CFD ANALYSIS IN AN EJECTOR OF GAS TURBINE ENGINE TEST BED

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ABSTRACT

An Ejector system has been used to provide high mass flow to the aero-gas turbine engine in a ground test bed facility. CFD method has been used to determine the performance of the ejector with and without a debris guard. In the first case of flow analyses without debris guard in the ejector, the back pressure was reduced to an extent to know the entrainment ratio. It was found that a pressure of 0.1 bar is required to attain this condition called double choking of the ejector. Further analysis was carried out for a back pressure of 0.9 bar with debris guard. Total pressure loss of 8.56% was found across the debris guard. Also the mass flow through the ejector has reduced by 15% due to debris guard.

Keywords: Ejector, Debris guard, Entrainment ratio.

NOMENCLATURE

\( \dot{m}_p \) - Primary mass flow rate, Kg/s
\( \dot{m}_s \) - Secondary mass flow rate, kg/s
\( P_g \) - Inlet stagnant pressure, Pa
\( T_g \) - Inlet temperature, K
\( A_t \) - Nozzle throat area, m²
\( \eta_i \) - Isentropic efficiency of nozzle
\( P_0 \) - Total pressure, bar
\( T_0 \) - Total temperature, K
\( P \) - Static pressure, bar
\( \gamma \) - Ratio of specific heat
\( R \) - Universal gas constant, J/kg-k

1. INTRODUCTION

Gas Turbine engines are used for land, water, and air applications. The aero version of gas turbine engines are the power plant for civil and military aircrafts which operates successfully from zero to Mach number 2 at an altitude of zero to 20 km range. The performance of the aero engines is obtained by testing the engines in ground, altitude and flying test beds. Generally, ground test bed simulates the normal aspirated conditions. The altitude test bed simulates the flow conditions (pressure and temperature) of various altitudes ahead of engine to be tested.
Figure 1 shows the components of a typical ejector system. A high pressure fluid is passed through primary duct which has a convergent divergent nozzle. This high velocity, low static pressure jet induces a secondary flow from the secondary duct which is open to the atmosphere and accelerates it in the direction of driving jet. The primary high pressure fluid and sucked secondary air flow combine in the mixing duct, which is generally a constant area duct. The kinetic energy of mixed flow is reduced in the diffuser located at end of mixing duct. This high mass flow enters the engine via a bellmouth located after diffuser.

Keenan and Neumann [1] have explained the basic concept of ejector based on 1-D analytical approach. BJ Huang et al [2] explained the effect of back pressure on the entrainment ratio. It is found that the ejector performs better at critical mode in order to obtain a better efficiency. A critical mode in ejector is obtained when the primary and entrained flow is choked and entrainment ratio becomes constant. At sub critical mode only primary flow is choked and entrainment ratio by changing back pressure. T Sriveerakul [3] in his paper has explained the ejector performance by varying the primary fluid properties and geometries.

Wojciech Sobieski [4] has studied the ejector flow using numerical modelling by using commercial code Fluent with various turbulence models and compared the results with the experiments. S Gurulingam [5] has also used numerical method to determine performance of ejector using irreversibility characteristics. He increased the efficiency of ejector by reducing the losses based on minimization of entropy method. This is achieved by forcing the propelled steam through a blower.

Jocob Kenneth Cornman [6] has published the CFD optimization of small gas ejectors used in navy diving system. Optimization of small gas ejector is typically carried out by selecting single set of operating conditions and optimizing the geometry for the specified condition. Pierre van Eeden et al [7] have derived the correlation for ejector efficiency with an accuracy of ±2% using commercial CFD simulation software.

The objectives of present study is to predict the behaviour of flow and mixing process in the ejector of the gas turbine engine ground test bed using with and without debris guard in the ejector. The CFD analysis has been carried out using a commercial CFD package ANSYS FLUENT [8]. The entrainment ratio and pressure drop across the debris guard of the ejector with varying back pressure of ejector has been determined.

2. EJECTOR CONFIGURATION

Figure 2 shows the ejector configuration considered for the present analysis.
This configuration has primary and secondary duct. The primary duct has a convergent divergent nozzle. The other components of the ejector are constant area mixing duct, diffuser, straight duct and the intake duct of engine.

