



AEROSPACE INFORMATION REPORT

AIR6355™

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Numerical Modeling Techniques for Jet Engine Test Cell Aerodynamics

RATIONALE

As a complement to AIR4827, this document presents best practices in the domain of numerical aerodynamic analysis tools for determining enclosed test cell aerodynamic performance. Correlated and compared to experimental systems, numerical tools represent an ideal way to reinforce the confidence in predicted performance while allowing for more cost effective and timely aerodynamic analysis.

AIR6355 has been reaffirmed to comply with the SAE Five-Year Review policy.

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FOREWORD

One of the most important design elements for a test facility is aerodynamic performance, which is closely coupled with the acoustic attenuation package. The test facility must allow the engine to be run in any weather condition with sufficient inlet airflow quality and quantity while protecting the environment from an acoustical nuisance (ARP5759). It is imperative to design and manufacture suitable airflow package components and sound abatement systems to meet the main operability criteria (AIR4869). Even if acoustic silencers are not, strictly speaking, a part of the aerodynamic package of a test cell, the intrusion of these elements generate some beneficial and adverse effects on the airflow quality. In addition, running an engine in an enclosed environment (a test cell) generates a number of subtle effects and risks linked to the interaction of the upstream and downstream stream tube with the walls and other features and equipment in the test room. Those constraints must be accommodated in order to provide a safe, stable, and reliable test system in terms of aerodynamics.

In order to manage these constraints in a cost-effective manner and to predict the aerodynamic performance, improvements in CFD (computational fluid dynamics) tools and calculation capabilities allow the international community to consider a new generation of software as an efficient and reliable way to assess test cell operability. Different varieties of tools exist in the market or in-house with different levels of complexity (1D to 3D, steady-state to transient), including continuously improved turbulence models and correlated pressure drop tables. The parameterized aspect of numerical tools also allows for rapid investigation of multiple competitive configurations without obliging the user to manufacture and test expensive physical prototypes. In addition, the continuous increase in computational power allows the test cell designers to include more and more configuration detail, which is convenient to capture the effect of disturbances generated by smaller structures (screen frames, stairs, fairings, lights, door pockets, thrust stand, etc.). Indeed, since the test cell market is willing to keep and maintain existing investments, test cell owners tend to keep using existing test cells to run larger engines, leading to increased risk for wall, ceiling, and floor aerodynamic instabilities ingested by the engines.

Finally, one might observe that simulation tools present some technical advantages over experimental investigations, since the latter may not be able to simultaneously respect all of the fluid flow characteristics, such as Reynolds number, Mach number, etc., due to constraints on experimental ejector simulation and sizes.

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ABSTRACT - OUTLINE

After describing the basis of the test cell aerodynamic design and performance requirements, this document deals with the state-of-the-art simulation processes and tools used to assess the airflow performance of aero-engines operated in enclosed test cells. Different families of tools exist with different levels of complexity and model sizes. This paper describes the main principles of 1D to 3D numerical tools that can be applied to a variety of configurations and engines (turbofan, turboprop, turboshaft, turbojet) within enclosed test cells.

Rather than being a specific software user manual, this document gives general guidelines to the engineering community to conduct the modeling process from CAD to post-processing, including the intermediate steps such as meshing, pre-processing, running, convergence and hardware requirements. In particular, some critical recommendations are highlighted in terms of mesh quality, choice of turbulence model, material properties, boundary conditions, etc.

The main objective of an aerodynamic simulation is generally to assess the adequate aerodynamic performance of the test facility. This Information Report describes methods to evaluate the main success criteria such as by-pass ratio, front cell velocity distortion, cell depression, fan inlet plane distortion, vortex avoidance, and exhaust dilution/cooling. Both flow quantity and quality indicators are considered, since both of them are mandatory to ensure a proper aerodynamic operability.

