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Radiant Energy Measurements From a Scaled Jet Engine Axisymmetric Exhaust Nozzle for a Baseline Code Validation Case

Joseph F. Baumeister
Lewis Research Center
Cleveland, Ohio

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Radiant Energy Measurements from a Scaled Jet Engine Axisymmetric Exhaust Nozzle For A Baseline Code Validation Case

Summary

A non-flowing, electrically heated test rig was developed to verify computer codes that calculate radiant energy propagation from nozzle geometries that represent aircraft propulsion nozzle systems. Since there are a variety of analysis tools used to evaluate thermal radiation propagation from partially enclosed nozzle surfaces, an experimental benchmark test case was developed for code comparison. This paper briefly describes the nozzle test rig and the developed analytical nozzle geometry used to compare the experimental and predicted thermal radiation results. A major objective of this effort was to make available the experimental results and the analytical model in a format to facilitate conversion to existing computer code formats. For code validation purposes, this nozzle geometry represents one validation case for one set of analysis conditions. Since each computer code has advantages and disadvantages based on scope, requirements, and desired accuracy, the usefulness of this single nozzle baseline validation case can be limited for some code comparisons.

Introduction

Evaluating thermal radiation propagation from partially enclosed nozzle surfaces can lead to complex analysis methods and expensive experimental testing. Using analytical tools to follow the propagation of radiant energy within and from a nozzle becomes a substantial problem as the complexity of the geometry increases. Various analytical approaches have been developed and applied to evaluate multi-reflecting nozzle radiation. Each technique has advantages and disadvantages based on its simulation of the fundamentals of radiation physics, analytical modeling requirements, computer requirements, solution convergence requirements, and accuracy and flexibility to solve both simple and complex problems. Since there are a variety of analysis tools available, a standard code validation case based on benchmark test data was defined to verify and calibrate these codes. A non-flowing, electrically heated test rig provided benchmark radiant energy propagation test data for a baseline axisymmetric convergent-divergent nozzle applicable to aircraft propulsion systems. The electrically heated rig consists of nozzle hardware, shields, and radiometer. For code validation purposes, this nozzle geometry represents one validation case for one set of analysis conditions. Since each computer code has advantages and disadvantages based on scope, requirements, and desired accuracy, the usefulness of this single nozzle baseline validation case can be limited for some code comparisons.

The primary objective of the electrically heated rig is the validation of computer codes that simulate nozzle surface radiant energy propagation. Computer code validation required a defined nozzle geometry, measured nozzle surface temperatures, angular measurements between nozzle and radiometer, and the spectral wavelength band of interest. Extreme care was devoted in providing a direct correspondence between measured test rig nozzle surface temperatures and the analytical nozzle geometry. This paper briefly describes the nozzle test rig and the developed analytical nozzle geometry used to compare the experimental and predicted thermal radiation propagation from of the nozzle. A major objective of this effort was to make available the experimental results and the modeling information in a format to facilitate conversion to existing computer code formats. The goal is to establish a baseline computer code validation tool.

Throughout this paper the term "model" will be used in two different applications. The term "model" will be applied when discussing the nozzle hardware geometry that is used in the test rig. The term "analytical model" is used to represent a data set that contains the information required to define the physical attributes of the test rig nozzle for analysis. The analytical model subdivides the nozzle geometry into a number of finite surfaces called nodes. The actual number of nodes and their geometry depends on the desired model representation, accuracy of results, structural design considerations, computer capabilities, and computer computational time requirements. Each nozzle node represents a uniform surface temperature over the entire node surface.

Axisymmetric Nozzle Test Rig Apparatus

A non-flowing, electrically heated rig was designed, calibrated, tested, and applied to verify calculated exhaust system radiant energy propagation from a fixed axisymmetric convergent-divergent nozzle. The main components in the electrically heated rig are the nozzle model hardware, shields to mask unwanted radiant energy, and a radiometer. The nozzle model hardware represents the propulsion system geometry from the rotor exit plane through the nozzle divergent flaps. The nozzle model is heated and controlled using resistance wire, which limits the maximum allowable temperature. A low-temperature limit is set by the test rig operating conditions and the sensitivity of the radiometer. The axisymmetric convergent-divergent nozzle model used in the test rig is shown in Figure 1. Figure 2 shows the orientation of the 24 turbine exit guide vanes included in the model. The turbine rotor exit plane was represented by an electrically heated flat plate attached upstream of the vanes. A view of the nozzle in the electrically heated test rig is given in Figure 3. This nozzle model is an arbitrary design that does not represent any particular engine configuration. Exhaust nozzle throat and surface areas, expansion ratios, and power conditions must be defined to calculate actual radiant energy propagation, but are not critical features for code validation purposes.

The nozzle model is constructed from .060" thick AISA 347 stainless steel with flanges of either spun or welded sheet metal. The model internal surfaces were grit blasted prior to final assembly. This grit blast operation provides the surface with diffuse reflecting characteristics. The nozzle model is mounted on a positioning system that provides dual axis azimuth and elevation orientation with respect to the radiometer. Extreme care was devoted to provide the required thermocouple instrumentation for determining nozzle model wall temperatures for use in the analytical model analysis. Thermocouples were required to record both axial and circumferential nozzle model temperature gradients. Axial temperature gradients were present through conduction between the model section flanges, while free convection inside the non-flowing model resulted in top-to-bottom temperature gradients from rising hot air.

