

## **Plume-on Base Flows of a Cylindrical Afterbody with Tails using RANS and DES Models**

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### **ABSTRACT**

Plume effects on base flows represent a significant source of uncertainties to understand the flows around bluff bodies, such as projectiles, missiles, and launched vehicles. Two-equations turbulence model in RANS and detached eddy simulation (DES) models are used in CFD simulations to predict the plume-on/off base flows around a cylindrical afterbody. First of all, computational results of base flow of a cylindrical afterbody are compared with the experimental results. The CFD results show good agreement with the experimental values. Also, effects of the plume on base flow are studied in that limitation of the empirical method was seen.

### **1. INTRODUCTION**

Until recently, two-equations turbulence model in Reynolds-averaged Navier-Stokes (RANS) methods have been widely used for practical engineering problems. However, RANS turbulence models may be inadequate in providing accurate predictions for the phenomena dominating flows characterized by massive separation. To overcome the deficiencies of RANS models for predicting base flows around bluff bodies, alternative methods such as Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), Detached Eddy Simulation (DES), and hybrid RANS/LES are has seen an increase in usage. Spalart (Spalart 1997) proposed Detached-Eddy Simulation (DES) with the objective of developing a numerically feasible and accurate approach combining the most favorable elements of RANS models and LES. It can be applied to analyze of high Reynolds numbers and massively separated flows but also resolves geometry-dependent, unsteady three-dimensional turbulent motions as in LES.

Base flow of a cylindrical afterbody having the apparently simple geometry includes extremely complicated flow physics. Fig.1 represents the schematic of the physical problem of base flows under supersonic free stream condition. Despite some restrictions like as simple geometry, plume-off, and supersonic, the physics of the base

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flow of the cylindrical body is highly complex with separation at the base, expansion waves at the corner, recirculation region downstream of the base, recompression process, and the trailing wake.

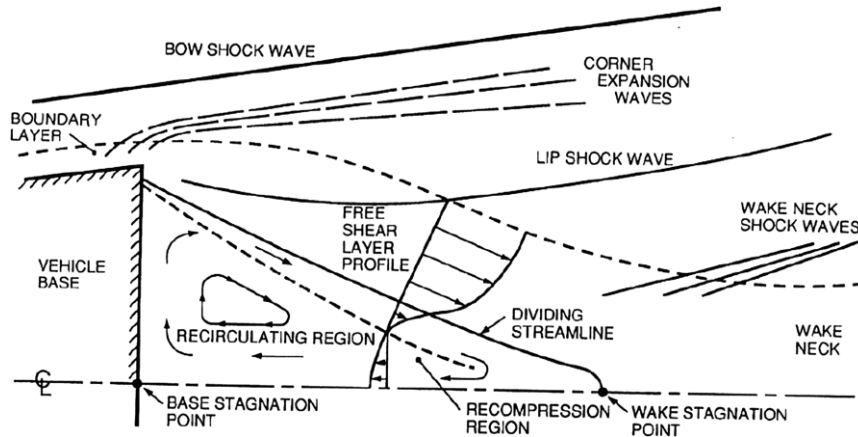


Fig. 1 Schematic of axisymmetric base flow features (Lamb 1995)

In this study, RANS and DES models are used to predict the plume-on/off base flows of the cylindrical afterbody. One of commercial CFD software, STARCCM+, was used to compare with the experiment. RANS is typically applied to analyze such separated flow problem. DES methods, its later improvements delayed DES(DDES) and improved DDES(IDDES), are also used to aims to solve well the complex, separated region of the flow. First, the CFD including RANS and DES methods were performed for plume-off on a cylindrical afterbody with experiment. Also, For the Plume-on case, both RANS and DES models were conducted, and the results are compared with empirical method.

## 2. Plume-off results with experiment

### 2.1 Experimental results

In this case, wind-tunnel test (WTT) have been conducted under subsonic, transonic, and supersonic flow. Pressure measurements have been made at 33 locations on the base to assess the radial distribution of the mean static pressure. Reynolds number based on reference length was  $Re \approx 6.657 \times 10^6$ .