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1. SCOPE

This SAE Aerospace Information Report (AIR) has been written for individuals associated with ground level testing of turbofan and turbojet engines, and particularly for those who might be interested in investigating steady-state performance characteristics of a new test cell design or of proposed modifications to an existing test cell by means of numerical modeling and simulation. It is not the intent of this standard to provide specific test cell design recommendations, which are covered in the reference documentation.

1.1 Purpose

The purpose of this information report is two-fold:

1.1.1 Provision of Guidelines

This report provides guidelines for creating numerical models and performing simulations of new configurations and/or proposed modifications to ground level enclosed test facilities for turbofan and turbojet engine applications, i.e., jet engine test cells. It addresses the major considerations for performing a numerical analysis of a full scale test cell running an aero engine. Requirements for the computer hardware and software are also presented and discussed.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

The following is a list of some applicable references and documents used in the preparation of this document:

- 2.1.1 SAE International Aerospace Information Report, "Design Considerations for Enclosed Turbofan/Turbojet Engine Test Cells," SAE Standard AIR4869, Reaf. Sept. 2015.
- 2.1.2 SAE International Aerospace Information Report, "Design Considerations for Enclosed Turboshaft Engine Test Cells," SAE Standard AIR4989, Reaf. Nov. 2018.
- 2.1.3 SAE International Aerospace Information Report, "Physical Modeling Techniques for Jet Engine Test Cell Aerodynamics," SAE Standard AIR4827, Rev. Oct. 2016.
- 2.1.4 SAE International Aerospace Recommended Practice, "Acoustical Considerations for Engine Test Cells," SAE Standard ARP5759, Reaf. Nov. 2018.
- 2.1.5 Adkins, R. and Anas, A., "The Blast Basket, A New Component Used in Testing Large, High Bypass Ratio, Fan Engines," The American Society of Mechanical Engineers. 96-GT-83, 1996.
- 2.1.6 Gilmore, J., "Computational Fluid Dynamics Analysis of Jet Engine Test Facilities," Ph.D. thesis, Mechanical Engineering Department, University of Canterbury, 2011,
- 2.1.7 Idelchick, I. E., "Handbook of Hydraulic Resistance, Third Edition," (Mumbai, Jaico Pub. House, 2003), ISBN: 81-7992-118-2.
- 2.1.8 Ho, W. H., "Investigation into the Vortex Formation and Infrasound Generation in a Jet Engine Test Cell," Ph.D. thesis, Mechanical Engineering Department, University of Canterbury, 2009.
- 2.1.9 SAE International Aerospace Information Report, "Test Cell Analytical Thrust Correction," SAE Standard AIR5436, Iss. Nov. 2012.

2.2 Symbols and Abbreviations

The following parameters, abbreviations, and subscript notations are used in this report:

2.2.1 Parameters

A	Cross-sectional area
D	Diameter
K	Kelvin, degrees temperature
kg/s	Kilograms per second
$\dot{m}$	Airflow rate
M	Mach number
p	Static pressure
ρ	Density
R	Specific gas constant
T	Temperature
v	Velocity
x	Axial measurement axis
γ	Ratio of specific heats, non-dimensional
ζ	Pressure loss coefficient

2.2.2 Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
CFD	Computational fluid dynamics
Dist	Distortion
ER	Test cell entrainment ratio (also referred to as test cell bypass ratio or BPR)
FC	Front cell
FC _{dist}	Front cell velocity distortion index (also referred to as velocity distortion index or VDI)
FOD	Foreign object debris
OEM	Original equipment manufacturer
RAM	Random access memory
RANS	Reynolds-averaged Navier-Stokes
SST	Shear stress transport, variation of the k-omega turbulence model

STP	Standard temperature and pressure
TPD	Total pressure distortion
1D	One dimensional
2D	Two dimensional
3D	Three dimensional

2.2.3 Subscripts

avg	Average
byp	Bypass
cell	Evaluated at test room cross-section
e	External
eng	Engine
int	Integral method
max	Maximum
min	Minimum
n	Iteration index n
s	Static
t	Total

3. NUMERICAL MODELING AS A TOOL

Numerical modeling (both 1D analysis and computational fluid dynamics) with varying levels of complexity can be used as a tool to size and configure new engine test cells, and evaluate modifications to existing test cells and to predict their aerodynamic performance in a timely and cost-effective manner. Numerical modeling offers technical advantages over experimental investigations, since a numerical model can simultaneously inspect and non-intrusively measure all aerodynamic characteristics throughout the test cell without the limitations of physical instrumentation. Numerical models also provide the ability to rapidly evaluate alternative configurations and their effect on aerodynamic performance.

