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Jet-Engine Test Cell Augmenter Performance

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The prime gauge of jet-engine test cell performance is the ability to provide repeatable results of the engine measurements. Based on this criterion, the U.S. military test cells are among the finest air-cooled turbojet test facilities in the world. But this high performance is being achieved at a relatively high cost. Switching from a round or obround augmenter tube to a square or rectangular tube will save up to 30% in construction and maintenance costs. Performance as well as cost, however, must be considered, and the objective of this work is to quantitatively assess the aerothermal performance of the rectangular tube. Round, square, and rectangular augmenter tubes of similar dimensions are compared using a mathematical model of the U.S. Navy's standard jet-engine test cell. Both the square and rectangular tubes are found to be acceptable alternatives.

Introduction

A JET-engine test cell (JETC) is an all-weather facility used for the postmaintenance testing of jet-engine performance. It is an enclosure designed to minimize noise exposure by test personnel and others in the vicinity.

Figure 1 is a drawing of a typical test cell. Briefly, the facility acts as a large eductor or fluid-driven pump. Engine exhaust gases, leaving the nozzle as a high-velocity, high-temperature, relatively small diameter jet, are directed into the augmenter tube. An expanding shear layer develops around the jet, pulling along a layer of cool ambient air. Momentum and energy are transferred to this augmentation air, decreasing the velocity and temperature of the jet.

Background

The concrete JETC was first constructed in the mid-1950s. Until the early 1980s, most of these facilities used water for cooling. By reducing the energy of the jet, the water both decreased noise and made the exhaust gases compatible with cell materials. Several problems were inherent in this type of test cell, however. The most severe was the fallout from the exhaust plume. The plume was composed of saturated steam, laden with unburned fuel and particulate matter, combined with exhaust gases consisting partially of NO_x and hydrocarbons remaining from incomplete combustion. The dirty wet fallout on adjacent buildings, aircraft, pavements, vehicles, and people was a nuisance. In addition, the plumes were highly visible. Activities in California, in particular, were being cited by air-pollution inspectors for violation of visible emissions regulations.

While the U.S. continued to test jet engines in water-cooled test cells, air-cooled facilities were being developed in Europe. The first U.S. air-cooled test facilities were hush houses (the engine remains mounted on the aircraft that is rolled into the test bay and secured) built by the U.S. Navy in the San Diego area in response to the California visible emissions problems. The hush house exhaust system design was based on the technology developed by the Swedish firm Granges NyBy Steel Company for test facilities built in Europe.

The test cell shown in Fig. 1 is the current standard U.S. Navy test cell. This facility is air cooled, with air entering through both a primary and secondary inlet. The secondary inlet provides additional cooling air without appreciably increasing engine intake air velocities or cell depression. The augmenter tube is circular; the flow is funneled into the tube through an obround section. Figure 2 is a photograph of the augmenter tube taken from inside the test bay. Exhaust gases are then diverted up the stack by a 45-deg ramp.

Cost vs Performance

The prime gauge of jet-engine test cell performance is the ability to provide repeatable results of the measurements of engine parameters with a minimum correction factor. Based on this criterion, the U.S. military test cells are among the finest air-cooled turbojet test facilities in the world.[1] But this high performance is being achieved at a relatively high cost, and, in the present cost-cutting climate, the best JETC may be too expensive to build.

There are a number of alternative approaches to the current designs that could be adopted to decrease the cost of the facility. Many features, however, also contribute to its high performance, and the effects of these design alternatives on the operation of the test cell are unknown. One approach is to switch from a round to a square or rectangular augmenter tube.

Rectangular Augmenter Tube

The augmenter tube, with a primary building cost as much as $1,500,000, is the most expensive component of the test cell. About half of this cost is the labor required to cut, align, and weld the round sections. In addition, the costs to maintain and repair the round tube could exceed $400,000 during a 20-year life cycle.[2]

The incorporation of the rectangular tube into the U.S. Navy's standard JETC design is expected to save $540,000 on the construction costs of each new facility. Much of these savings are attributable to decreased labor costs associated with the decreased parts tolerances required for a rectangular tube. The interchangeability of parts is an additional benefit not included in the preceding cost savings. Maintenance and repair costs are expected to decrease by a total of $260,000 over the operating life of the test cell.