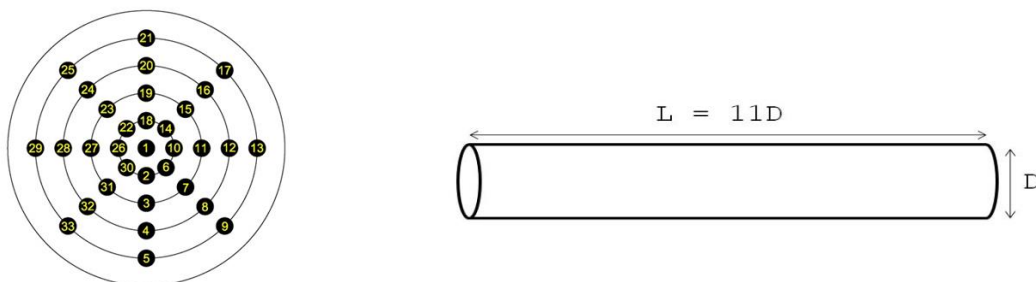


Fig. 2 Pressure hole positions (left) and geometry of the afterbody(right)

## 2.2 Computational framework

### 2.2.1. Grid

Computational domain and grid structure for a model of the vertically stacked the cylindrical body shown in Fig.3. Unstructured grid with lots of millions of cells was generated using STARCCM+ for RANS method in the whole computational domain. Also, the implementation of DES is based on the well establish LES framework contained in the STARCCM+. The mesh for DES simulation has a multi-block, structured grid. When generating meshes for DES, particular attention must be taken since the mesh distribution controls not only the accuracy of the RANS solution but also the resolution of the wavelength spectrum in the LES region. The region of main interest is the base flow including the separation flow and the shear layer characteristics. Therefore, a relatively high grid density is provided at the beginning of the separation where the shear layer is very thin.

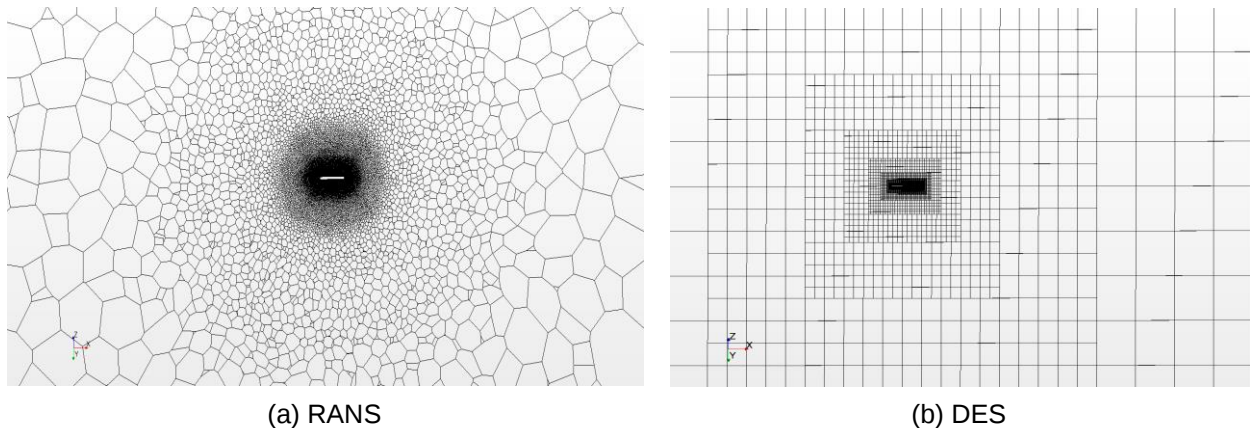


Fig. 3 Computational grid structure: RANS(left) and DES(right)

### 2.2.2. Turbulence model

RANS based on  $k-\omega$  SST model has been widely used to aerodynamic problems and is currently a viable and affordable engineering tool. DES is a modeling approach that combines features of RANS simulation in part of the flow and LES in unsteady, separated regions. Recent updates by Spalart (Spalart 2006) called as delayed detached eddy simulation (DDES) have been incorporated to enhance the ability of the model to distinguish between LES and RANS regions. Also, the improved delayed detached eddy simulation (IDDES) formulation of Shur (Shur 2008) is available additionally. The CFD code contains not only based on Spalart-Allmaras (S-A) model but also a very well validated  $k-\omega$  two equation turbulence model that solves additional scalar-fluctuation equations.