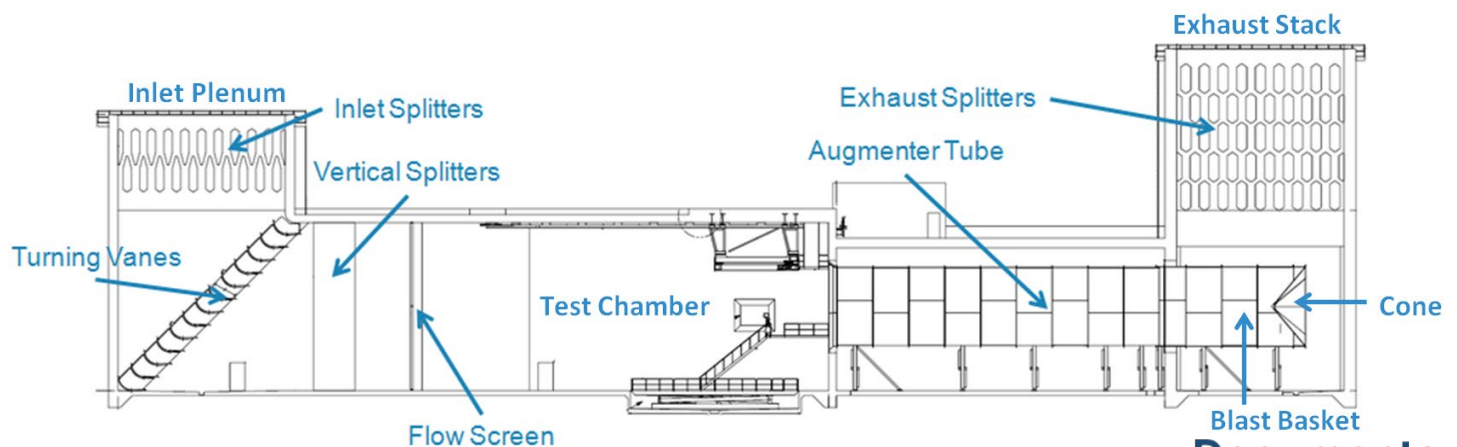


Figure 1 - Typical U-shaped test cell configuration



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4. ENGINE TEST CELLS

4.1 Test Cell Design Considerations and Performance Requirements

The minimum performance requirements for a typical jet engine test cell are [2.1.1]:

- Test cell entrainment ratio (ER) $\geq 80\%$
- Front cell velocity distortion index (FC_{dist}) or velocity distortion index $\leq 35\%$
- Engine bellmouth total pressure distortion $\leq 0.15\%$

Other typical aerodynamic requirements include:

- Cell depression that does not exceed the test cell structural design limits for operation loads
- Sufficient acoustic attenuation to meet local ordinances and operating requirements
- No observed engine-ingested vortices
- No exhaust gas flow recirculation
- No significant flow quality degradation or recirculation in the presence of a prevailing exterior wind
- Exhaust temperature low enough to not damage the structure or the acoustic treatment
- Test cell airflow velocities that do not generate objectionable levels of noise or damage equipment in airflow path

There are other requirements that are related to the logistics of efficiently testing engines in the cell, but the above are the primary requirements related to the aerodynamic performance of the test cell. Each component of the test cell must be designed carefully to achieve acceptable performance with the airflow assessed for each engine or range of engines to be tested in the facility over their full operating regimes. It should also be stated that test cell aerodynamic requirements may be changed due to specific requirements from the engine OEM or the customer. For information on specific test cell design considerations, refer to AIR4869 [2.1.1].