Only a handful of JETCs employing square or rectangular augmenter tubes have been built. McDonnell Douglas Aerospace, St. Louis, Missouri has the only such facility in the U.S.; it is a hush house using a rectangular tube. There are a few in Europe[3]; for example, the Danish Air Force has one at Skrydstrup with a square tube, although with a forcing cone and secondary inlets provided inside the tube.

Performance as well as cost must be considered. McDonnell Douglas is satisfied with their hush house, but its aerothermal

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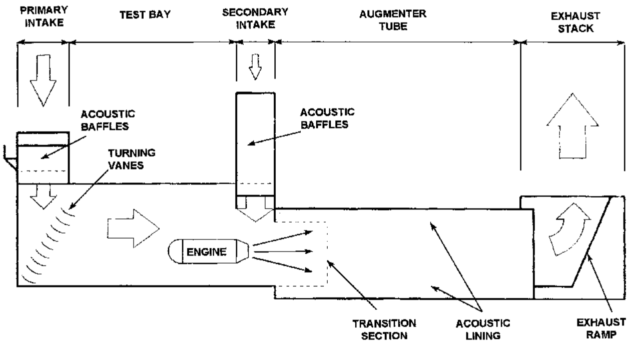

Fig. 1 Components of the standard Navy test cell.

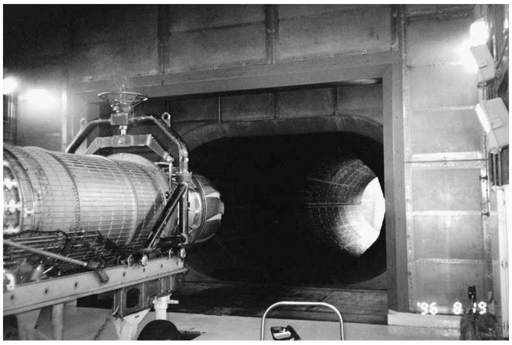

Fig. 2 View in test bay, looking aft.

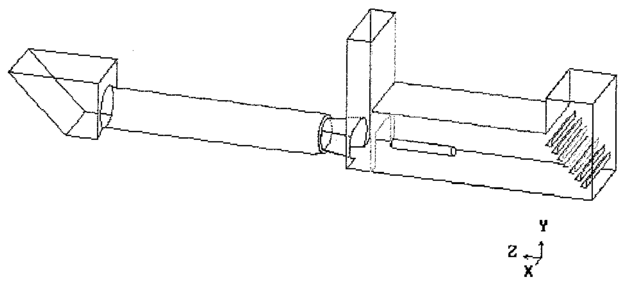

Fig. 3 Sketch of the standard U.S. Navy test cell showing the obround-to-round augmenter tube.

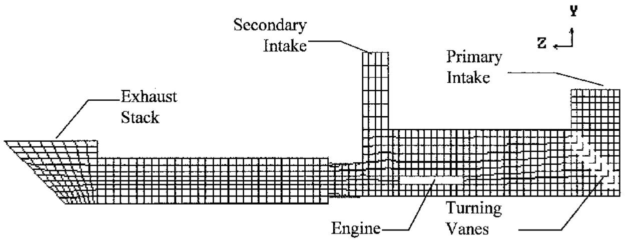

Fig. 4 Elevation view of JETC grid.

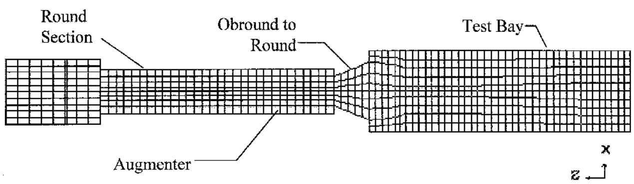

Fig. 5 Plan view of JETC grid.

performance has never been measured. Nothing has been published in the open literature assessing the performance of the European test facilities.

The objective of this work is to quantitatively evaluate the rectangular augmenter tube concept by calculating the change in the aerothermal performance of the U.S. Navy's standard jet-engine test cell when a square or rectangular tube is used in place of the 4-m-diam round tube.