## 2.3 Results

Dimensionless base pressure coefficient, defined as

$$C_{p,base} = \frac{2[(P_{base}/P_{\infty})-1]}{\gamma M_{\infty}^2},$$

Where  $P_{\infty}$  is the static pressure. Fig.4 shows that RANS (left) and DES (right) results of pressure coefficient on the base surface. The contour distribution from DES method is relatively constant across the base, but RANS method is highly concentrated pressure coefficient on the center of the base surface and predicts the lower value with a radial variation. Previous experiments such as Herrin et al. (Herrin 1995), Kawai et al. (Kawai 2005), Simon et al. (Simon 2006) show that measured pressures across the base of the cylindrical body are relatively constant. Table.1 represents that an area-weighted average of the experimental value across the base was performed to determine an average base pressure coefficient.

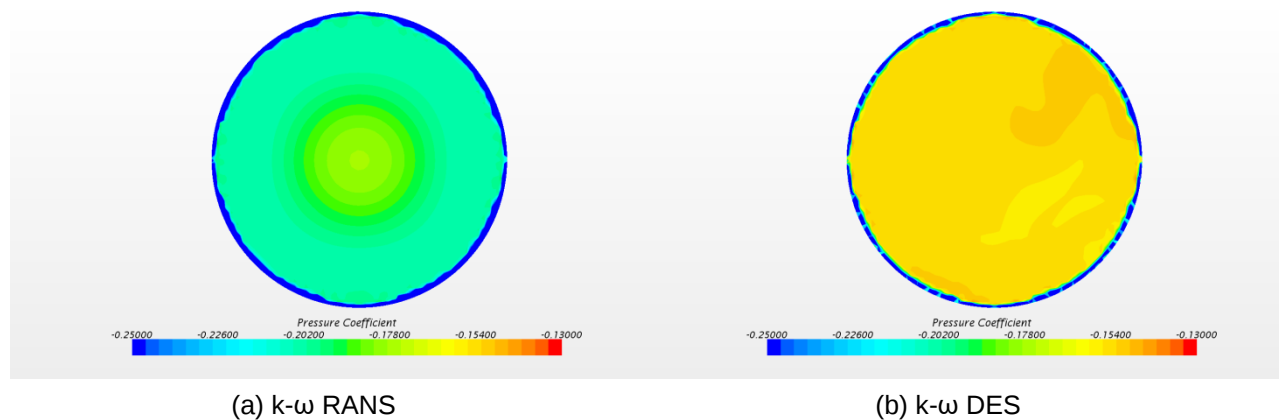


Fig. 4 Instantaneous pressure coefficient,  $M_{\infty} = 1.05$ : RANS(left) and DES(right)

Table.1 Errors comparing with the experiment of area-weighted average  $C_p$  at the base surface

|                   | $M = 1.05$ |
|-------------------|------------|
| k- $\omega$ RANS  | 23.39%     |
| k- $\omega$ IDDES | -3.51%     |
| S-A IDDES         | -9.36%     |

RANS model tends to over-predict compared to experiment. Both of DES methods show good agreement with experimental base pressure. When comparing with experimental results, the errors using DES models were smaller than the RANS model. Their tendency is consistent not only transonic but also supersonic flow.

