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3D NUMERICAL STUDY
OF
VELOCITY PROFILES AND THERMAL MIXING IN PASSIVE, INFRARED SUPPRESSION DEVICES FOR GAS TURBINE ENGINE DRIVEN GENERATORS

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ABSTRACT

A 3D numerical study was conducted and compared to experimental data from a venturi-type, infrared (IR) suppression device for exhaust ducting. The results, for a gas turbine driven generator, yield a novel design that is more compact and allows for shorter duct lengths, hence enabling associated camouflage netting to be lower in height and also reducing engine power loss due to reduced backpressure.

Venturi-type, infrared suppression devices are of interest due to low-cost, low-maintenance, duct-type construction. This information is reported to demonstrate the value of virtual prototyping and testing for design optimization, hence impacting system design and providing the best product to the soldier.

INTRODUCTION

Computational Fluid Dynamics (CFD) is becoming a increasingly popular tool for designing air-mixing types of IR suppression devices, for engine exhaust gases, that are integrated into the system design, so that space claim intensive, add-on kits are not required. Venturi-type, infrared suppression devices are of interest due to low-cost, low-maintenance, duct-type construction (Figure 1).

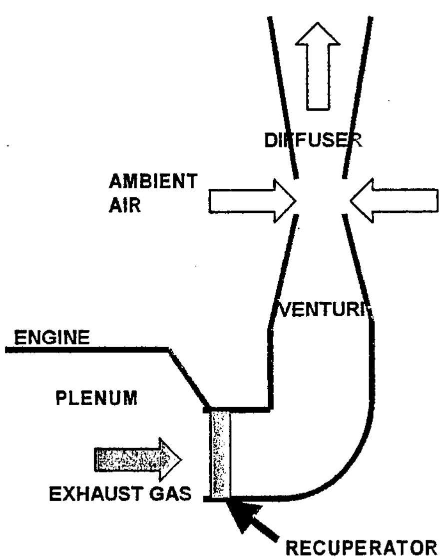

Figure 1. IR Suppression Device with Venturi for Drawing in Cool Ambient Air.

Space claim and engine power loss for venture-type, exhaust IR suppression devices are often the driving factors, over cost and weight, in design selection because venture-type, air-mixing designs are typically inexpensive and lightweight. Judicious use of lightweight and inexpensive ducting materials is common.

Space claim, due to duct length requirements. is typically driven by the length of the ducting required to accelerate the hot exhaust in the converging section of the venturi, so that 1) pressure of the accelerated, hot exhaust drops below atmospheric, hence, drawing in cooler ambient air and 2) the fluid is accelerated at a rate that does not cause excessive exhaust backpressure to the engine. Backpressure must be limited because the performance of the engine used in this study was degraded by backpressure following the equation:

$$\text{Engine power loss (hp)} = 0.367 * \text{backpressure (inches of H20 gage)} - 0.367 \quad (1)$$

Historically, Army generator sets for this application marginally pass the full-load, high temperature and full-load, high altitude tests without parasitic venturi losses (Howden, 1990 and Monaghan, 1990). Improvements to reduce pressure losses from exhaust driven, IR suppression devices can make the difference in passing and failing these tests. Additionally, engine fuel consumption decreases as exhaust backpressure increases.

Additional ducting is required after the convergence section of the venturi for proper mixing of ambient air with hot exhaust. In addition, this latter section of ducting is often a divergence section to 1) enhance mixing and 2) decelerate the flow to provide longer residence times to cool the mass of the individual particles that radiate to IR sensors. Hence, the main disadvantage of space claim, mainly the duct length, can be minimized if these converging and diverging sections can be integrated into system designs. Typically, the top of these IR suppression devices are designed to be flush with the camouflage netting (Walker, 1991). An integrated design could result in shorter duct lengths, hence enabling associated camouflage netting to be lower in height, perhaps hiding the weapon system more effectively.