Plan of Attack

First, aerothermal performance of the U.S. Navy's test cell will be mathematically modeled employing the PHOENICS computational fluid dynamics (CFD) code.[4]

The model will then be validated by simulating tests of different engines at different power settings and comparing predictions with measured performance.

Next, this model will be duplicated, but a square and then a rectangular augmenter tube for the round tube used in the standard test cell will be substituted.

Finally, using these models, the aerothermal performance of the U.S. Navy test cell with a round and a rectangular augmenter tube will be compared, specifically: 1) cell depression, 2) augmentation ratio ≡ (total flow–engine flow)/engine flow, 3) the flow split between primary and secondary inlets, 4) test bay air velocities, 5) engine back pressures, 6) augmenter tube wall temperatures, and 7) exhaust stack gas temperatures and velocities.

Test Cell Model

Figure 3 is a sketch of the U.S. Navy's standard test cell as it was modeled. The engine is approximated as a cylinder with a diameter equal to the diameter of the nozzle; therefore, the diameter of the engine changes slightly when different engines and different power settings are simulated. The length of the engine was set at approximately 6 m, but also changes slightly to axially position the nozzle of the engine being tested. The primary and secondary inlet baffles are not included; the decrease in cross-sectional flow area was accounted for by adding the appropriate flow resistance. The curvature of the primary inlet guide vanes is not modeled; a sharp 90-deg turn is assumed.

Overall, a $10 \times 17 \times 84$ grid is employed. Top and side views of the resulting JETC grid are shown on Figs. 4 and 5, respectively. The simulation of the inlet guide vanes can be seen on the side view. These figures also show how the grid necks down to fit the geometry of the obround to round section (that funnels the engine exhaust into the augmenter tube) and then expands into the round portion of the tube.

Boundary Conditions

The boundary conditions used in the test cell modeling are typical of CFD analyses:

1) The tops of the two inlets and the exhaust stack exit are set at ambient pressure and temperature.

2) The region surrounding the test cell is not simulated; the effects of weather conditions such as wind and rain are not considered.

3) The engine mass flow rate is directly input, treated as a sink at the intake and a source at the nozzle; the nozzle gas velocity and temperature are inputs.

4) The jet velocity is assumed constant across the nozzle; there is no velocity profile.

The jet is assumed to be air. The effects of the combustion products on flow properties are neglected.

Typical Predictions of the Model

Figures 6–8 are contour and vector plots showing predicted aerothermal conditions inside the test cell when testing an afterburning TF30 engine. Figure 6 shows air pressures along the side wall of the test bay, that is, this figure shows the cell depression. Note that the pressure varies by more than 2 cm of water inside the test bay. There is no single cell depression; it depends upon where the pressure is measured.

Figure 7 is a top view of the entrance to the augmenter tube, showing both velocities and temperatures. This is the obround

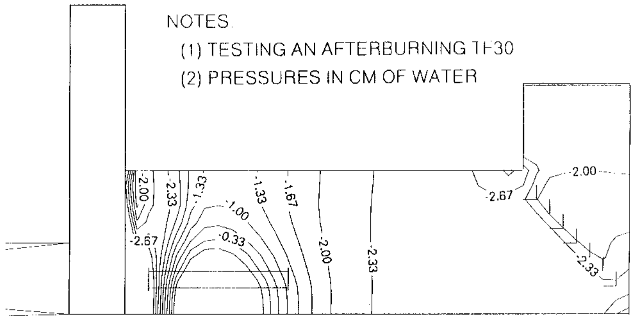

Fig. 6 Air pressures predicted along the side wall of the test bay.

