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Numerical analysis of utilizing the given blast basket exhaust cluster for small size ramjet testing

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Abstract

This paper describes compatibility assessment of testing a small ramjet combustor with nozzle exit diameter of 208 mm in the given exhaust cluster which has been originally developed for subsonic gas turbine testing. Exhaust hot gas for analysis has mass flow rate of 14.2 kg/s with nozzle inlet total pressure Pt = 7 bar and total temperature pressure Tt = 2000 K. The fixed exhaust cluster contains the dry augmentor tube of Φ1m x 5m length, the deflector cone, the blast basket, and the exhaust stack, the nozzle-to-augmentor spacing is about 1 m. By means of Computational Fluid Dynamics (CFD) analysis, it was shown that the whole flow field runs continuously to the outside environment without flow reversal and the whole structure's surface temperature is less than 280 ^{o}C, which is safe for its materials and installation of a periscope. It was found that by inserting the small primary augmentor tube in tandem between the engine nozzle and the fixed augmentor tube, secondary cooling flow was boosted 4% more, promoting lower structural temperature and more uniform flow in the exhaust stack. Since the primary augmentor shielded most of supersonic jet from the surrounding environment, near-field acoustics analysis was conducted to examine sound pressure level inside the test cell to compare different configurations. Results suggested that due to the primary augmentor presence, peak noise at low frequency hearing range could be reduced up to 20 dB.

Keywords: *Engine test cell, Blast basket, Tandem augmentor, Ducted jet, Test cell acoustics*

Nomenclature

D – Augmentor tube diameter
L – Augmentor tube length
d – Nozzle diameter
l – Distance nozzle exit to augmentor inlet
L_b – Blast basket length
A – Augmentor tube's cross-sectional area
A_b – Blast basket's open area
D' – Primary augmentor tube diameter

1. Introduction

An exhaust cluster using a blast basket consists of the following basic components: an augmentor tube, a deflector cone, a blast basket, and an exhaust stack. Its working principles and design guidelines were presented in references [1] and [2]. The very first application of this configuration is for high bypass gas turbine testing, as mentioned in [2].

The role of an augmentor tube is to induce large amount of secondary cooling air flow from the surrounding environment to mix with small amount of hot exhaust gas. Cooling air ingestion and mixing process should be given sufficient space so that exhaust plume should fully occupy an augmentor's internal section and attach to an augmentor's wall prior to the end of an augmentor. Otherwise reversed flow of hot exhaust gas will be re-entry to the test cell [3] or flow may be drawn from the exhaust stack side [4].

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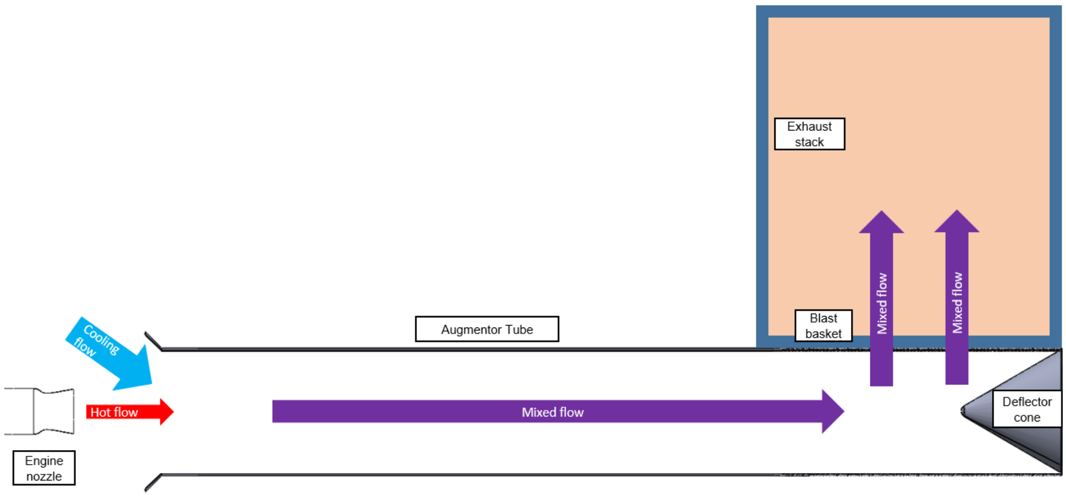


[redacted]Exhaust cluster components

Downstream of an augmentor tube, there are a deflector cone and a blast basket. The role of a deflector cone is to turn the already-well-mixed flow from axial direction to radial direction. A slender conical shape with 25° half angle was pointed out to offer less noisy and less velocity distorted flow inside an exhaust stack [5]. A blast basket having the same diameter as an augmentor tube is responsible to push 90° already-turned flow to an exhaust stack via a number of perforations on its surface.