Two radiant energy shields exist between the nozzle model and the radiometer. The first shield was installed at the nozzle exit plane to remove nozzle external surfaces, instrumentation, and various test rig apparatus from view of the radiometer. This shield provides an inside view of the nozzle, and is shown in Figure 3. A second, or foreground, shield was placed between the test rig and the radiometer. This shield was used to prevent background radiation from entering the radiometer. Both shields were cooled to 35 degrees Fahrenheit and painted with high emissivity paint. This high emissivity paint was added to absorb room radiation and prevent it from reflecting into the radiometer. The repositioning of the test rig nozzle model for different elevations and azimuths can require adjustments in the foreground shield and radiometer position. The placement and dimensions of the foreground shield were determined from the desired optical field of view of the radiometer. To maintain a radiometer response greater than 95%, an instrument incremental scan angle of five degrees was selected, based on a calibration with a small 1000 degree Centigrade blackbody source positioned at various angles from the radiometer centerline. This provided the shield center aperture dimensions.

A Barnes Spectralmaster Infrared Research Radiometer Model 12-550 Mark II was used to acquire the radiant energy. This spectral radiometer was positioned 36 feet away from the axisymmetric nozzle. The radiometer optical head contains the following major components:

- A radiation telescope (Fore-Optics) for collecting radiation
- A 1000 Hz chopper for optically modulating the radiation
- A reference cavity (~56 degree's Centigrade) for comparison of target radiation with a standard reference radiation
- A cycling 340 position continuously variable spectral filter system for target wavelength determination from 1.306 to 14.536 microns
- A detector to convert the received radiation to electrical signal. An indium antimonide (InSb) sensor for wavelengths to approximately 5.5 microns, and mercury cadmium telluride (HgCdTe) sensor for wavelength above this level.

The precise wavelength band used in the test rig for code validation purposes was 2.9904 to 5.0201 microns.

Axisymmetric Nozzle Analytical Modeling Information

There are a variety of analysis techniques used to simulate the propagation of radiant energy. Each analysis technique has advantages and disadvantages based on its simulation of the fundamentals of radiation physics, analytical modeling requirements, computer requirements, solution convergence requirements, and accuracy and flexibility to solve both simple and complex problems. Since each computer code may have different operating efficiencies and computational tradeoffs, this nozzle analytical case was not optimized for any particular code, analysis conditions, or computational time minimizing techniques. So for code validation purposes, this nozzle analytical model represents only one validation case for one set of analysis conditions. Since each computer code has advantages and disadvantages based on scope, requirements, and desired accuracy, the usefulness of this single nozzle baseline validation case can be limited for some code comparisons.

To simulate the radiation propagating inside and outside the nozzle, typical analysis techniques calculate view factors and radiation interchange factors between the nozzle surfaces and the outside environment for different azimuth and elevation positions. These results relate the percent of emitted surface energy that is incident and absorbed for each surface through direct and reflected radiant energy propagation. The percentages of absorbed energies can then be applied to energy balance equations. The influence of multi-reflecting radiation can lead to non-uniform incident and reflected radiant energy fluxes. Since some analysis techniques require uniform incident and reflected radiant energy fluxes on each surface node, smaller nozzle sectioning may be a requirement. See reference 1 for further information regarding limitations, advantages and disadvantages of analysis techniques. For this validation case, the objective of the nozzle analytical model surface sectioning was to achieve the greatest possible accuracy in representing the test rig nozzle model. To accomplish this, the nozzle analytical model was sectioned to directly correspond with areas of uniform surface temperature in the test rig nozzle model. The sectioning of the nozzle model surface geometry for use in the analytical model is shown in Figure 4 through Figure 7.

The complete interior surface geometry of the analytical model is defined by 288 surface nodes. The transition duct and exhaust nozzle are sectioned as shown in Figure 4. Figure 5 shows how the turbine rotor exit plane was modeled along with the vane support structure. The vane orientation sequence and surface numbering sequence are shown in Figure 6 and Figure 7. Two additional surface nodes (289 and 290) are supplied if the user needs a nozzle external surface cover, as shown in Figure 8. The complete nozzle analytical model is composed of four surface types: cylinder, disk, slant cone and polygon. These surface types are shown in Figures 9 and 10. In this case, a circular cone geometry is applied by defining the slant cone surface with a vertex displacement of 0.0 (see Figure 10). Each of the 288 nodes in the complete analytical model represents surface areas of uniform temperature. The actual locations used to measure the nozzle emitted radiant energy are listed in table 1. This table represents the locations where the nozzle analytical predictions are to be compared to test rig radiometer data. The 0.0 degree azimuth and elevation location represent the axial direction, or angle normal to the nozzle exit plane.

AZIMUTH (degrees)	ELEVATION (degrees)
0.0	0.0
2.5	0.0
5.0	0.0
10.0	0.0
15.0	0.0
20.0	0.0
30.0	0.0
40.0	0.0
50.0	0.0
60.0	0.0
70.0	0.0
80.0	0.0

TABLE 1, RADIOMETER POSITIONING WITH RESPECT TO THE NOZZLE TEST RIG

In analyzing the nozzle geometry, diffusely emitting and reflecting surface thermophysical property characteristics for the nozzle surfaces can be assumed, and a 0.6 hemispherical emissivity value is a reasonable approximation in the 3 to 5 micron wavelength band of the IR spectrum. Surface thermophysical properties as a function of angle were also measured. Although this latter information would more accurately represent the radiation propagation, the geometry and surface temperatures for this model produce conditions where the uniform hemispherical emissivity produces calculated results that compare favorably to the test rig results for the total nozzle. For additional information regarding the analytical model, surface temperatures or modeling information, contact the author.