3. COMPUTATIONAL DETAILS

3.1 Grid generation
A 3D hybrid (combination of structured and unstructured) grid of six million elements is generated using GAMBIT software [9], pre-processing of the ANSYS FLUENT software. While generating the grid, it is ensured that the aspect ratio and skewness are in the required range. The aspect ratio is in the range of 5 to 60 and skewness is found to be in the range of 0.01 to 0.9 (skewness close to 1 indicates bad grid quality). The skewness of 0.9 is found near the convergent region of nozzle due to large convergent angle. Figure 3 shows the cross sectional view of the computational grid of the ejector. The exploded view of the grid near the convergent divergent nozzle is shown in Figure 4.

3.2 Boundary conditions
The boundary conditions used for the ejector configuration are as follow:

**Primary duct inlet**: Total pressure and supersonic gauge pressure is specified at the primary inlet, along with total temperature and hydraulic diameter

**Secondary duct inlet**: Total pressure and supersonic gauge pressure is specified at the secondary inlet along with total temperature and hydraulic diameter

**Outlet**: Static pressure and temperature are specified at the outlet of ejector.

**Wall**: All faces enclosing the flow are defined as walls. Adiabatic no-slip boundary condition has been applied.

The computations for the fluid flow in the ejector were performed using the commercial solver ANSYS FLUENT 14.5. A 3-Dimensional compressible N-S equation mode of computer code has been used. Realizable k-ε turbulence model combined with standard wall function has been chosen.

The grid has been chosen based on the grid independence studies performed using grids with 4.2, 6 and 7.8 million cells. The fluid is considered to be compressible. To reduce the numerical errors, a second order volume discretization scheme was used. The SIMPLE algorithm was used for pressure-velocity coupling in the computations. All predicted quantities were steady state. The minimum convergence criteria for the continuity equation, velocity and turbulence quantities are $10^{-6}$. The outlet pressures as well as the mass flow rate at the outlet of the ejector section were carefully monitored as the computation convergence criteria.
3.3 Debris guard

Debris guard is a perforated hemispherical component which is located ahead of the intake duct of engine. The air passes through this mesh like structure. This mesh is considered as porous material to carry out flow analysis in the ejector. The porosity of the debris guard is found to be 0.8. The porous model of the FLUENT computer code is used to simulate the debris guard. The inertial resistance and viscous resistance used to simulate the porous model is tabulated in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Inertial resistance and viscous resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction 1</td>
</tr>
<tr>
<td>Direction 2</td>
</tr>
<tr>
<td>Direction 3</td>
</tr>
</tbody>
</table>

4. PROCEDURE AND CALCULATION

In the present study, the ejector analysis has been carried out in two parts

**Case I: Ejector without debris guard:** There are four analyses carried out by varying outlet pressure of the ejector as shown in Table 2.

<table>
<thead>
<tr>
<th>Table -2: Input Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary inlet</td>
</tr>
<tr>
<td>Case I</td>
</tr>
<tr>
<td>P₀, bar</td>
</tr>
<tr>
<td>i) 10</td>
</tr>
<tr>
<td>ii) 10</td>
</tr>
<tr>
<td>iii) 10</td>
</tr>
<tr>
<td>iv) 10</td>
</tr>
</tbody>
</table>

**Case II: Ejector with debris guard**

Ejector flow analysis has been carried out for one operating condition as given in Table 3.

<table>
<thead>
<tr>
<th>Table -3: Input data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary inlet</td>
</tr>
<tr>
<td>Case II</td>
</tr>
<tr>
<td>P₀, bar</td>
</tr>
<tr>
<td>i) 10</td>
</tr>
</tbody>
</table>

The following performance parameters have been determined from the analyses.

4.1 Primary flow through nozzle

For a given inlet stagnant pressure P₀ and temperature T₀, the mass flow through the nozzle at choking condition is given by the following gas dynamic equation
Total pressure loss across debris guard is calculated by following formula

\[ \dot{m}_p = \frac{P_g - A_t}{\sqrt{T_g}} \sqrt{\frac{\gamma}{R}} \left( \frac{2}{\gamma+1} \right) \left( \frac{Y-1}{\gamma-1} \right) \sqrt{\dot{m}_p} \quad \text{....... (1)} \]

The above equation gives the mass flow passing through primary duct.