Instantaneous velocity streamline contours are shown in Fig.5. The RANS model relies on accurate turbulence modeling, but it still needs significant improvement when large regions of separated flow are present in the flow. The base pressure is not constant, and the averaged value is too high. From the figures, a larger recirculation region in RANS results leads to a larger turning angle of the flow and, hence, to a lower pressure on the center of the recirculation region. That is, a higher reverse velocity leads to a larger variation in pressure. As a consequence, the drag increases. While RANS can simulate the mean flow structure, DES methods can predict more

satisfactorily the velocity and base pressure distribution. Instantaneous and chaotic structures can also be reasonably well captured by DES methods, especially the thin helical structures in the shear layer behind the base.

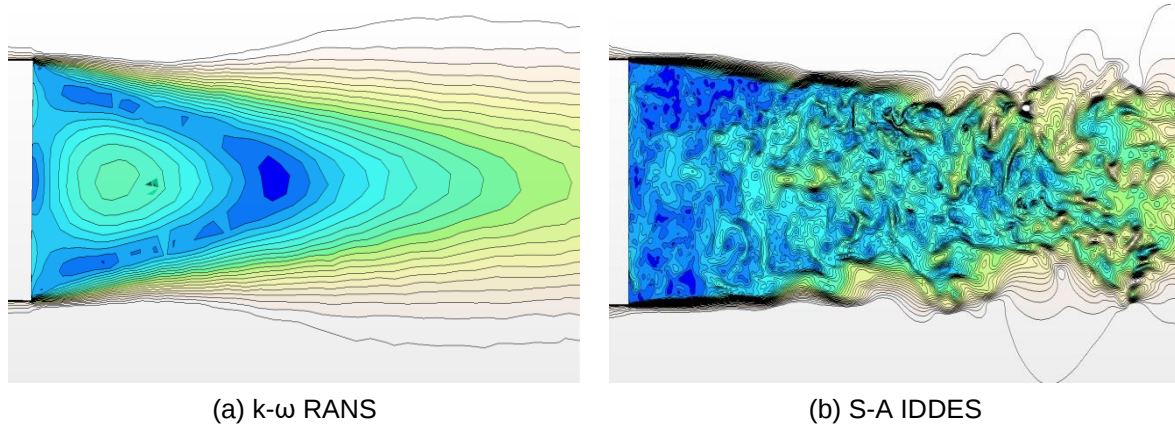


Fig. 5 Instantaneous velocity streamlines at the side view position,  $M_\infty = 1.05$ : RANS(left) and DES(right)

To identify the level of resolution of the simulation and to evidence the coherent structure in such flows, the Q-criterion (Jeong 1995) has been used.

$$Q = \frac{1}{2}(\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij}) = -\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)^2 > 0$$

Where  $\Omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$ ,  $S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$

The Q-criterion is presented in Fig. 6 under the supersonic flow. If Q-criterion is positive, this is vorticity dominated flow, and flow is strain-dominated where negative. Using the RANS model, one can notice the development of some bidimensional vorticity structures just after the separation.