This follow-on study was a continuation of the work by Blackwell (1991 and 1992) for the purpose of 1) including the more comprehensive 3-dimensional nature of the accelerating flow, 2) including the solution of the coupled energy equation for thermal mixing, 3) including smooth curved surfaces and 4) demonstrating an example of CFD modeling to converge upon an integrated design that reduces space claim and engine power loss. The CFD model used in Blackwell (1992) 1) was a 2-dimensional model, 2) did not include the energy equation, hence, thermal mixing was not included, and 3) was a single block code that did not have the capability of modeling the duct bends as smooth curved surface.. Rather, Blackwell (1992) used a stair-stepping approach to approximate bends in the duct. The 3D CFD code used in this study is a multi-block code with body-fitted coordinate capability for each block. Hence, the smooth bends of the exhaust geometry were more accurately modeled in this study.

Commercially available gas turbine and diesel engines are often used in military systems to avoid the high cost of development and low quantity production. Hence, such engine designs typically do not include IR suppression of the particles in the exhaust. Even with low particle concentrations in gas turbine exhaust streams, there is still a concern for exhaust IR suppression (Petraska, 1992). This is particularly true for heating secondary objects, such as fine soil particles which become airborne or overhead tree leaves and branches.

METHODS

Numerical Code Description

A numerical, conservative finite volume formulation was used to solve the steady state equations for mass, momentum, energy and the transport equations for turbulent kinetic energy and the dissipation of turbulent kinetic energy. The commercial code is licensed by AEA Technology under the name of CFX4 and has multi-block and body-fitted coordinate capability. For this work, discretation in space was conducted with the 1st order, Hybrid Upwind scheme for advective terms, which, upon convergence, were later switched to the 2nd order, Higher Order Upwind scheme. Also, the 2nd order, Central Differencing scheme was used for the diffusion terms. Velocity – pressure coupling, for continuity, was achieved using the SIMPLEC algorithm (Van Doormal and Raithly,1984) for collocated (non-staggered) grids, which was developed on the basis of the SIMPLE algorithm (Patankar and Spaulding, 1972) for staggered grids. Rhie Chow

Interpolation (Rhie and Chow, 1983) was used to smooth out checkerboard oscillations in pressure and velocity and yield an error on the order of the 4^{th} derivative. Pre-processing was conducted with MeshBuild from AEA Technology and post – processing was conducted with FieldView by Intelligent Light.

Boundary Conditions

Engine exhaust flowed from the manifold, to a large plenum and then through recuperator fins located at the inlet of the exhaust duct (Figure 1) (Blackwell, 1991 and 1992). This arrangement was expected to encourage uniformity of the velocity profile, hence, a uniform velocity profile was assumed. The inlet Reynolds number was $9.7x10^4$ and the exhaust gas temperature at the inlet was specified as Tin from measurements by Blackwell (1991). Turbulence intensity at the inlet was specified as 30% (Martin, 1989). Turbulent kinetic energy and the dissipation of turbulent kinetic energy at the inlet were calculated using the equations by Launder and Spalding (1972 and 1974).

A pressure of 0.0 gage, was specified at the boundaries of the ambient space. Rather than simply applying this boundary condition at the ambient air intake slot, the surrounding ambient space was gridded in order to increase the accuracy of the predictions of air being drawn into the venturi. The ambient space grid allowed for a more accurate model of the shear layer interaction at the ambient intake and also allowed for more accurate predictions of the pressure distribution in the vicinity of the intake. Ambient air was specified as 32 C (90F).

DISCUSSION

Baseline Simulation: M&S Comparison With Measurements

3D CFD simulations agreed well with predictions from Blackwell (1992). No IR suppression devices were installed for these baseline measurements.

Novel Integrated Design To Take Advantage Of Existing Geometry

A novel integrated design (Blackwell, 2002) was possible using the predicted pressure distribution resulting from the 90 degree mitre bend in the exhaust duct. An existing separation region that produces a low pressure could be used to draw in ambient air for IR suppression. An ambient air inlet installed in the low pressure region. This integrated design was modeled to predict the exhaust cooling and the engine power loss due backpressure.