4.1.1 Inlet Plenum

A well-designed inlet plenum provides protection from exterior wind, reduces noise from engine testing, and, most importantly, provides uniform, high-quality airflow going into the engine.

Generally, there are two types of intakes for a test cell: horizontal and vertical. The horizontal inlet allows the flow to enter the test cell parallel to the cell flow direction. Equipment in these inlets typically consists of acoustic treatment, exterior wind conditioning, and interior flow conditioning devices.

Vertical inlets are more common in modern test cell designs. They usually consist of an inlet stack with the air first going through an exterior wind conditioning device at the top, acoustic treatment, turning vanes, and then interior flow conditioning devices. Sometimes there is additional acoustic treatment downstream of the turning vanes. This type of design has been preferred because it provides more protection against external wind conditions. This type is shown in Figure 1.

4.1.2 Test Chamber

The test chamber is where the engine is mounted and measurements are taken. Typically, the mounting hardware consists of a thrust stand and adapter. Other notable features may include a staircase/ladder, catwalks, work platform, observation window, lights, cameras, door pockets, and a monorail for engine delivery. All pieces of equipment must be designed to minimize impact on airflow entering the engine and prevent recirculation of the engine exhaust.

Special attention must be placed on the proximity of the engine bellmouth to nearby surfaces, such as test room walls, work platform railings, engine adapter, thrust stand, and monorail. All of these surfaces have potential to trigger vortex formation, which may cause instability or damage the engine during testing. The thesis by W. H. Ho [2.1.8] contains useful experimental data from wind tunnel studies for use in designing and sizing the test chamber for a given engine size. The data considers an engine bellmouth above the ground in open air. This data correlates vortex formation with the height of the suction inlet centerline above the ground, the suction inlet velocity, the upstream ambient velocity, and the suction inlet diameter.

Another important consideration in designing the test chamber is the front cell length of the test chamber (i.e., the distance between the last conditioning device and the engine inlet). If the test chamber is designed without sufficient length, wakes from upstream flow control devices (flow control screen, acoustic splitters, turning vanes, etc.) may not be sufficiently dissipated. Wakes that have not sufficiently dissipated may cause excess total pressure distortion in the bellmouth or front cell velocity distortion index upstream of the bellmouth.

The test chamber should also be carefully designed to prevent internal exhaust recirculation caused by incomplete capture of the jet engine exhaust by the augments tube. The diameter of the engine exhaust, jet expansion angle, diameter of the augments tube entrance, axial distance between engine exhaust plane and augments entrance plane, and axial offset between the engine and augments tube are all inputs necessary to determine whether or not the engine and augments arrangement will capture the exhaust jet effectively and prevent exhaust recirculation in the test chamber.

4.1.3 Augments Tube

The augments tube collects the engine exhaust and the bypass air. This device is primarily responsible for the jet-pump effect that induces the flow of bypass air through the test cell. Both diameter and length of the augments tube play important roles in determining the amount of bypass air the engine exhaust entrains. See 7.3 for more information on the relationship between turbulent mixing and augments dimensions.

One important aspect when designing the augments tube is the distance between the engine exhaust plane and the augments entrance. If the distance is too great, the engine exhaust may not be captured, leading to exhaust gas re-ingestion and excess acoustical noise in the test room. If too short the cell entrainment ratio will be reduced.

In addition to the augments diameter, length, and distance from the engine, the entrance shape is also an important characteristic. If the augments entrance tube has a sharp entrance, the resultant pressure loss can become excessive due to the high velocities at the entrance to the augments tube.