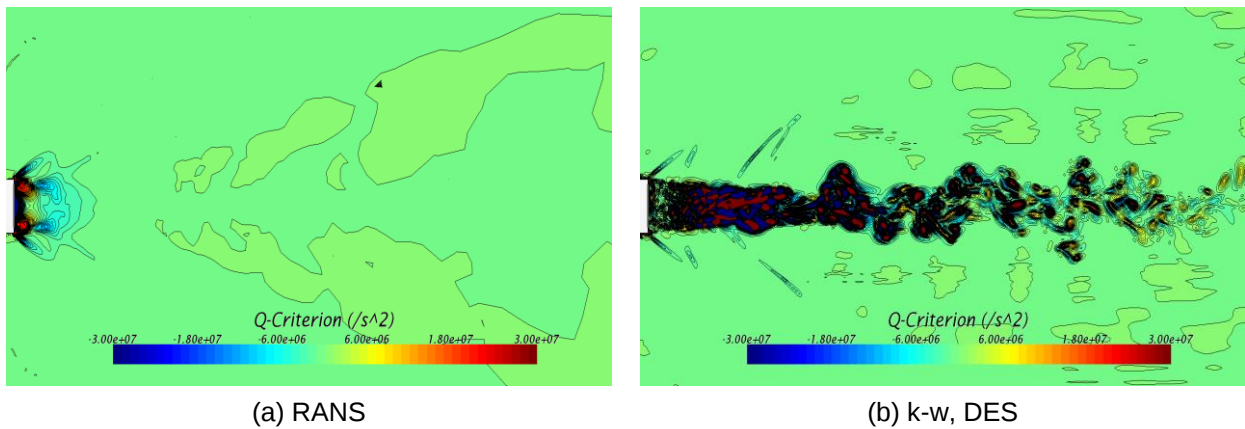


Fig. 6 Instantaneous Q-criterion contours,  $M_\infty = 1.6$  : RANS(left) and DES(right)

### 3. Plume-on results with empirical method

Despite the interaction between base flow and plume being studied for decades, the major problems still remain unsolved. In this case, for which there is no experimental data, the plume-on case has been validated by comparing CFD results with the results provided by Moore et al. (Moore 2002). The empirical method will be discussed next section.

#### 3.1 Empirical method

In plume-on case, the empirical method provides results that are acceptable for engineering design purpose. To make formulation predict plume-on base pressure, they gathered experimental data and set an empirical relation for the variables under consideration. Moore method defines the base pressure  $P_b$  as

$$P_b/P_\infty = (T_j/T_j^*)^N \left[ C_1(C_T, M_\infty) + C_2(M_\infty) \left( \frac{RMF}{1 + RMF} \right) \right] \times \\ f(d_b/d_r) + 0.047(5 - M_\infty) \left[ 2(x_j/d_b) + (x_j/d_b)^2 \right]$$

Where  $C_1(C_T, M_\infty)$  and  $C_2(M_\infty)$  are coefficient, and  $(T_j/T_j^*)$  is physical parameter, and distance of jet exit from body base  $x_j = 0$  in here. Jet momentum flux ratios ( $RMF$ ) come from isentropic flow relationships.

#### 3.2 CFD condition

In this case, both RANS and DES models were conducted, but results using RANS model are compared with empirical method. Because of computational cost, DES simulation has been carried out under some specific conditions.

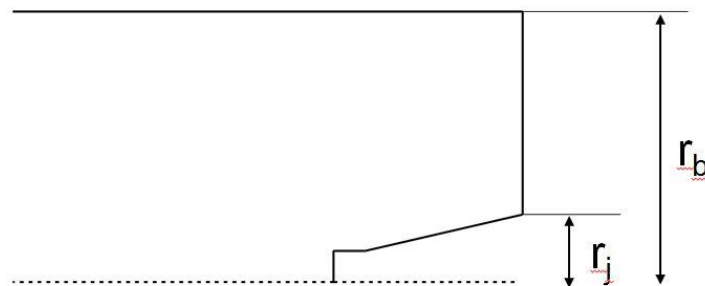


Fig. 7 Geometry of Nozzle and its parameter

Where, the nozzle exit radius  $r_j$ , the base radius  $r_b$ , and its ratio  $r_j/r_b = 0.25$ . The CFD was simulated for different Mach number and ratios of jet stagnation pressure to free stream static pressure,  $PR = p_j/p_\infty$ ,  $0 < PR < 1000$ .