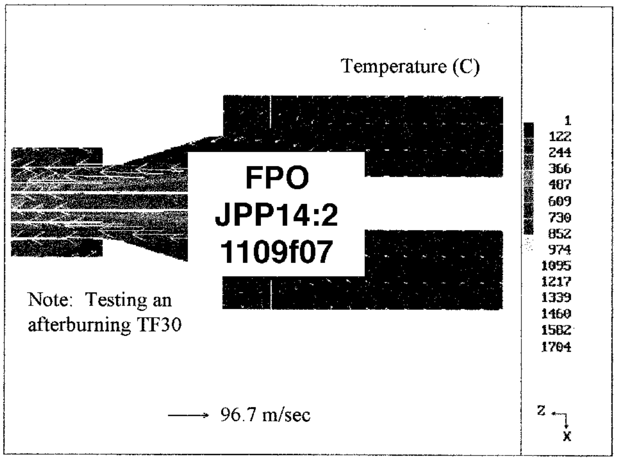

Fig. 7 Predicted flow characteristics through entrance to standard U.S. Navy augmenter tube.

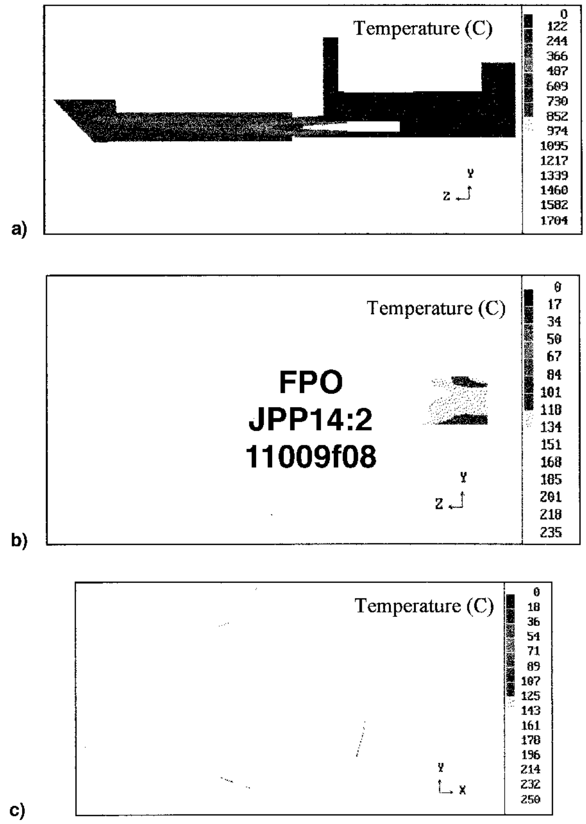

Fig. 8 Temperatures predicted throughout JETC while testing an afterburning TF30. Temperature along the a) centerline and b) augmenter wall, and c) near the augmenter exit.

to round section that guides the flow into the tube. There are recirculation regions on both sides of the tube following the abrupt expansion at the entrance. This explains the pressure drop and cool walls shown experimentally.

Figure 8a shows temperature contours throughout the test cell. For this example, ambient air enters at a temperature of 20°C. The engine is afterburning with a nozzle temperature of 1700°C. The profile of the jet is clearly shown. The jet is slowly rising as it progresses down the tube, a characteristic that has been observed experimentally. A pressure contour plot of the tube would show a low-pressure region, circumferentially, at the top of the tube entrance. Figure 8b is another contour plot, this one showing temperatures along the metal walls of the augmenter tube. These walls reach a maximum of 230°C. The jet reaches the walls about two-thirds of the distance down the tube. Figure 8c shows temperatures across the exit plane of the augmenter tube. The rising jet is clearly shown. The maximum temperature of the hot gases striking the ramp is about 250°C.

Validation of the Model

It would be foolish to use any type of simulation, mathematical or physical, without first assessing its accuracy. The most credible validation is to simulate a configuration of known performance and compare predictions of the model with actual (measured) values. This method was used here. The aerothermal performance of the U.S. Navy standard test cell is well documented, in particular, the facilities at the Naval Air Stations (NAS) Cubi Point, Republic of the Philippines[5] and Oceana, Virginia Beach, Virginia.[6]

The procedure followed was to adjust turbulence and flow restrictions to make the model accurately predict the aerothermal performance of the Cubi Point facility when testing an afterburning TF30-P-414 and then, retaining these settings, assess its accuracy by simulating other power settings, engines, and facilities, and comparing predictions with data. The JETC at Cubi Point was selected for the calibration because of the large and varied amount of test data available. The afterburning TF30 was the highest performance engine tested at this facility. The adjustments were minor. They consisted of the selection of the Chen and Kim turbulence model[7,8] and the addition of intake and exhaust stack resistances to achieve the proper mass flow rates.