4.1.4 Blast Basket

The typical blast basket configuration is a perforated cylinder placed at the downstream end of the augments tube and is primarily used to turn airflow from axial to vertical (through the exhaust stack). The blast basket often is terminated with a cone designed to help with turning the air. The factors that most strongly affect the pressure loss coefficient are porosity, length, and diameter. The blast basket is often the largest pressure loss present in the test cell system. As such, it is important to carefully define the blast basket so as to not produce excess pressure loss.

4.1.5 Exhaust Stack

Once the air has been re-directed upwards by the blast basket, the exhaust stack provides another level of acoustic attenuation to prevent excess sound pressure levels from propagating to the surrounding environment. A well-designed exhaust stack provides sufficient acoustic attenuation while not providing excess aerodynamic impedance and avoids exhaust gas re-ingestion. The aerodynamic resistance in the exhaust stack is dictated by the frontal area (the area seen by the upstream airflow) and the leading and trailing edge angles of the acoustic treatment present. The risk of exhaust gas re-ingestion can be reduced by carefully choosing the height of the exhaust stack in relation to the inlet stack and taking into account the direction of prevailing winds.

4.1.6 Surrounding Environment

While the test cell's surrounding environment may not have a significant impact on the internal aerodynamic and acoustic performance of the test cell, the test cell alignment and proximity of occupied structures dictates the amount of acoustic attenuation material needed. In addition, the alignment of the test cell should be taken into consideration in regards to the direction of the prevailing wind. To the extent possible, the test cell should be aligned with the prevailing wind direction such that flow separation in the inlet plenum is minimized even in the presence of a prevailing wind, and exhaust is not re-ingested.

5. CHOOSING A NUMERICAL MODELING TECHNIQUE

Before committing to one type of numerical modeling, it is important to assess both the type of result and the level of detailed required.

5.1 1D Simulation

Because detailed CFD models require a significant amount of time to create the geometry, mesh, converge, and post-process, it is advantageous to have an alternative tool that quickly and accurately models the bulk flow behavior of the test cell. This allows the engineer to size the key features of the test cell to achieve the quantity of airflow desired before performing a CFD analysis.

A 1D model of a generic (U-shaped) test cell with a vertical inlet stack, test room, augments tube, blast basket, and vertical exhaust stack can be created by solving a system of equations. This system of equations obtains the primary airflow variables (static pressure, density, velocity, and static temperature) at each section of interest by solving the appropriate airflow equations. The airflow rate through the test cell is determined by the pressure losses present in the cell, the turbulent mixing of the exhaust gas and bypass air in the augments tube, and the sizes of the test cell and augments tube.

5.2 2D and 3D Simulations

2D and 3D CFD simulations provide valuable information that cannot be obtained from experimental testing. By interrogating the CFD solution, the engineer can investigate and visualize flow patterns using contours, streamlines, and iso-surfaces. The engineer can also iterate the test cell design until the desired airflow quality is achieved without having to build expensive physical models. 3D CFD model results can provide an accurate comparison to full-scale engine tests, provided the operating conditions for both the CFD and full-scale engine test are comparable (see Section 9 for discussion of comparison between CFD and full-scale measurements).

6. SIMULATION EQUIPMENT

6.1 Hardware

Computer hardware should be one of the first things to consider when deciding to perform numerical simulations. Because the cost for computational hardware can increase exponentially, it is best to determine the minimum amount of computing power needed to perform a simulation. For 1D and some 2D simulations with less than one million elements, a 1 to 12 core workstation should be enough to converge a simulation in a matter of minutes.

3D simulations may have mesh sizes of 20 to 50 million elements for cell sizes up to 14 m or more and can require significant computing power. The appropriate mesh size for a specific application is to be determined by a mesh sensitivity study. The specific geometry of the test cell and the internal wetted area contribute most significantly to the required mesh size.

Two options are available that allow simulations to be performed in a matter of days or even hours: cloud computing and building an in-house cluster.

Cloud computing is the newest processing choice and allows a simulation to be run on an unlimited amount of processors. It is a great option for running several simultaneous simulations, but becomes less financially efficient with increased simultaneous runs and cores per run.