A deflector cone - blast basket configuration has advantage of simple construction from bunched steel plate and lower low frequency sound from 3 to 6 dB compared to turning flow by ramp solution [6]. A blast basket has been guided by [6] to have open area of several times of cross sectional area of an augmentor tube.

This operating principle is called a dry test cell where cooling is based on secondary air only, no water cooled is needed. This configuration has pros of good flame observation if a periscope is installed downstream near a deflector cone while has cons of high level of noise at low frequencies [6].

Geometrical design of a complete exhaust cluster is governed by the following dimensionless parameters recommended in [1] and [6]:

- Main augmentor tube diameter (D) to nozzle diameter (d) ratio D/d

- Augmentor tube length (L) to augmentor tube diameter ratio L/D

- Distance from nozzle exit to augmentor inlet (l) to nozzle diameter (d) l/d

- Blast basket length (L_b) to augmentor tube length (L) ratio L_b/L

- Blast basket open area (A_b) to augmentor tube's cross sectional area (A) ratio A_b/A

Based on those parameters, the given test cell facility originally configured for small size turbojet testing has the following dimension: D = 1.0 m, L = 5.0 m, l = 1.0 m, L_b = 2.0 m, and A_b/A = 4.5 with 10 mm hole size in an equilateral triangle distribution and 54% openness ratio. The exhaust stack has 2.4 m x 2.4 m square section and 6.0 m height. More detailed performance description of this given configuration could be found in [7].

The given exhaust cluster now have been under assessment to see whether it could be used for testing of small ramjet combustor in direct connect testing mode. It means there is no other flow but only ramjet's nozzle hot exhaust gas and induced cooling flow interacting, see Fig. 1.

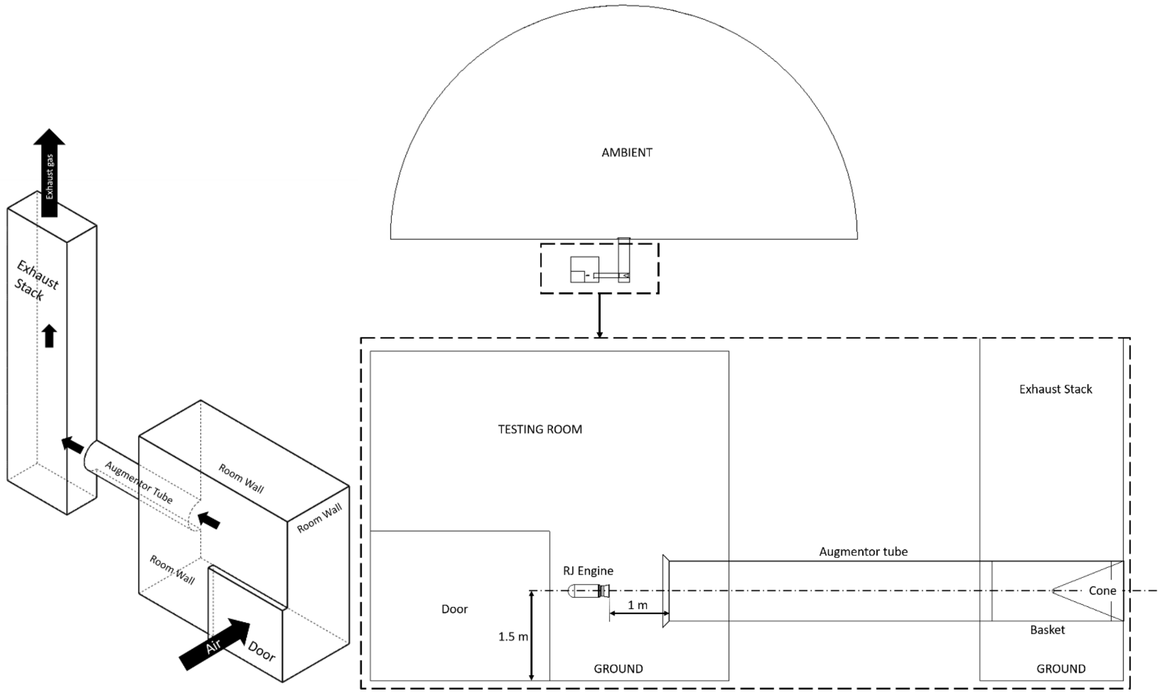
The test ramjet nozzle has exit diameter d = 208 mm having mass flow rate of 14.2 kg/s with nozzle inlet total pressure Pt = 7 bar and total temperature pressure Tt = 2000 K. These working parameters resembles flying condition of Mach 2.0 at sea level.

Moreover, attempts have been made to further ingest more secondary cooling air and improve aero-acoustic quality of the test cell.