The TF30 being tested at military power (100% power) at Cubi Point was selected for the first validation. The ambient temperature is the same. The engine mass flow rate and test cell augmentation ratio are about the same. The jet temperature is, of course, considerably cooler and its density greater. The nozzle diameter is also somewhat smaller.

The J52-P-408, running at military power and being tested in the facility at NAS Oceana, was also simulated to assess the accuracy of the model. This was a more difficult test for the model. The ambient temperature is cooler. Engine flow rates are lower, less than half the TF30 airflow. The test cell augmentation ratio is nearly double that associated with the TF30. In addition, by including a second test facility in the validation, the possibility of having modified the model to fit erroneous data has been reduced.

Table 1 provides an overall summary of the calibration and validation of the jet-engine test cell model, comparing predicted and measured performance. This table is nearly self-explanatory. Engine approach velocities are test bay air velocities 5 m directly in front of the engine inlet. The engine back pressure is the maximum gas pressure behind the nozzle. The augmenter exit wall temperature is the metal temperature at the downstream end of the tube.

At the top of Table 1 is the model calibration using an afterburning TF30 as the test engine. Stack resistances were adjusted until the predicted inlet flows and cell depression were equal to measured values. On this same table are validation summaries, comparisons of predicted and measured aerothermal performance when a TF30 and then a J52 are tested at

Table 1 Performance of U.S. Navy standard jet-engine test cell

	Primary inlet, kg/s	Secondary inlet, kg/s	Augmentation ratio	Cell depression, cm H_2O	Engine approach velocity, m/s	Engine back pressure, cm H_2O	Augmenter exit wall temperature, °C
			Calibration				
TF-30 A/B							
T-10 Cubi Point	525	400	7.1	−1.5	10.7	——	249–288
T-10 Oceana	575	431	8	−2	——	——	288–338[a]
T-10 Model	491	411	7.1	−2.3	12.2	27.7	223–268
			Validation				
TF-30 MIL							
T-10 Cubi Point	541	441	7.7	−1.8	11[a]	——	71–80
T-10 Oceana	575	480	8.5	−2	——	——	52–99[a]
T-10 Model	508	506	8.2	−3	11.6	76.2	74–90
J52 P408 MIL							
T-10 Cubi Point	459	395	11.9	−2	——	——	——
T-10 Oceana	445	418	12	−1.4	——	——	55–71
T-10 Model	449	449	13	−3.4	9.5	13.7	68–77
			Prediction				
TF-30 A/B							
Square (4 × 4 m)	500	402	7.06	−3.2	11.9	14.7	141–227
Rectangular (2.7 × 4.6	354	244	4.2	−3.3	10.1	9.7	217–330

[a]Temperature 0.5 m from wall.

military power. The agreement is excellent, within a few kilograms per second through both inlets. Particularly noteworthy are the augmentation ratios. The model correctly predicts JETC airflows induced by the J52, a much smaller engine than the TF30 used to calibrate the model.

The calibration of the model and complete results of the validation are presented in the report by Kodres and Murphy.[9] An assessment of the accuracy of the test cell aerothermal data is also included in this report.

Performance of Rectangular Augmenter Tubes

Two alternative augmenter tube configurations were examined. The first was the standard U.S. Navy test cell with a square tube installed. All test cell dimensions are identical to the standard configuration except for a square tube with side length equal to the 4-m diameter of the round tube. The cross-sectional area is, therefore, slightly greater than the area of the standard tube. The length of the tube was not changed. There is no transitional necking down the flow path into the tube; the augmenter tube starts abruptly beneath the back of the secondary inlet. Figure 9 is a sketch showing this configuration.

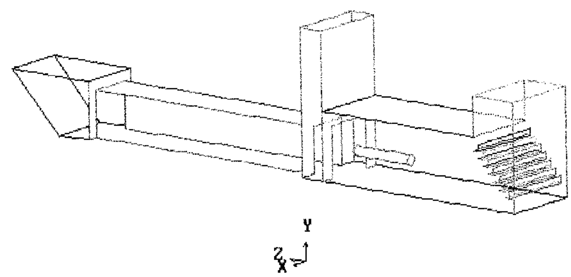

Fig. 9 Jet-engine test cell with square augmenter tube.