Axisymmetric Nozzle Hot Parts Radiation Experimental Data

After the calibration, data reduction phase, and increased experience gained with the radiometer, a high level of confidence was established with this test rig. The radiometer test data established the total nozzle emitted radiant energy propagation pattern for comparison to analytical code predictions. The following table gives the experimental measured total nozzle emitted radiant energy, in watts/steradian after integrating over the 3 to 5 micron wavelength band. These results correspond to a test rig temperature condition of 800 degree Fahrenheit for the entire axisymmetric convergent-divergent nozzle. This data includes atmospheric attenuation. Atmospheric radiation transmissivity data can be applied to simulate the atmosphere absorption effects.

AZIMUTH (degrees)	ELEVATION (degrees)	ENERGY (Watts/steradian)
0.0	0.0	65.4
2.5	0.0	63.9
5.0	0.0	61.8
10.0	0.0	59.2
15.0	0.0	57.9
20.0	0.0	56.3
30.0	0.0	49.2
40.0	0.0	40.1
50.0	0.0	30.1
60.0	0.0	20.0
70.0	0.0	12.0
80.0	0.0	3.0

TABLE 2, TEST RIG NOZZLE MODEL RADIOMETER RESULTS

The results in table 2 are for comparing analytical predictions using the analytical modeling information. This experimental test data will be used as a standard baseline code validation case for comparing different analysis techniques. With this standard baseline code validation case, differences between analysis codes will become apparent.

Concluding Remarks

To verify computer codes used to calculate aircraft propulsion nozzle radiant energy propagation, a non-flowing electrically heated test rig was developed. This paper briefly describes the nozzle test rig and the developed analytical nozzle geometry used to compare the experimental and predicted thermal radiation results. The data from the test rig radiometer established the total nozzle emitted radiant energy propagation pattern for comparison to analytical code predictions. The experiment measured total nozzle emitted radiant intensity in the 3 to 5 micron wavelength band for a nozzle geometry with a given set of nozzle temperatures and surface thermophysical properties. For code validation purposes, these nozzle test conditions represent a single validation case. Since each computer code has advantages and disadvantages based on scope, requirements, and desired accuracy, this validation case may represent conditions that limit code comparison effectiveness. The results may also be used for code calibration information or as a code development tool. A major objective of this effort was to make available the experimental results and the analytical model in a format that would facilitate conversion to existing computer codes.

References

1. Baumeister, J.F.: "Application of Ray Tracing in Radiation Heat Transfer", NASA TM-106206, 1993.

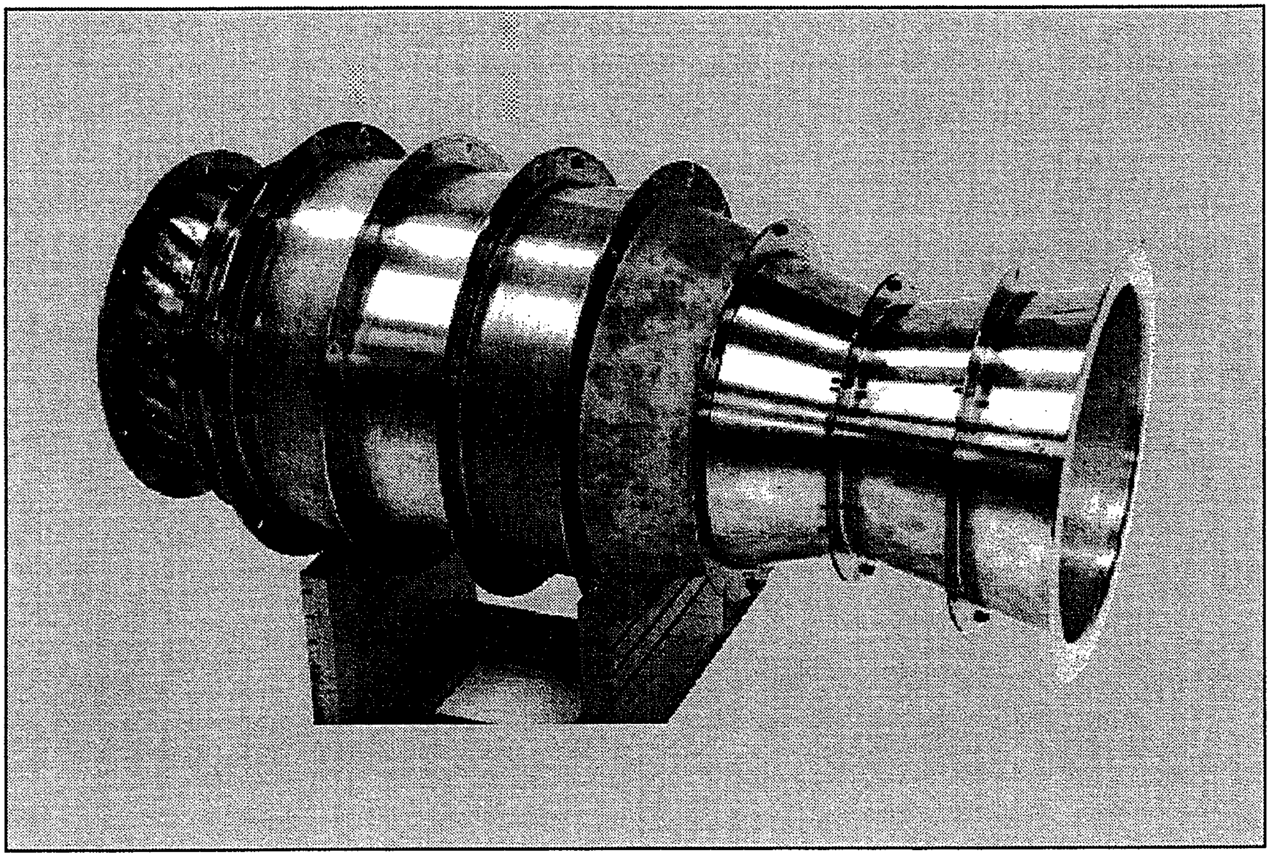

Figure 1. - Axisymmetric Nozzle test rig model.