2. Numerical method

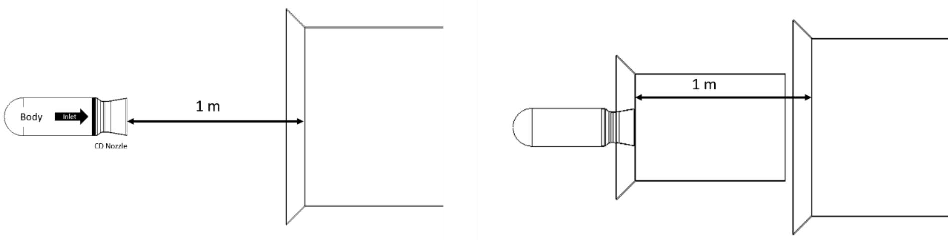
To predict test cell's internal aerodynamic behavior before construction, computational fluid dynamics (CFD) plays an important role [3]. A significant consideration in developing the computational model is the presence of numerous small holes and surfaces, which substantially increases the mesh number of elements and, consequently, the computational load. To address this challenge and streamline calculations, the approach involves constructing a three-dimensional model representing only half of the physical domain, leveraging symmetry to reduce the number of required mesh elements. This strategic simplification not only hastens the simulation process but also ensures that the features of the system are faithfully captured, laying the groundwork for robust analysis of airflow, temperature distribution, and pressure variations throughout the simulated environment.

The test cell forms the core simulation domain for this study. Its dimensions are 12 meters long, 10 meters wide, and 5.5 meters high, with the center line of the augmentor tube positioned 1.5 meters above the ground. The access door serves as the ambient inlet, supplying cooling air to the augmentor. The exhaust stack is designed with a square cross-section measuring 2.4 by 2.4 meters, and it also extends 1.5 meters below the tube's center line. This layout produces a ground effect that notably influences how air flows through the stack.



[redacted]Computational domain for steady state investigation

The ramjet details were eliminated since they have no influence on test cell's flow quality, only nozzle with exit diameter of 208 mm was modeled. The nozzle is a converging-diverging (CD) nozzle, with the cross section before the converging section serving as the inlet plane for the hot jet air from the engine. Its arrangement is depicted in Fig. 3 below.

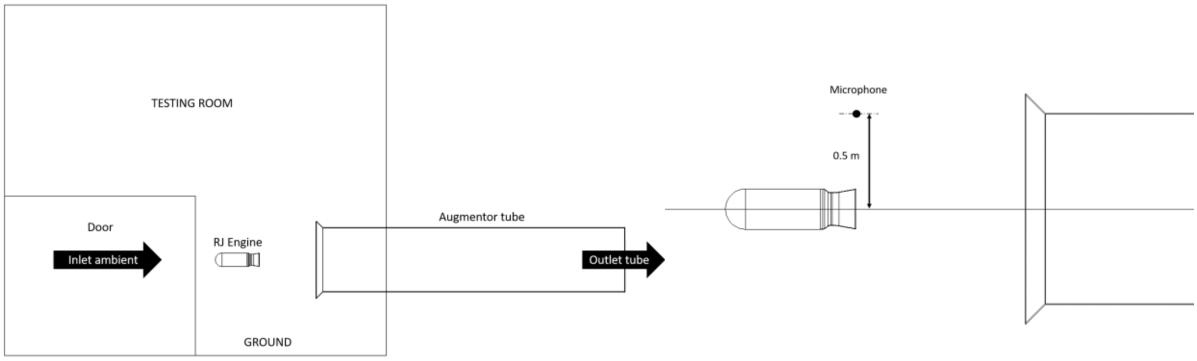


[redacted]Ramjet nozzle and its relative position. Left: 1st case with main augmentor only. Right:2nd case with the primary augmentor tube insertion.

Investigations were divided into 02 steps: the first one is steady state type to examine aero-thermal characteristics and the second one is transient type for acoustic analysis.

For the steady-state investigation, which focuses on the mixing of the hot exhaust stream from the ramjet nozzle with the induced cooling air, the full system configuration is utilized. A large hemispherical area at the stack's outlet represents the surrounding atmosphere. Ambient condition as follows: both inlet and outlet pressure being 1 atm, inlet temperature being 300K. To reduce computational workload, the simulation domain is halved, taking advantage of symmetry, as the phenomena under study are considered symmetric. The model is incrementally modified to include or exclude tubes and mini tubes, allowing for a thorough assessment of their impacts.

For acoustic assessment, the case becomes transient, which allows for further simplification of the model. In this case, there is no need to evaluate flow mixing or component surface temperatures downstream of the augmentor main tube. The computational domain is thus reduced to the region near the outlet end of the augmentor tube. Here, the tube's cross-section serves as the outlet boundary, with its pressure outlet conditions captured from the steady-state simulation profiles. To capture the pressure changes over time, a spherical microphone with a diameter of 30 mm is positioned 0.5 m from the tube's center line, which is similar to experimental set-up in [8].