Typical predictions of the square augmenter tube model are illustrated in Figs. 10 and 11 for an afterburning TF30. Figure 10 is a top view of the entrance to the tube. Both velocity vectors and temperature contours are included in this figure. Note that the recirculation induced in the entrance to the round tube by the abrupt expansion has been eliminated. Compare Fig. 10 with Fig. 7. Note, however, the stagnation regions in the outer corners of the test bay and secondary inlet. Figure 11 is a side view showing the same two variables at the same location. There is a significant recirculation at the top entrance to the tube.

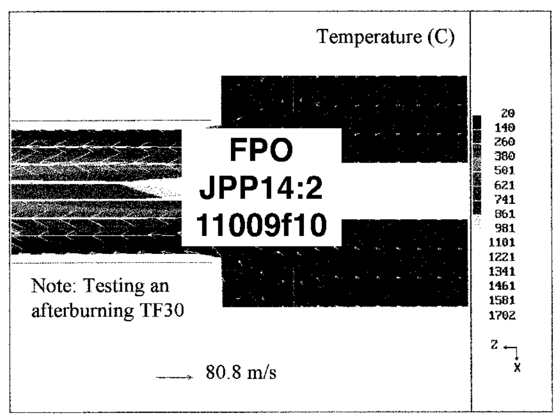

Fig. 10 Predicted flow characteristics through entrance to square augmenter tube (top view).

The second configuration modeled was the U.S. Navy standard test cell with a 2.7-m-high by 4.6-m-wide (9 by 15 ft) rectangular augmenter tube installed. Again, the length of the tube is not changed. The engine was lowered to make the nozzle centerline coincide with the center of the tube. This is the cross section of the augmenter tube used in the McDonnell Douglas hush house.

The aerothermal performance of test cells with square and rectangular tubes is assessed primarily by comparison with the standard U.S. Navy test cell rather than by using absolute values. If the performance of the standard JETC is acceptable and the relative performance of the facility with a square or rectangular tube is as good or better, the switch to one of these configurations will not create aerothermal problems.

Table 1 compares the aerothermal performance of the three configurations when testing the afterburning TF30. There is little difference in performance between the standard JETC and the square augmenter tube configuration. The inlet flow split is slightly different with a little more air entering through the primary inlet. The engine back pressure in the square tube test cell is lower. This would be expected; flow rates are similar

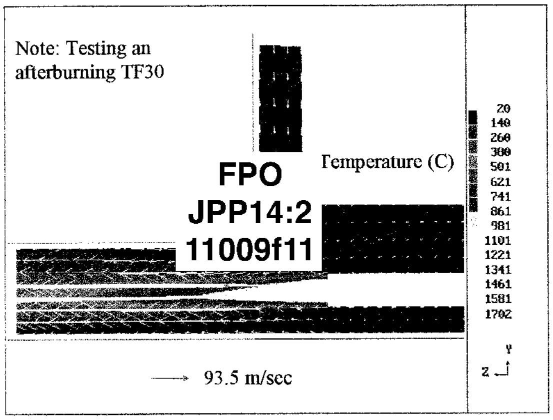

Fig. 11 Predicted flow characteristics through entrance to square augmenter tube (side view).