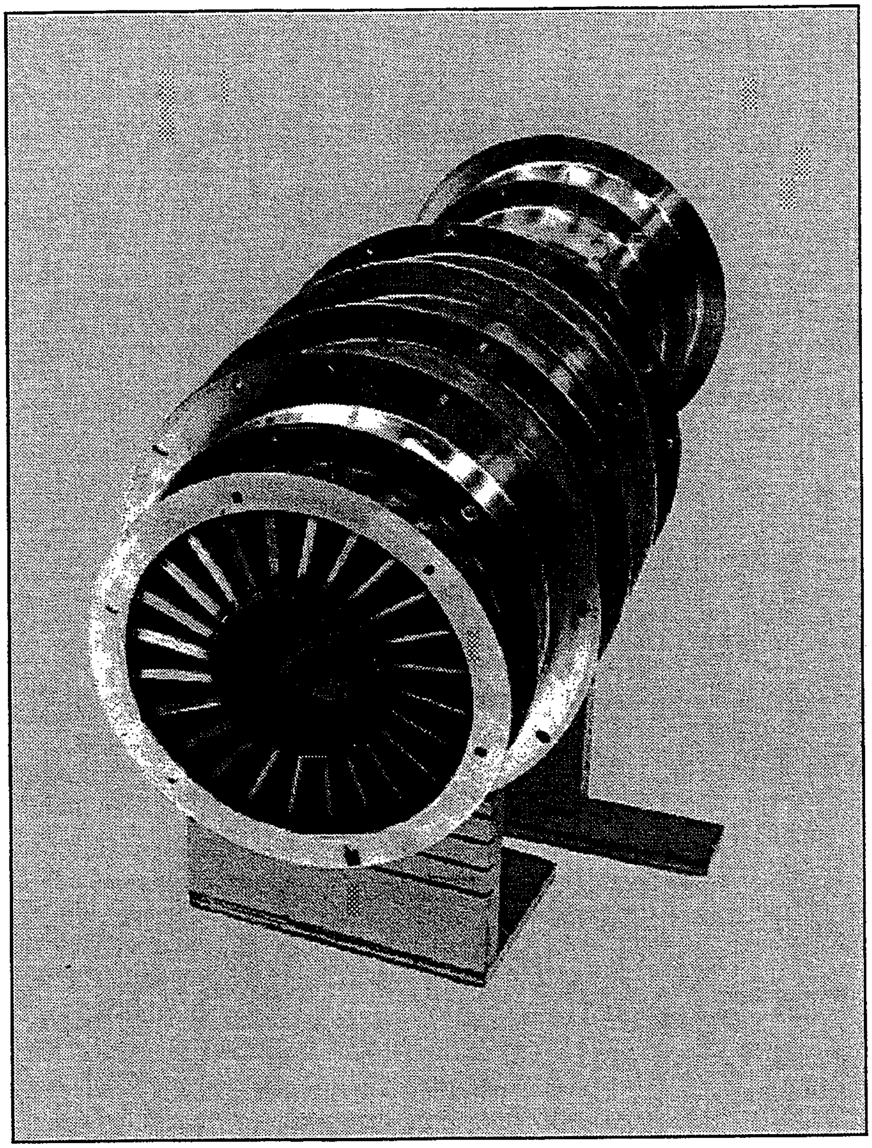

Figure 2. - View of nozzle test rig model vane orientation.