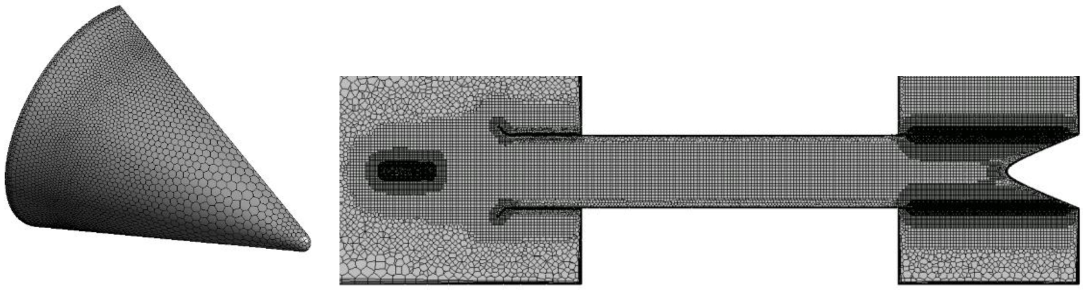
[redacted] Computational domain and microphone position for transient acoustic analysis

For the steady-state problem, the domain employs a poly-hexa core mesh, which significantly reduces the number of elements while effectively capturing complex surfaces and small geometries [3]. Within the domain, the exhaust plume expands and decelerates in the regions between the nozzle and the deflector cone and undergoes sharp directional turn through blast basket's perforations.

To ensure mesh consistency in these critical areas, two bodies of influence (BOI) are established: BOI 1 inside the augmentor tube with an element size of 20 mm, and BOI 2 within the exhaust stack at 40 mm. The blast basket is meshed with elements sized at 1 mm for the holes and 5 mm along the cylinder surface. The ramjet body and nozzle feature mesh elements ranging from 1 to 5 mm, while remaining surfaces are discretized with elements from 1 to 1000 mm, using a uniform growth rate of 1.1. With these settings, the mesh typically comprises 18–20 million cells. Mesh quality is maintained by ensuring the skewness remains below 0.95 and the orthogonality above 0.05. Pre-simulation studies have shown that, above 14 million elements, the results become mesh independent. Key quantities analyzed for mesh-independence include flow rate, cone surface temperature, stack outlet temperature, and velocity distribution fields.

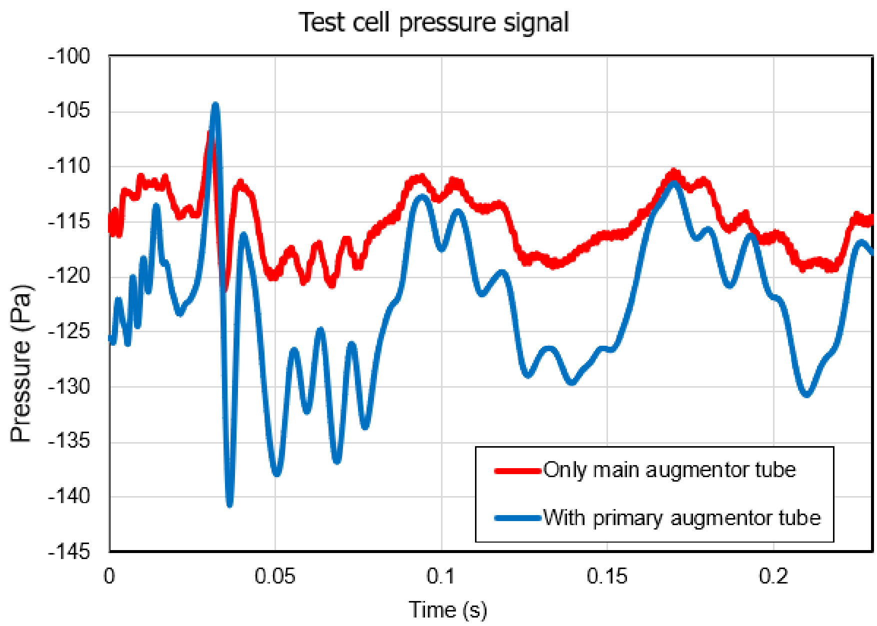
For the transient case, the meshing method is similar to the above. But instead of the BOI domain for the stack, the BOI domain is used to cover around the microphone with a size of 2 mm, and the maximum size for free cell is 200 mm. The number of elements after meshing process usually falls between 8-10 million elements. Pre-survey CFD simulation have shown that the number of elements above 6 million the results are independent from the mesh size.

The three-dimensional Navier-Stokes equations are solved by using the commercial ANSYS FLUENT. For turbulence modelling, both the Reynolds-Averaged Navier-Stokes (RANS) and Unsteady Reynolds-Averaged Navier-Stokes (URANS) approaches are employed, allowing the simulation to capture steady and transient phenomena within the flow in each case. The turbulence closure is handled using the realizable k-epsilon model, combined with Enhanced Wall Treatment to ensure accurate resolution of the near-wall regions—an approach recognized for its efficiency and reliability across a range of research applications and experiences. This method balances computational speed and solution accuracy, making it well-suited for complex simulations such as those involving ramjet exhaust and augmentor interactions. Throughout the domain, the working fluid is modelled as an ideal gas, which is standard practice for high-temperature, high-velocity jet flows where real gas effects are negligible.