4.2 Total pressure loss
Total pressure loss across debris guard is calculated by following formula

\[ \text{Pressure loss} = \frac{\text{Total pressure before debris} - \text{Total pressure after debris}}{\text{Total pressure before debris}} \quad \text{......... (2)} \]

4.3 Entrainment ratio (E.R)
Entrainment ratio is defined as ratio of primary mass flow rate to the secondary mass flow rate.

\[ \text{ER} = \frac{M_{\text{PRY.DUCT}}}{M_{\text{SEC.DUCT}}} \quad \text{...............(3)} \]

5. RESULTS AND DISCUSSION

5.1 Ejector flow analysis – CASE I

The ejector analyses have been carried out for a fixed primary inlet pressure and varying the outlet back pressure. Figure 5 shows the Mach number distribution in Case I (a) to (d). It can be observed that the flow in the Convergent-divergent nozzle accelerates to Mach number of 3.1. The secondary air flow mixes with the primary air in the mixing and straight ducts. The exit Mach number increases as the back pressure has been reduced. It attains a Mach number of 0.4, 0.65, 0.8 and 1.0 respectively.

It can be observed that the Mach number at the convergent divergent nozzle and the ejector exit region have Mach number more than 1.0 in Case-I(d) condition. This is a special case of double choking found in the ejector. The entrainment of the secondary mass flow rate cannot be increased beyond this back pressure.

![Mach Number Distribution for Case I Condition](image)
The static pressure distribution in all four cases has been shown in Figure 6 (a to d) for all the cases.

Table 4 shows the mass flows determined for all four conditions. It can be observed that the mass flow rate at the exit of ejector has been decreasing.

<table>
<thead>
<tr>
<th>Back pressure, bar</th>
<th>Primary mass flow rate, kg/s</th>
<th>Secondary mass flow rate, kg/s</th>
<th>Outlet mass flow rate kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>18.01</td>
<td>45.41</td>
<td>63.42</td>
</tr>
<tr>
<td>0.6</td>
<td>18.01</td>
<td>56.29</td>
<td>74.3</td>
</tr>
<tr>
<td>0.3</td>
<td>18.01</td>
<td>60.01</td>
<td>78.01</td>
</tr>
<tr>
<td>0.1</td>
<td>18.01</td>
<td>62.53</td>
<td>81.46</td>
</tr>
</tbody>
</table>

Table 5 shows the entrainment ratio determined for the above conditions.

<table>
<thead>
<tr>
<th>Back pressure, bar</th>
<th>Entrainment ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0.40</td>
</tr>
<tr>
<td>0.6</td>
<td>0.32</td>
</tr>
<tr>
<td>0.3</td>
<td>0.30</td>
</tr>
<tr>
<td>0.1</td>
<td>0.29</td>
</tr>
</tbody>
</table>
5.2 Ejector flow analysis with debris guard CASE II

The ejector with debris guard condition is analysed by treating debris guard as porous material and applying suitable porous model across debris guard.

Figure 7 shows the Mach number distribution in Case II. It can be observed that the convergent divergent nozzle exit plane has a Mach number of 3.1. Figure 8 and 9 show the static pressure and total pressure distribution along the ejector. It can be seen that there is a large difference in total pressure near the debris guard. The flow faces an obstruction of debris guard and hence velocity vectors reduce at the exit plane of duct.

Mass flows passing through the ejector is shown in Table 6. As compared to the mass flows in Table 4, the secondary mass flow has become less for a constant primary flow of 18.01 kg/s. The secondary mass flows have decreased from 45.41 kg/s to 36.07 kg/s.
Table 6: Mass flows in ejector Case II

<table>
<thead>
<tr>
<th>Back pressure, bar</th>
<th>Primary mass flow, kg/s</th>
<th>Secondary mass flow (kg/s)</th>
<th>Outlet, Kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>18.01</td>
<td>36.07</td>
<td>54.08</td>
</tr>
</tbody>
</table>

Table 7 shows the mass flow entrainment and the total pressure loss across the debris guard. The entrainment ratio has become 0.5 from 0.4.

Table 7: Entrainment ratio

<table>
<thead>
<tr>
<th>Back pressure, bar</th>
<th>Entrainment ratio</th>
<th>Pressure loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0.50</td>
<td>8.56</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

In the present study, the ejector flow analyses have been carried out with and without debris guard using ANSYS FLUENT software. The ejector flow without debris guard has been analysed for four back pressures to determine the double choking condition of the ejector.

The ejector flow with debris guard has been analysed using porous model approach. It was found that the entrainment ratio has increased for the case with debris guard as compared to case without debris guard for the back pressure of 0.9 bar. There is a total pressure loss of 8.56% found due to the debris guard which reduces the ejector mass flow from 45.41 kg/s to 36.07 kg/s.

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REFERENCES