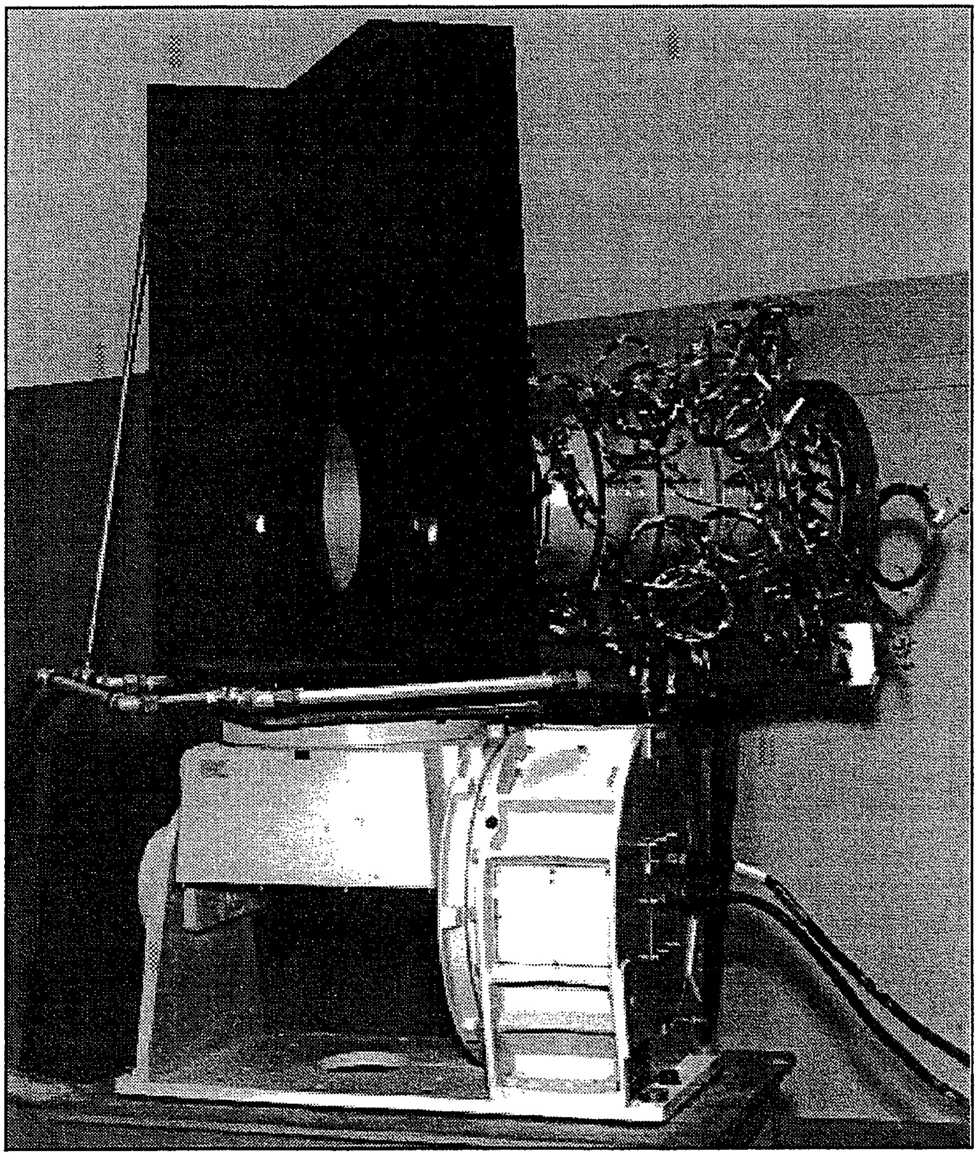

Figure 3. - Intstrumented nozzle test rig model with water cooled shield.

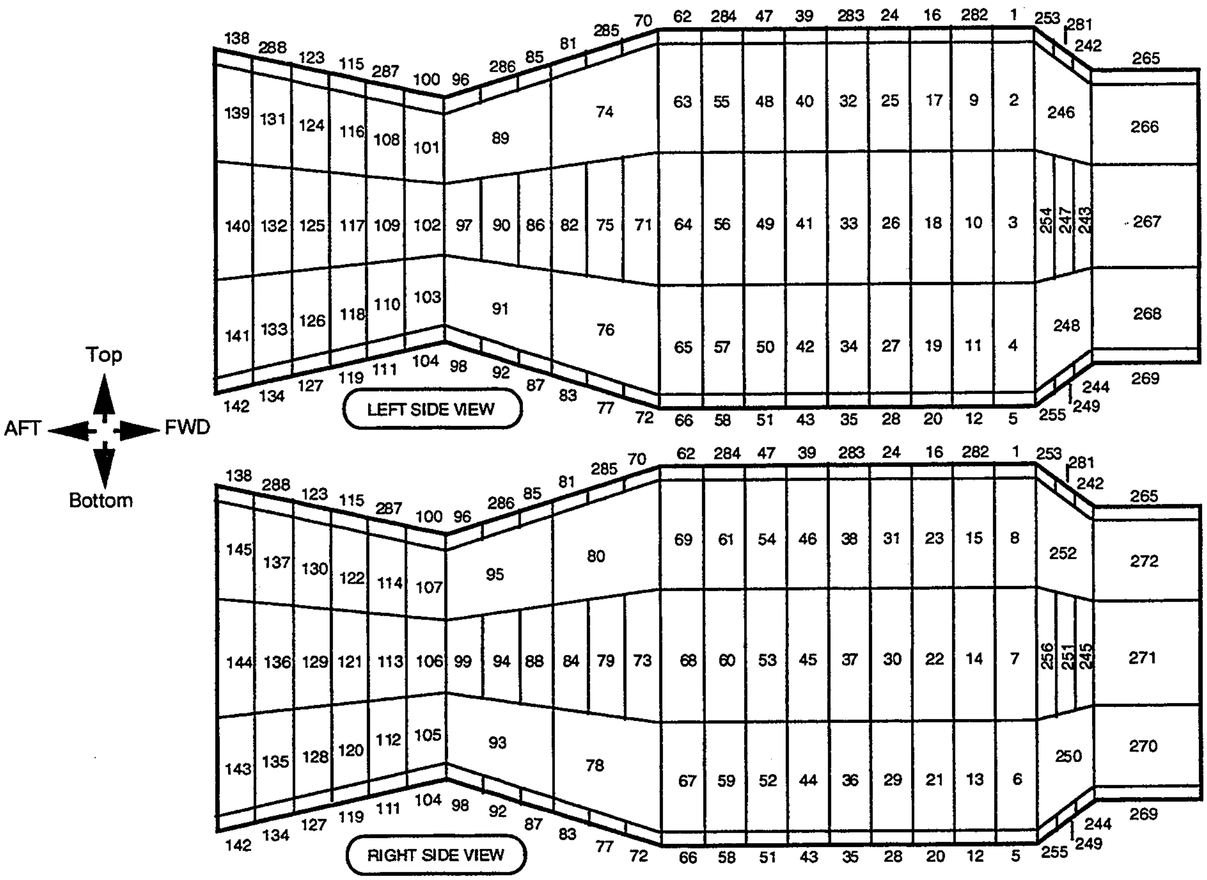

Figure 4.- Nozzle surface numbering sequence.