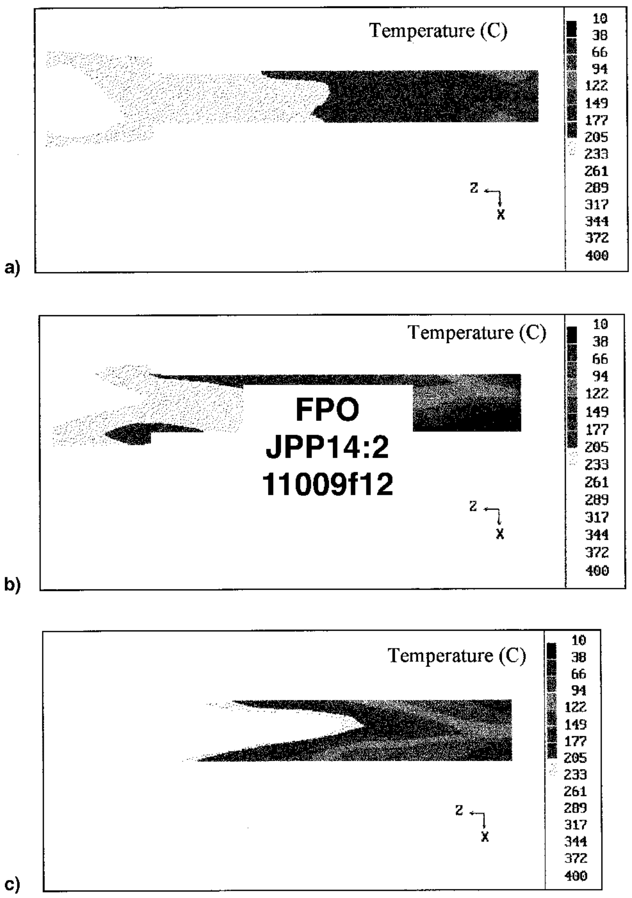

Fig. 12 Predicted augmenter tube top wall temperatures while testing an afterburning TF30: a) standard jet engine test cell, b) JETC with square augmenter, and c) JETC with 2.7 × 4.6 m rectangular augmenter tube.

and the cross-sectional area of the square tube is about 27% greater. The walls of the square tube are slightly cooler.

The cross-sectional area of the rectangular tube is approximately 8% smaller. Less augmentation air is induced. The augmentation ratio is 4.2, compared with 7.1 for the standard JETC testing the afterburning TF30. Because of the very low flow through the tube the engine back pressure is even less than induced by the square tube. The temperatures of the rectangular tube walls are considerably hotter, however.

Figures 12 and 13 are contour plots directly comparing the three configurations. Figure 12 compares augmenter tube temperatures along the top wall. The square tube is the coolest; the rectangular tube is the hottest. Figure 12 also shows the ramp temperature downstream from the top wall of the tube. The ramp behind the rectangular tube is reaching a temperature of 375°C.

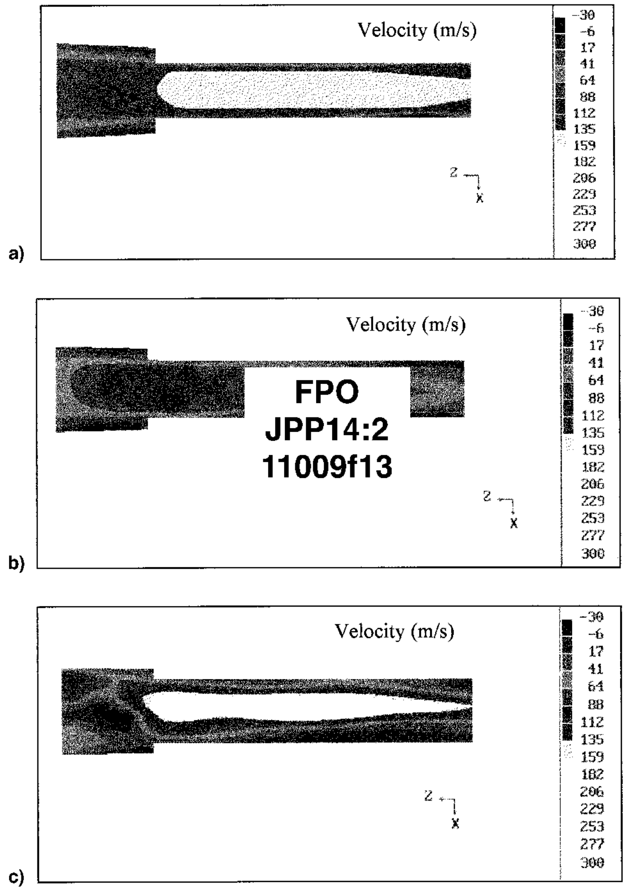

Fig. 13 Predicted augmenter tube velocities along top wall while testing an afterburning TF30: a) standard U.S. Navy test cell, b) JETC with square augmenter, and c) JETC with 2.7 × 4.6 m rectangular augmenter tube.

