LAPCAT II INTAKE STARTING TESTS

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ABSTRACT

As part of the EU LAPCAT II programme, the University of Oxford tested and analysed a 1:100 scale Scramjet intake for starting capabilities. Tests were performed at a Mach 7 condition in the Oxford Gun Tunnel, with a unit Reynolds number of $20x10^6$/m. The model was instrumented with 61 measurements of wall static pressure throughout the intake and isolator, 24 thin film heat transfer gauges on the end of the intake and start of the isolator and video Schlieren of the cowl closure region of the inlet. A comparison of the intake wall pressures showed that the LAPCAT MR2 intake exhibited higher intake pressures than the tests completed by DLR using the same geometry and flight condition. Analysis of the Schlieren and the pressure data has revealed that the most likely cause of the higher inlet pressures is a small separation that originates from the corner at the mid-plane of the intake. With a reduced exit area 25.4%, which is analogous to an increased back pressure from the combustor, a normal shock sits stable in the isolator. At extreme AoA (i.e. above +4°), the external part of intake shows a very low pressure as it is being processed by a Prandtl-Myer expansion, resulting in low pressure in the isolator with minimal external compression achieved. Testing showed that the intake was capable of self-starting across the range +4 degrees to -12 degrees AoA. This was observed through rapid start-unstart or buzz on the intake once a sufficient level of blockage was applied. Body wall pressure, body heat flux and crotch area Schlieren for various times throughout the inlet start/unstart/start process will be presented and discussed in the final paper. The presence of intake buzz confirms that this geometry is self-starting.

1. INTRODUCTION

Reduction in transit times for long haul flights could drastically change the civil aviation market. To achieve this, supersonic to hypersonic transportation vehicles and associated engines are required. One potential configuration is a dual mode ramjet/scramjet that can operate over a large Mach number range. However, currently many of the components require further research and development to access the viability of such a concept. As each component is highly dependent on associated components (*eg.* intake is dependent on vehicle forebody), true evaluation requires the full vehicle to be designed in an integrated system.

The LAPCAT II programme aimed to develop a concept for a high speed civilian transportation cruise vehicle, feasible of flight from Brussels to Sydney in less than 4 hours [1]. The programme was split into two, with a vehicle being powered by a dual mode scramjet at Mach 8 (LAPCAT MR2), the other being powered by an inter-cooled gas turbine at Mach 5 (LAPCAT A2). As pictured in Fig. 1, the MR2 vehicle is a liquid fuelled waverider based vehicle, with the engine operating from Mach 4.5 to 8. The intake in particular was mounted on top of the waverider, with an elliptical capture area of 12 x 4 m, with a contraction ratio of 7.7.

Figure 1: LAPCAT MR2 Vehicle (taken from [2]).

The objectives of the University of Oxford in the EU LAPCAT II was to test the Mach 8 mixed compression intake for sensitivity to combustion induced back pressure using area blockage and to test the self-starting limits of the intake. It was also decided to test this capability at angle of attack. As the intake had been Mach number scaled for the DLR HEG tests, a Mach 7 condition was chosen with a Reynolds number which matched the DLR H2K tests [2]. This paper describes the experimental setup including a description of the Gun Tunnel facility, flow condition applied in testing, intake model design and manufacture and instrumentation/data acquisition applied in the testing.

2. EXPERIMENTAL SETUP

2.1. Oxford Gun Tunnel

The Oxford Gun Tunnel is a cold impulse facility, which produces approximately 25 ms of quasi-steady flow. The facility was originally installed at the Southwell labs in the 1970's, originating from Bristol Sidley engines. As the Osney Thermofluids lab had recently moved locations, the facility had been recommissioned for LAPCAT II tests and required several upgrades to the HP air system. Fig. 2 shows the installation of the facility in the new building.

Figure 2. Photo of the University of Oxford Gun Tunnel recommisioned in the Southwell Building.

Fig. 3 shows a schematic of the facility including overall dimensions and critical properties. It operates by compressing the test gas through a fast moving piston creating a series of shock waves as it moves towards the end of the barrel, with the test gas then passed through a converging/diverging contoured nozzle into the test section, and eventually into the dumptank. To drive the piston, the reservoir is filled with high pressure dried air and the breech is filled to an intermediate pressure. The breech is separated from the barrel and the reservoir by two scored aluminium diaphragms (3 mm thick, 0.4 mm score depth). The barrel is filled with the test gas at pressures typically near atmospheric, with the piston initially just downstream of the breech. To initiate the test, the breech air is vented to atmosphere, creating enough pressure difference to rupture the aluminium diaphragms, allowing the reservoir gas to vent behind the piston in the barrel. The facility currently has two nozzles, a Mach 7 and 8 nozzle, with the Mach 7 nozzle used in the LAPCAT MR2 testing.