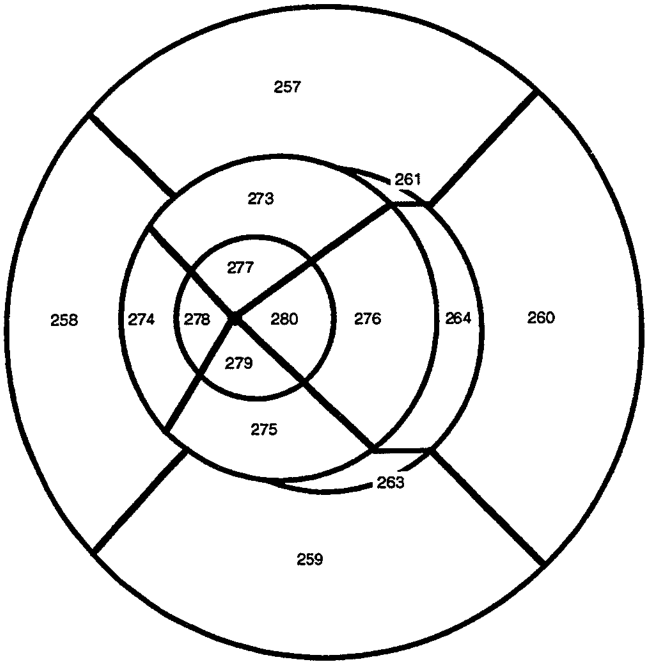

Figure 5. - Forward turbine and vane support surface numbering sequence.

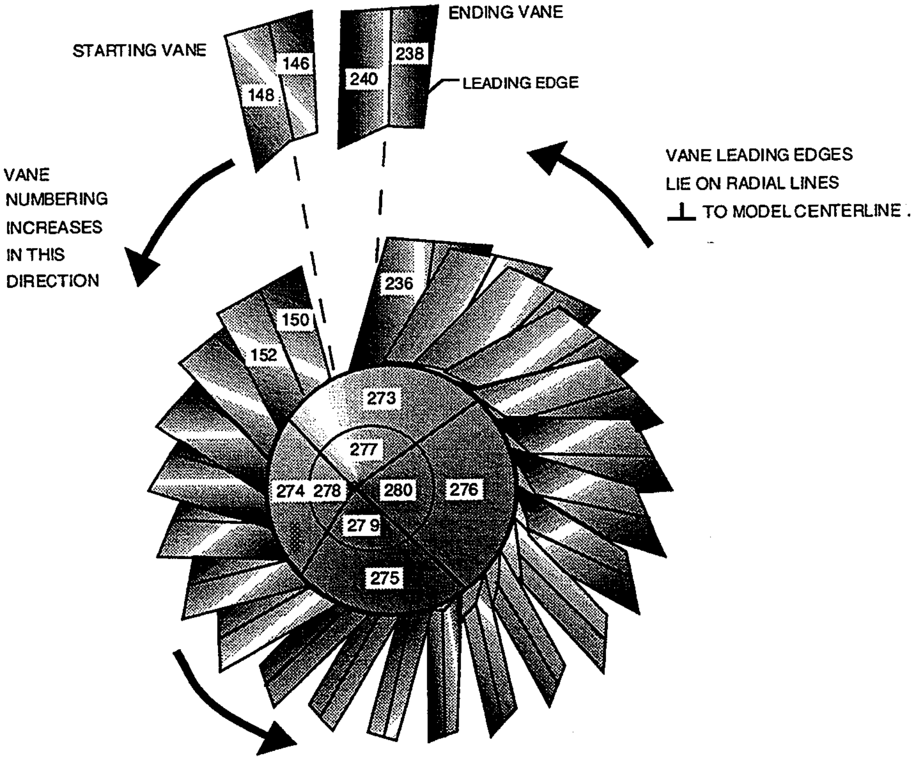

Figure 6. - Vane orientation sequence.

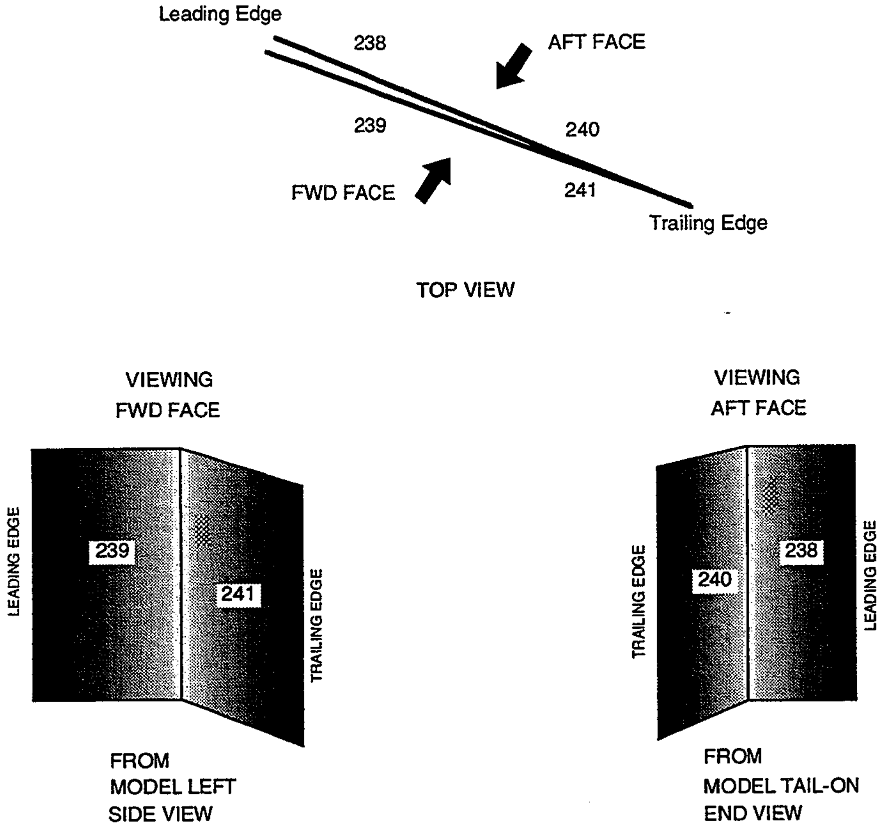

Figure 7. - Vane surface numbering sequence.