Figure 13 compares gas velocities along the top walls of the augmenter tubes. As would be expected, velocities along the walls of the square tube, with its larger cross-sectional area, are slower. Gas velocities along the walls of the rectangular tube are the highest. The significance of this variable is its correlation with noise; high-velocity gas flows along the tube walls are a noise source.[10,11]

Comments

Noise, as a dependent variable, was not included in this study. Noise is a complicated function of the flowfield, and there are major differences in the flow characteristics through the three test cells analyzed. Figures 12 and 13 illustrate some of these differences. Figure 14 shows these differences even better. Figure 14 is a side-view vector drawing comparing flows through the exhaust stack of each configuration. The only acceptable way of examining noise generation is to calculate absolute values, mathematically coupling noise to the pertinent variables. This approach must include validation in a manner analogous to the technique used for the aerothermal model.

Structural considerations were not included in this study. For example, vibration of the structure could eventually induce component damage. Other factors being equal, the rectangular tubes, with their structurally weaker flat sections, are more likely to experience vibration problems than the round tubes. Intuition suggests a correlation between vibration and turbulent kinetic energy.

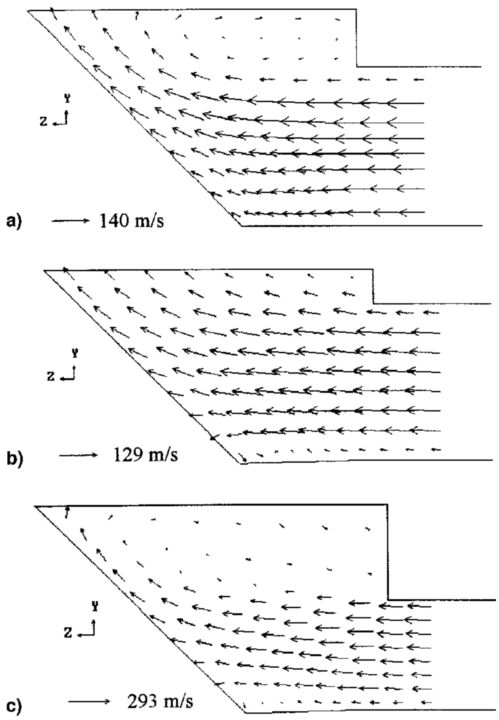

Fig. 14 Predicted exhaust stack gas velocities: a) standard U.S. Navy test cell, b) JETC with square augmeter tube, and c) JETC with 2.7 × 4.6 m rectangular augmenter tube.

Conclusions

Judged on aerothermal performance, both the 4-m-square and 2.7- by 4.6-m-rectangular augmenter tube configurations are acceptable alternatives to the 4-m-diam tube currently used in the U.S. Navy standard test cell. By all performance criteria, the square tube configuration functions at least as good. Wall surface temperatures are appreciably lower. It is reasonable to extrapolate these conclusions to test facilities with larger or smaller augmenter tubes, that is, jet engine test cell construction and maintenance costs can be decreased by switching from a round to a square augmenter tube of approximately the same size without any decrease in aerothermal performance.

Although not currently a serious problem, a 2.7- by 4.6-m-rectangular tube installed in the standard U.S. Navy JETC may experience unacceptably high wall temperatures when, in the future, higher-performance engines are tested. The short vertical dimension is the culprit; the expanding jet reaches the wall before it has been sufficiently cooled by mixing with the augmentation air. The tendency for the jet to rise exacerbates the problem. Increasing the height of the tube is a probable solution.

A comparison of rectangular and obround tube performance would be more significant. Hush houses are usually constructed with obround augmenter tubes for testing engines on multiengine aircraft. The jets do not discharge down the centerline of the tube. Often, more than one engine is running. It is perhaps reasonable to extrapolate the conclusions of these analyses even further: hush house construction and maintenance costs can be decreased by switching from an obround to a rectangular augmenter tube of approximately the same size without any decrease in aerothermal performance.

Acknowledgments

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