[redacted] Mesh at cone and inside augmentor tube domain

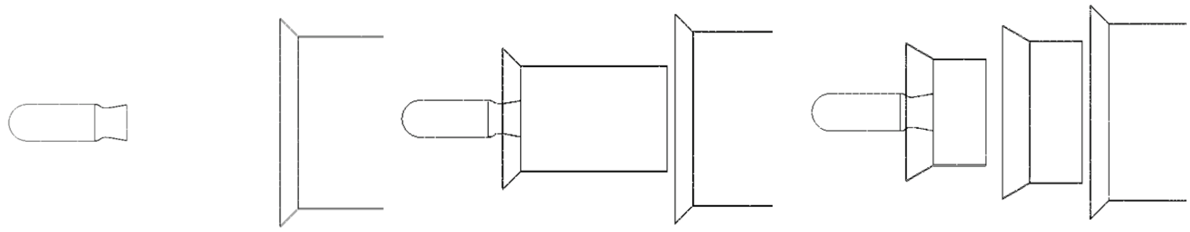
For the transient case, jet noise velocities can approach Mach 2, necessitating a cell dimension near the microphone of approximately 2 mm. To accurately capture rapid changes, the simulation uses a time step of 1 microsecond (1e-6 s), with a total investigation period of 0.2 seconds sufficiently cover several fluctuational cycle (figure below). Time step is based on cell size divided by highest velocity possible, i.e., 2 mm divided by approximately 1500 m/s. This setup enables detailed analysis of the dynamic behavior and noise characteristics as conditions evolve over time, ensuring both spatial and temporal resolution are sufficient for reliable results.



[redacted] Investigation period of test cell pressure signal for near-field noise analysis

3. Design variants

The basic configuration inside the test cell used originally for gas turbine engine testing contains only the engine nozzle and the main augmentor tube. This basic configuration worked satisfactorily in terms of thermal and aerodynamic aspects, as explained below. However, several design variants were attempted to improve augmentation ratio and acoustic aspect, which becomes more important as ramjet velocity gets higher than that of gas turbine. Since things were fixed, the only open space to be modified is the 1 meter distance between engine's nozzle exit and main augmentor tube's entry plane.



[redacted]Three variants of augmentor tube design

Inspired by works by Sapp et al. in [9] multiple concentric augmentor tube in tandem were designed and tested in CFD environment. It was found that tandem augmentor configuration where a smaller size - primary augmentor tube upstream of a larger – main augmentor tube can boost overall augmentation ratio, i.e., inducing more cooling air. On another hand, the double augmentor configuration was widely applied in jet engine test cell from small engine to fighter class engine, such as [10], [11].

In [9], it was assumed that spacing from nozzle exit to primary augmentor would have little effect to performance, so the primary augmentor's entrance plane is set to be coincident with nozzle exit plane. Also, the primary augmentor's exit plane is set to be ahead of the main augmentor's entrance plane by 0.15D, here it is 150 mm. Primary augmentor tube's diameter D' was chosen to be 600 mm, as [1] recommended D'/d should be at least as 3. This paper is not to pursue of the optimum design but to analyze the working concept of various designs. In addition to the double augmentor tube configuration, it was designed the triple augmentor tube configuration for comparison.

All designs were analyzed in terms of augmentation ratio, temperature distribution, velocity distribution and acoustic aspect.

4. Results and discussion

4.1. Augmentation ratio

Here are results regarding hot flow and induced cooling flow from CFD analysis:

