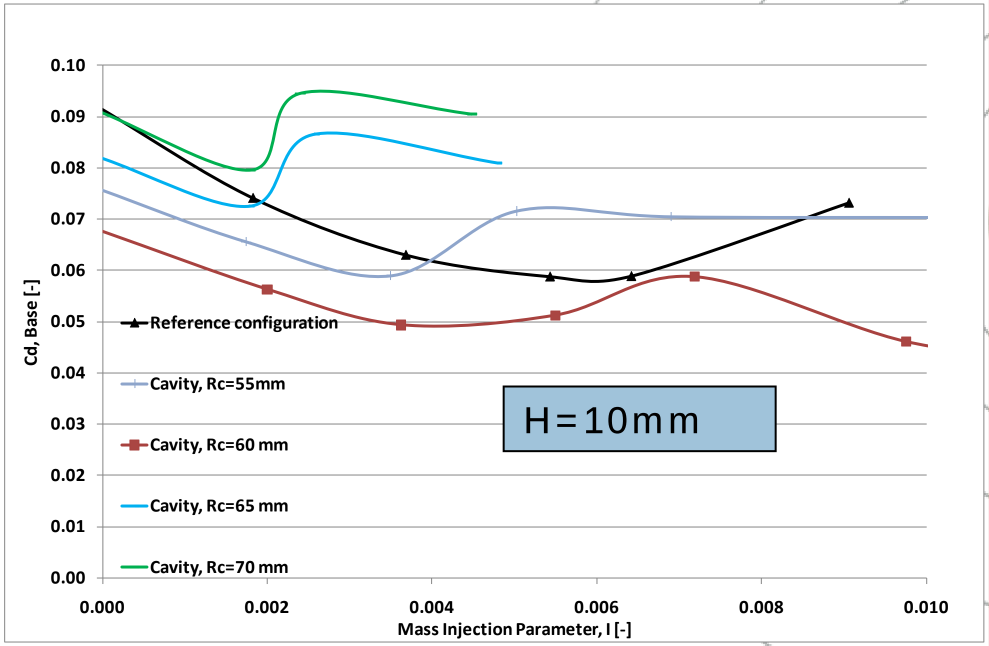
Mach=2.5, I=0, no injection

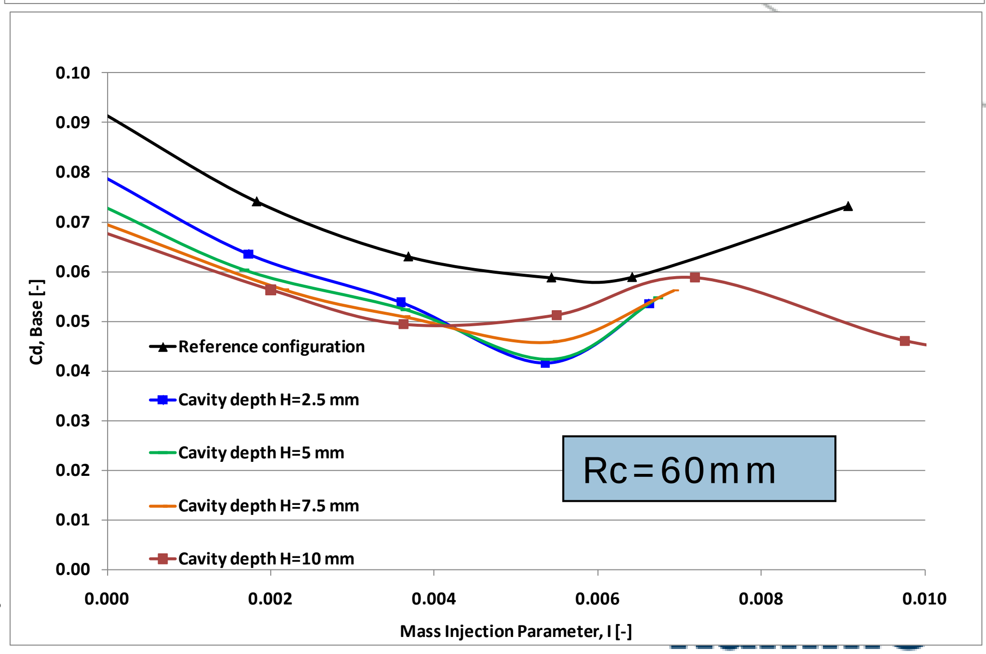
Mach=2.5, I=0.004, with injection

Effect of base cavity

- Most efficient with Rc=60mm

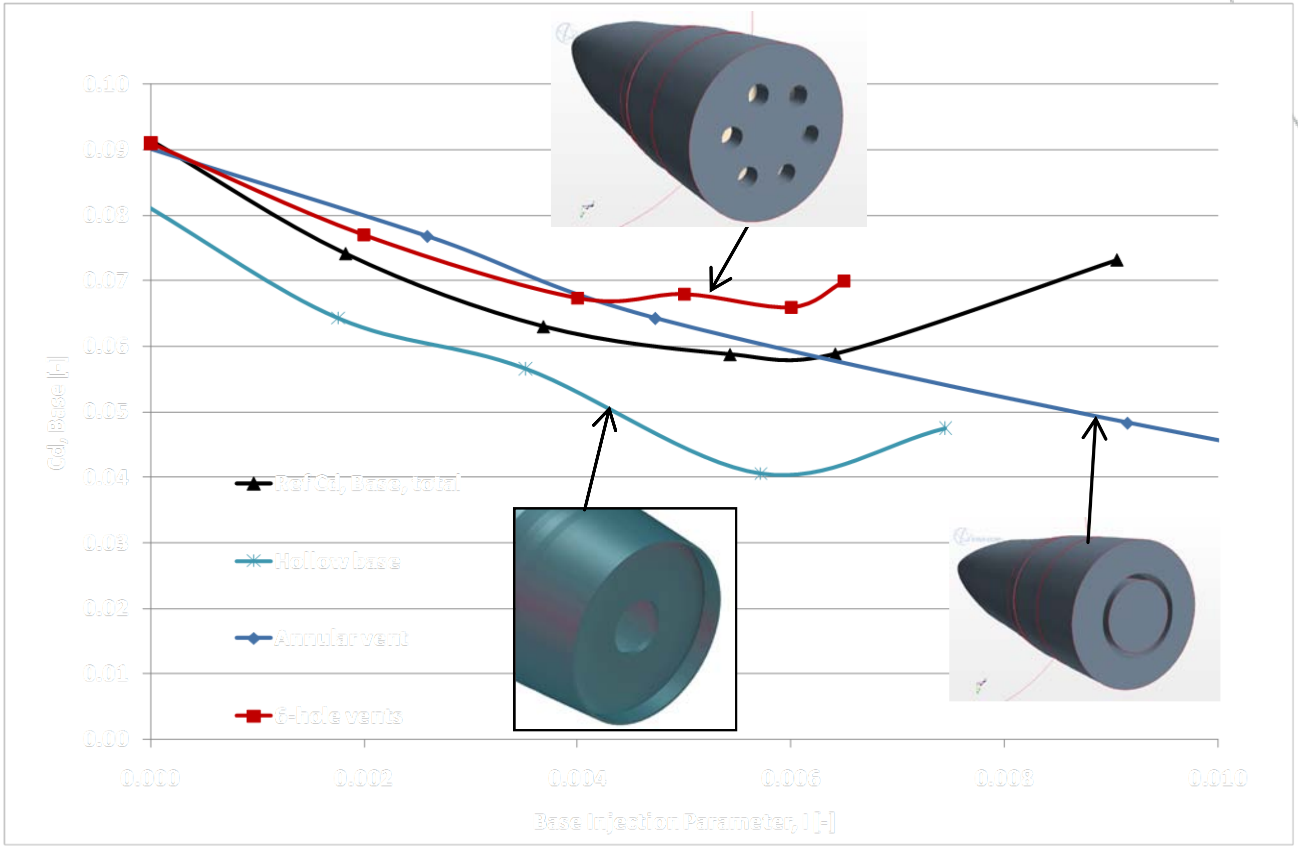






Effect of gas vent layout

- Most efficient with a hollow base having a thin rim protruding



Conclusions

- Numerical tools was applied to the prediction of the 155mm Heer artillery shell performance, both in terms of projectile drag without base-bleed and the drag reduction with such a device
  - Two CFD codes for compressible flows were engaged, the in-house developed CFDnFlow code and the commercial available STAR-CCM+
  - Comparison of drag with available firing data showed good agreement for all supersonic speed
  - DES modelling approach improved the predictions of the effectiveness of the base-bleed device on base drag reduction
- By computing the drag reduction coefficient empirical expressions for base drag was derived enabling complete trajectory simulations
  - The computed trajectories for two elevations compared well with available firing data
- Using the CFD tools, the shape of the base was modified to achieve better pressure recovery, thus reduced base drag
  - Among the analyzed configurations, the one with a hollow base having a thin rim protruding was most efficient