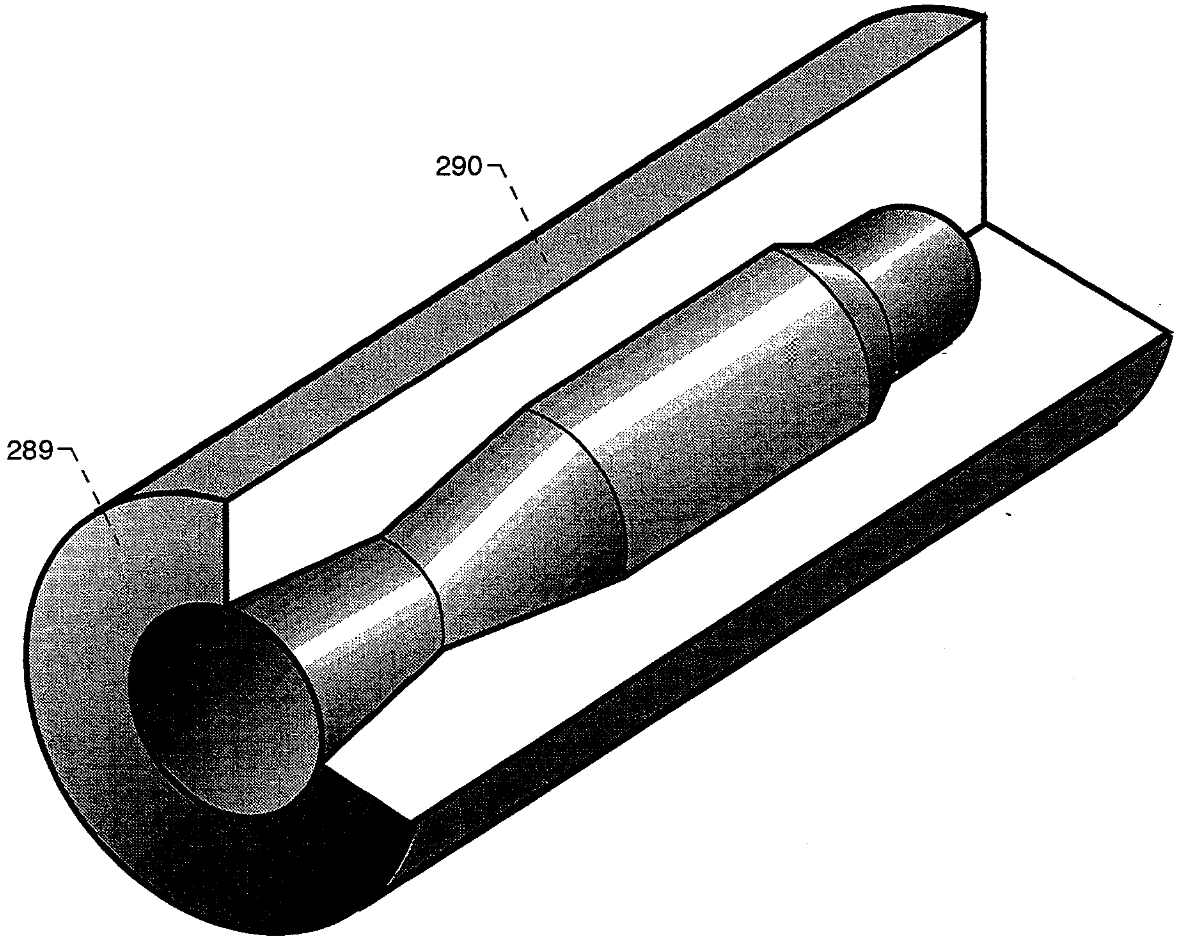

Figure 8. - Nozzle external surface cover numbering sequence.