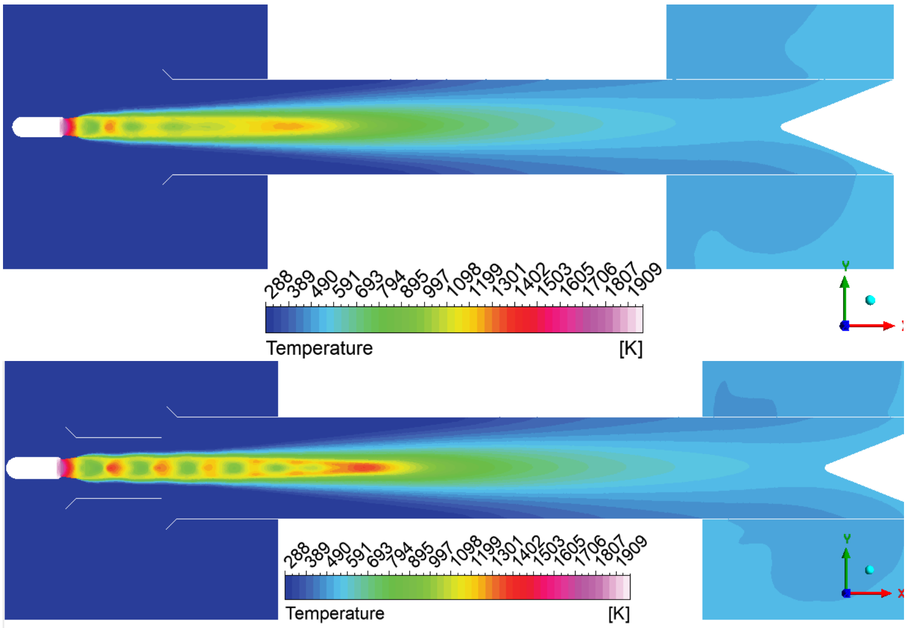
Table 1. Mass flow rate analysis

Cases	Hot flow (kg/s)	Cooling flow (kg/s)	Augmentation ratio
Main augmentor tube	14.2	92.0	6.48
Double augmentor tube	14.2	95.4	6.72
Triple augmentor tube	14.2	95.6	6.73

It was shown that by adding the primary augmentor tube, augmentation ratio was boosted ~4% while adding more augmentor tube did not improve noticeably. Compared to usage of turbojet testing, this ramjet testing attracts more 26-30% more cooling flow.

4.2. Temperature distribution

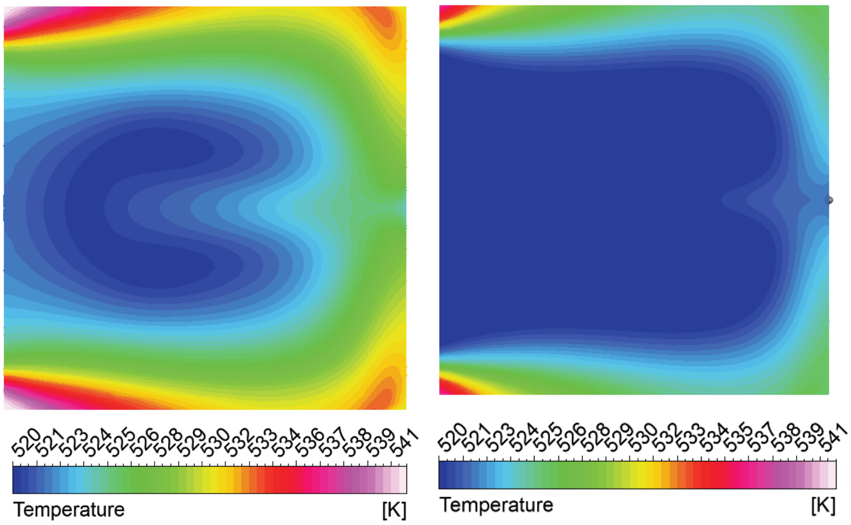
One of important aspect of exhaust cluster design is that cooling air must be well mixed with exhaust hot gas such that exhaust plume is well diluted to not harm steel structure. In this aspect, all 03 configuration met expectation. All exhaust plume's near wall temperatures did not exceed 550 K, which is safe for intermittent working of galvanized steel structures.
At the end of the main augmentor tube, plume's temperature for the basic case is ~490 K while those of double and triple augmentor tube are almost the same ~464 K. Thus, it could be concluded that while having more complex structure, the triple augmentor did not contribute noticeable aero-thermal benefit. Therefore, the double tandem augmentor tube configuration is chosen.



[redacted]Gas temperature distribution in symmetry plane

In overall, it can be observed that the double augmentor tube configuration keeps the high temperature region longer, but in the end touching the deflector cone, centerline's temperatures are almost the same. Augmentor's wall temperatures, in contrast, is lower in case of double augmentor.