Comparison of Exhaust Gas Temperature Reduction

The novel design reduced the maximum temperature of the engine exhaust gases to a lower value and with a lower space claim or duct length requirement than the venturi case (Figure 2). Assuming that the engine exhaust gas contains soot particles that exhibit black body radiation, the novel design reduces the emissive power of the soot particles by a factor of $T^4_{venturi}$ minus T^4_{novel} . The maximum local pressure drop between ambient air and the venturi ambient air intake was predicted to be a factor of 3.6 times larger than the pressure drop at the ambient air intake of the novel design. The ratio of the novel/venturi total surface area of the ambient intakes was 1.03. However, the mass flowrate of ambient air into the novel design was predicted to be a factor of 1.9 times larger than the ambient air flowrate for the venture case. The relatively low mass flowrate of ambient air in the venturi case is estimated to be due to the resistance of the ambient air velocity component normal to the intake slot due to the relatively large downstream momentum of the venturi jet. It is estimated that the high rate of temperature reduction, of the maximum exhaust gas temperature, in the venture case, was higher than that of the novel design because of higher levels of turbulent kinetic energy (TKE) generated by the venturi jet. The engine backpressure in the venturi case was of factor of 2.6 times larger than for the novel design. As a result, the engine power loss due to backpressure in the venturi case was 3.6 larger than for the novel design case. Hence, the novel design reduced engine power loss by 72%. The challenge with practically applying the novel design is that the ambient air intake is typically located 1) in close proximity to the engine and 2) inside of a generator housing. As a result, a short, well-insulated intake duct may be required.

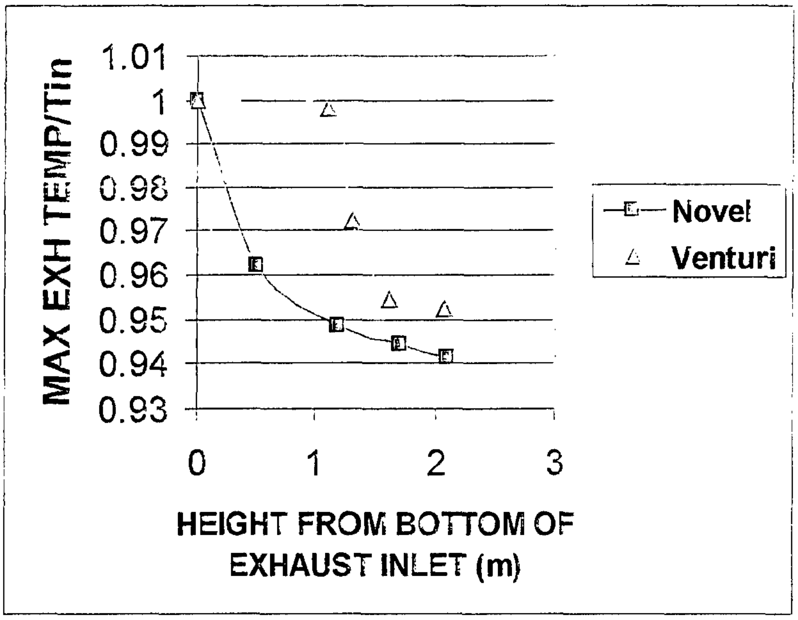

Figure 2. Comparison on Maximum Exhaust Gas Temperature as a Function of Height.

CONCLUSIONS

The novel design reduced the maximum temperature of the engine exhaust gases to a lower value and with a lower space claim or duct length requirement than the venturi case. Typically, the top of these IR suppression devices are designed to be flush with the camouflage netting (Walker, 1991), hence, the lower space claim of the novel design will enable associated camouflage netting to be lower in height, perhaps hiding the weapon system more effectively. Also, the novel design reduced engine power loss by 72% because of reduced exhaust backpressure. Future work will extend the comparisons in this paper to include the predictions of a venturi design by Haase (1990) and thermal mixing enhancement with the counter rotating vortices that were observed by Mattingly and Yeh (1991) in 90 degree bends in circular pipes.

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