### 3.3 Results

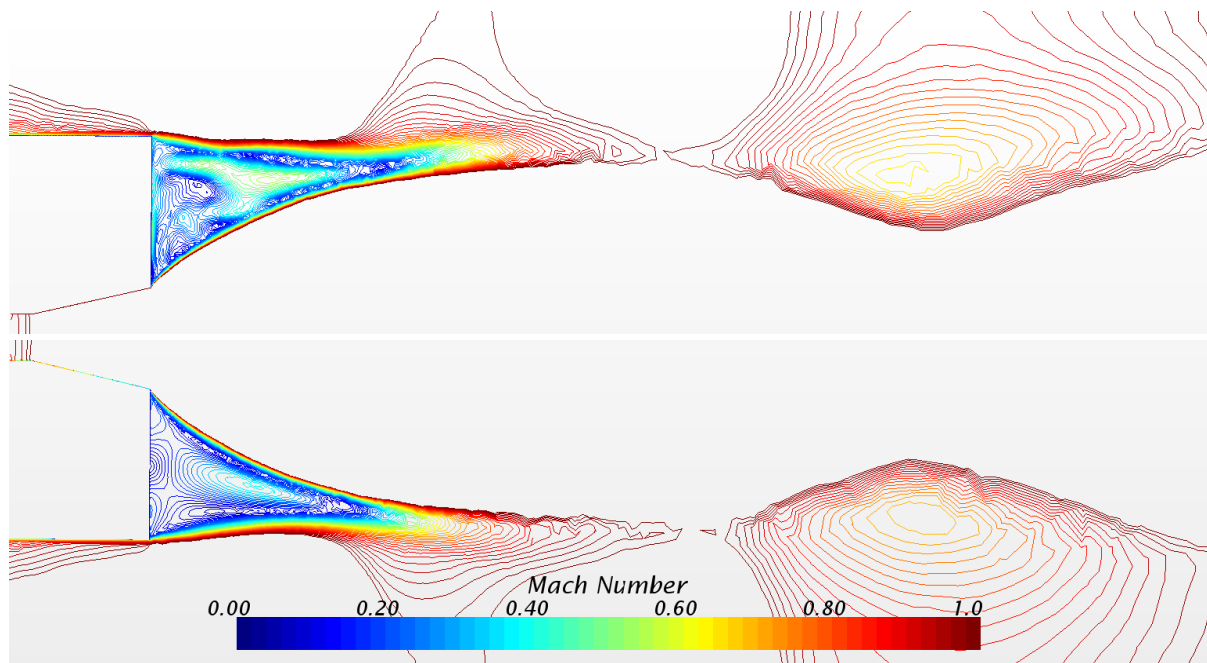


Fig. 8 Instantaneous streamlines of Mach number behind the base,  $M_\infty = 1.05$ : DES (upper), RANS(lower).

Table.2 Area-weighted average Cp at the base surface

|                  | M = 1.05 |
|------------------|----------|
| k- $\omega$ RANS | 0.439    |
| S-A IDDES        | 0.395    |
| Empirical        | 0.421    |

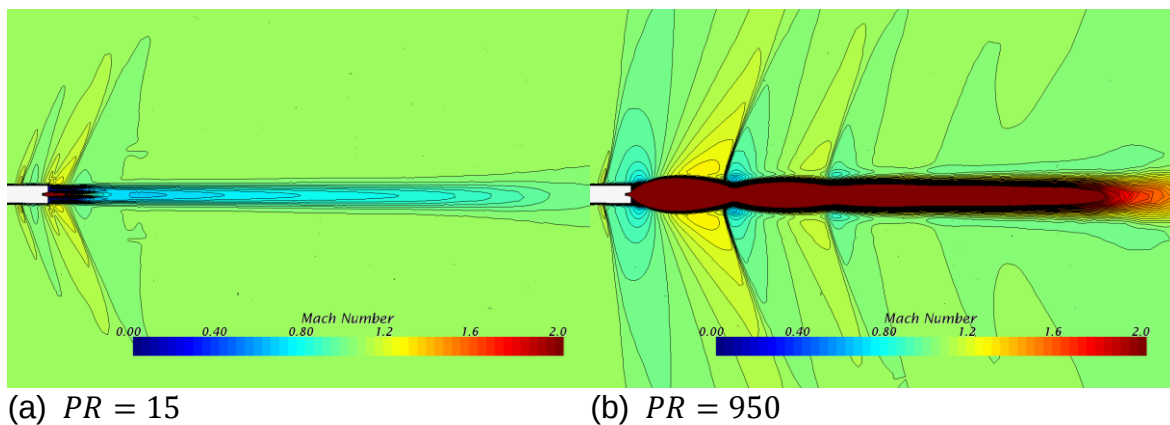


Fig. 9 Mach number contour using RANS model,  $M_\infty = 1.05$ : (a) PR =15 (b) PR = 950

Fig.8 shows that instantaneous Mach number contour with different CFD model. Like as plume-off case, RANS results leads to a larger turning angle behind the base

flow and, hence, leads to a larger pressure coefficient at the edge of the base. As can be seen in Table 2, RANS predicts highest base pressure coefficient among them.