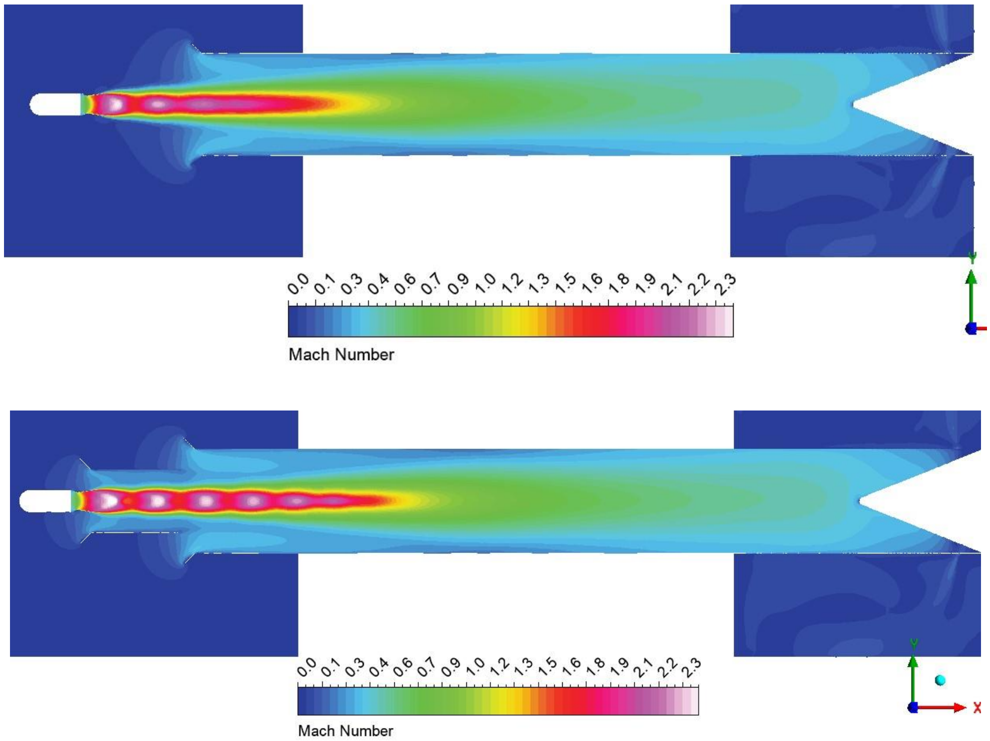
At the exhaust stack's exit plane, average temperature of the double augmentor tube case is lower as well, thanks to higher augmentation ratio.



[redacted]Temperature contours at the exit plane, exhaust stack (right: double augmentor tube case)

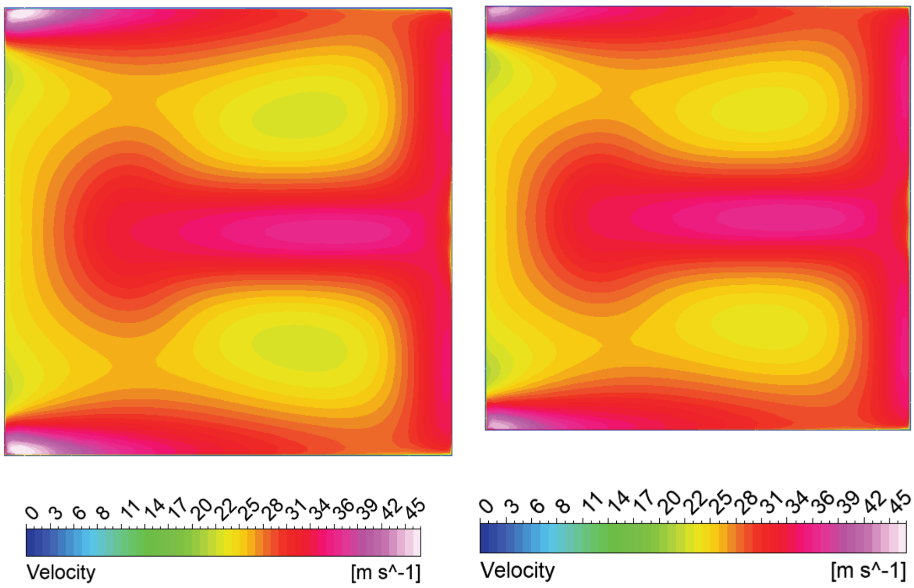
4.3. Velocity distribution

Results showed that in both configurations, at the end of the main augmentor tube, exhaust plumes fully occupied its internal space and there is no flow reversal. As approaching the deflector cone and the blast basket's internal side, flow decelerated quickly to incompressible type. The blast basket worked as expected, where flow velocities reduced several times along its perforated surface. This effect further lower far-field noise.



[redacted] Mach number distribution on the symmetry plane

Again, on the exit plane of the exhaust stack, the double augmentor tube configuration mixed flow better to have lower peak velocity and lower velocity distortion, 97% versus 112%, where velocity distortion is defined in [17]. This lower peak velocity and more uniform distribution will contribute to lower far-field noise outside of the test cell.