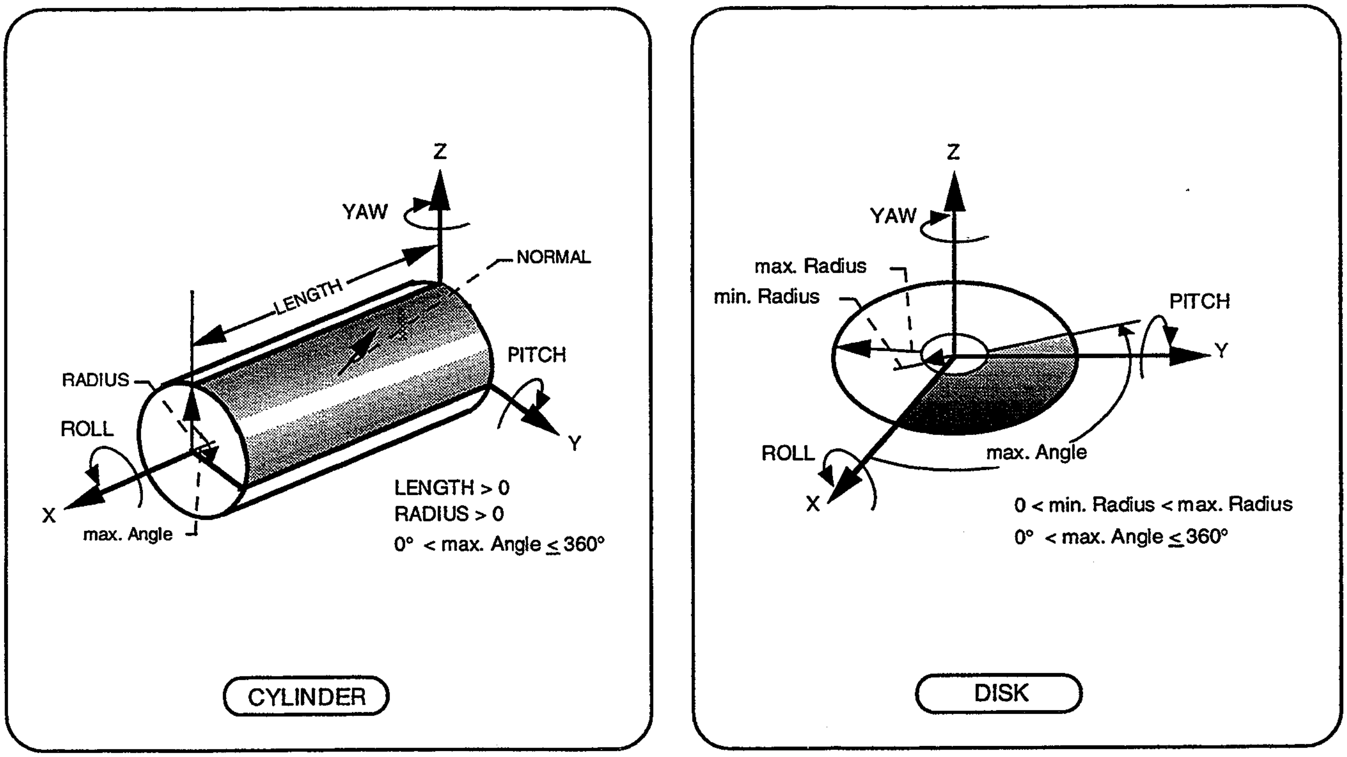

Figure 9. - Cylinder and disk surfaces primitives.

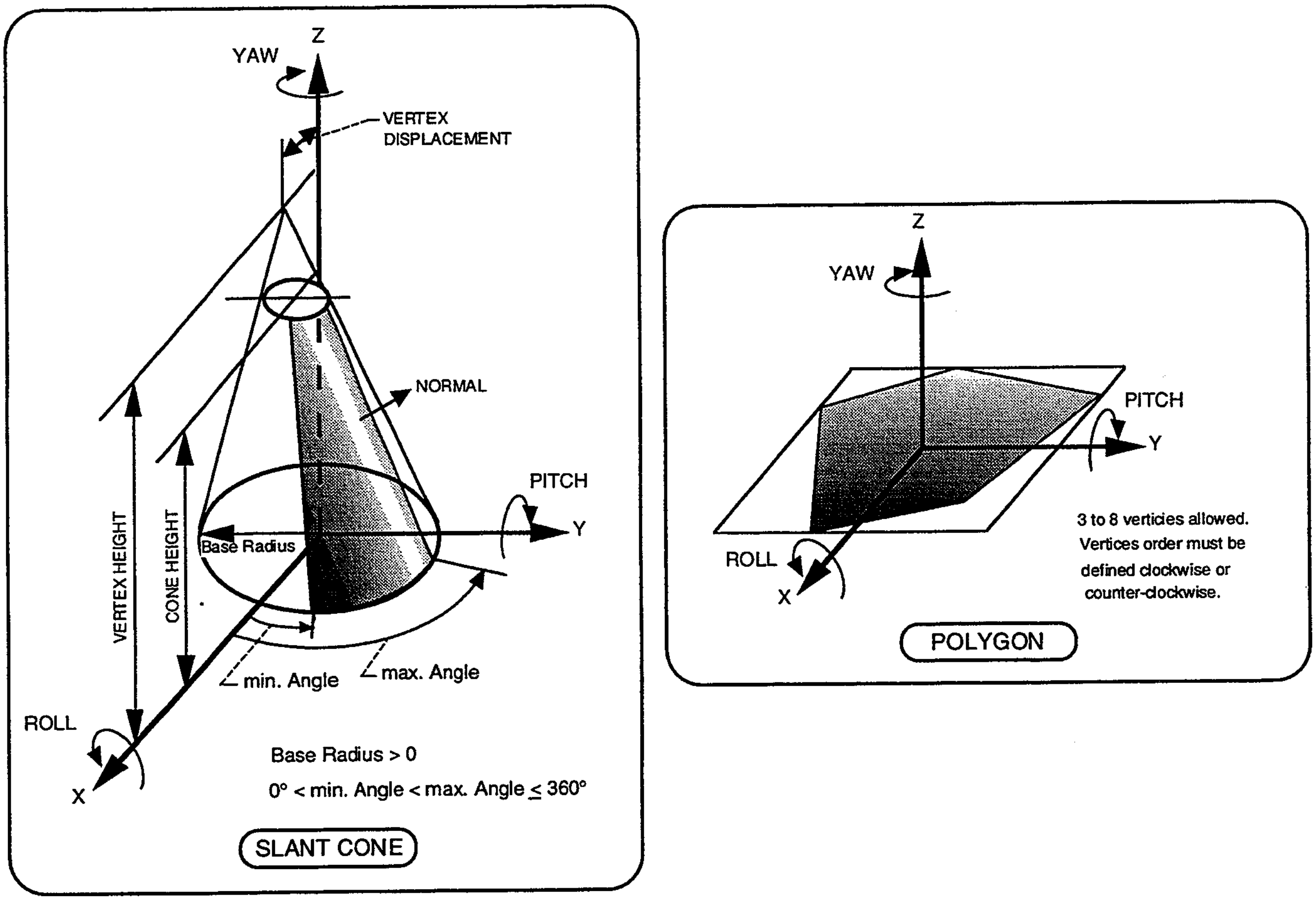

Figure 10. - Slant cone polygon surfaces primitives.

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