Fig.9 shows that Mach number contour under different pressure ratios ( $PR$ ). As can be observed in Fig.9, exhaust plume experience a further expansion in size with the increase of the pressure ratio. Moreover, when the freestream flow interacts with the plume, the shockwave is formed on tail-surface because change of the pressure rapidly occurred. The plume induced shockwave was shown in Fig.9. With the increasing of pressure ratio, low velocity zone was found on tail-surface. When Mach number moves from  $M_\infty = 1.05$  to  $M_\infty = 1.6$ , the location of plume induced shockwave also moving toward flow direction due to the reduced expansion of plume. It would be affect to flight stability of a cylindrical afterbody with tails to control.

In comparing the CFD for plume-on base drag prediction to the empirical method is shown in Fig.10. The empirical results have been shown to give reasonable estimates of plume-on base drag for a limited range of flight condition only when  $PR > 150$ . Although the approach of empirical method has it strengths, it also has several weaknesses when approached from whole aerodynamic condition. First, it can be applied only transonic and supersonic regime because of lack of experimental data. Also, it has not been validated at angle of attack or when fins were present. The difference between CFD and empirical method when  $PR$  less than 150 will be further studied.

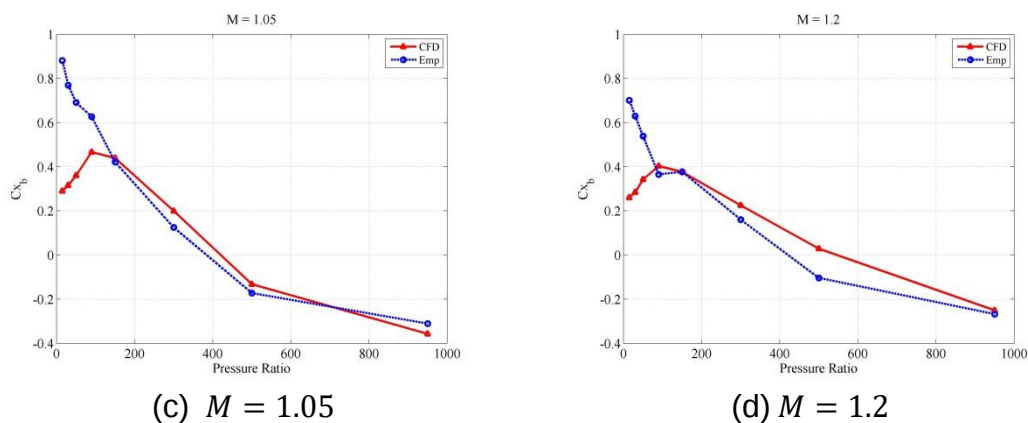


Fig. 10 Axial-force coefficient at the base surface with Mach number: CFD(Red), Empirical method(Blue)

### 3. CONCLUSIONS

The CFD simulations using RANS and DES have been performed on plume-off base flow case. Comparisons of the results between CFD and experiment results show in good agreement. Turbulence models used in this study could give a reasonable qualitative description of base pressure coefficient. Especially, two DES models were seen to give a reasonable comparison with experimental base pressure.

The CFD simulations were also conducted to analyze plume-on effects using RANS model. The compressible flow field around a cylindrical body with tails under

transonic and supersonic regime was investigated at pressure ratios of  $0 < PR < 1000$ . The results were compared with empirical values. In comparing empirical method to CFD, it was shown good agreement when  $PR > 150$ .

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