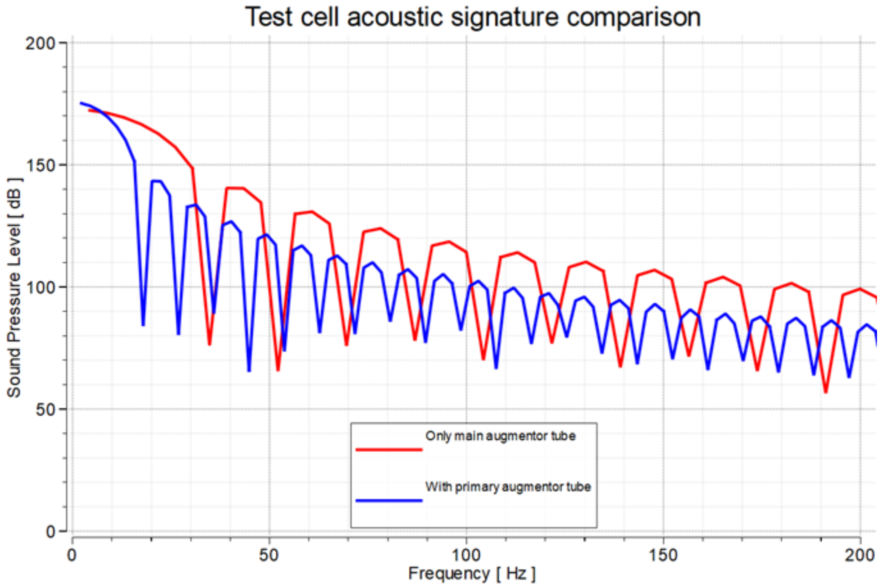
[redacted] Velocity contours at the exit plane, exhaust stack (right: double augmentor tube case)

4.4. Acoustic aspect

Perhaps this is the most significant contribution of the tandem augmentor tube to the test cell's working environment. As jet speed increases from gas turbine to ramjet testing, so does jet noise. By shielding high speed exhaust jet from the surrounding, it seems obvious that the primary augmentor tube can partially isolate this noise source.

By applying the numerical method presented above, noise analysis agreed with results from [6] that most of jet noise are around and less than 100 Hz, i.e., low frequency noise. Moreover, it pointed out that the tandem augmentor tube can reduce about 20 dB of noise in hearable region above 20 Hz. This is significant for small size test cell.

Without shielding by the primary augmentor tube, at 0.5 m distance from the engine nozzle, noise could reach up to ~165 dB at 20Hz frequency. It is within dangerous level. Therefore, relieving it to ~145 dB by a simple device like the primary augmentor tube's wall is meaningful. This CFD works may not be as accurate as experimental measurements, but it could be exploited as a predictive tool showing the trend. Here the trend is that the primary tube's wall can shield supersonic jet noise to the surrounding significantly.

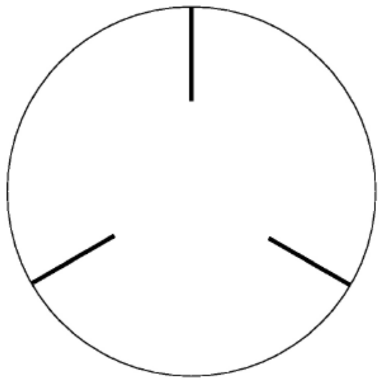


[redacted] **Sound pressure level comparison**

Surveys were conducted to look for further improved noise absorption mechanism for the primary augmentor tube. One potential candidate is the perforated acoustic liner similarly applied in jet engine [12]. However, since other experimental sources agreed with the CFD above that test cell noise is low frequency noise which maximum sound pressure level occurs at frequencies around 100 Hz [6], the perforated liner method is impractical to implement due to prohibited honeycomb depth and narrow absorption bandwidth [12].

However, despite of gaining noise benefit in the perpendicular direction, several experimental data pointed out that understanding of jet noise is far from complete understanding [13] and CFD alone could not detect all complex flow behaviour. Within the primary augmentor tube, there is a ducted supersonic jet with high and broadband disturbance level. So, there might happen resonance between jet and an augmentor tube, producing screech tones, [13] and [14].

Fortunately, here is empirical evidence that the higher jet temperature, the lower screech tone intensity [15]. Regardless of that, in case of resonance between supersonic jet and a primary augmentor tube, a simple solution proposed by Tam [16] is to use triple longitudinal fins. Its mechanism is to break up helical or flapping mode of the jet from forming.



[redacted] Triple longitudinal fins to disallow flapping duct modes formation [16]

5. Conclusion

Results showed that the exhaust stack concept using blast basket, which has been originally developed for high bypass jet engine testing, could be effectively repurposed for testing of small size ramjet engine as well. Hot exhaust gas and induced cooling air flow were well-mixed to uniform temperature exhaust plume and were fully attached to augmentor tube's internal wall without any flow reversal. The blast basket turned axial flow to vertical direction and further decelerated it several times into the exhaust stack before discharging into the surrounding environment.
Furthermore, by arranging the primary augmentor tube upstream, in tandem with the given main augmentor tube, secondary cooling air flow was ingested more 4% and peak sound pressure level is considerably lowered up to 20 dB in near-field thanks for shielding effect of hot exhaust gas from the test cell environment. However, this ducted supersonic jet may cause screech tones; therefore, anti-screech method such as triple longitudinal fins should be prepared.
Adding another augmentor tube to form triple augmentor tube configuration will complicate structure without showing beneficial aero-thermal effect.

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