2.2. Mach 7 Flow Condition

Although lower total pressure conditions were used in the commissioning of the model, a single Mach 7 condition was used in testing of the LAPCAT MR2 scramjet intake. The initial fill conditions for the shot were 7.3 MPa in the reservoir, 3.7 MPa in the breech and 2.5 bar of nitrogen in the barrel (nitrogen used to ensure zero condensation once gas is expanded). The nominal flow properties of the core flow are shown in Tab. 1, which has a nominal unit Reynolds number of 20 million/m. Using the test period averaged measurement of stagnation pressure and derived stagnation temperature, the flow conditions at nozzle exit are calculated assuming isentropic expansion to the average Pitot pressure across the core flow and test period. The wall to freestream gas temperature was 0.225, which would give an equivalent flight wall temperature of 1100 K, which is a reasonable approximation.

In each shot, stagnation pressure is measured 148 mm from the throat of the nozzle using a Kistler 601A piezoelectric transducer, with a 150 kHz bandwidth and 250 bar max pressure. A time history of this measurement is shown Fig. 4. This shows the series of shocks/expansions in between the tube end wall and the moving piston. After this process settles

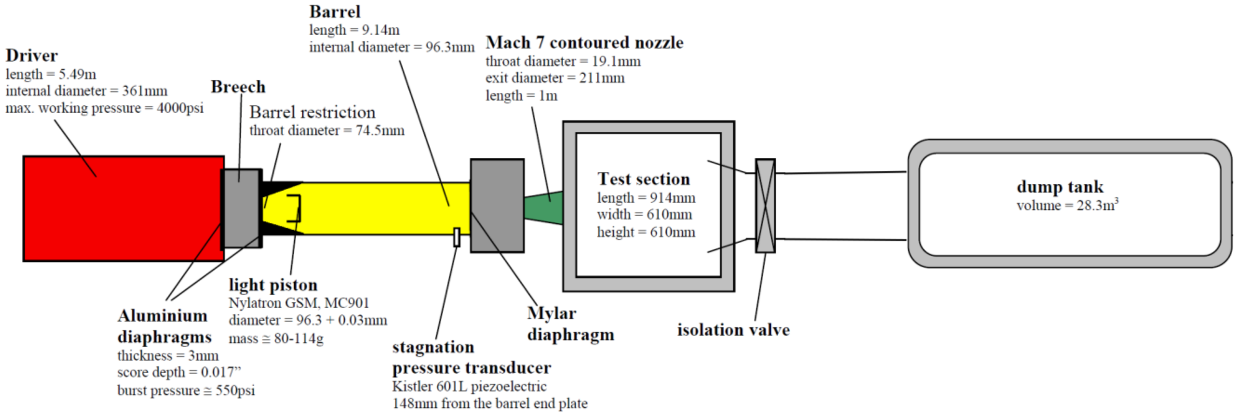


Figure 3. Schematic of University of Oxford Gun Tunnel, including nominal dimensions and pressure.

Table 1. Averaged flow properties for the flow condition used in the LAPCAT MR2 testing.

Property	**Value**
Total pressure, p_0 (MPa)	6.37
Total temperature, T_0 (K)	721
Pitot pressure, p_{pitot} (kPa)	96.7
Mach number, M_∞	7.03
Velocity, U_∞ (m/s)	1147
Static pressure, p_∞ (kPa)	1.497
Static temperature, T_∞ (K)	66.3
Unit Reynolds number, Re_{unit} (1/m)	20.3×10^6

down, the quasi-steady test time used in all the tests was taken between 40-60 ms (i.e. test time of 20 ms) after the initial shock. This provides additional flow before the scramjet intake at approximately the correct conditions to ensure flow establishment (approximately 80 flow lengths through the entire intake). The stagnation temperature history was predicted using the method developed by Matthews *et al.* [3], which uses the initial fill conditions and stagnation pressure history in the calculation. As seen in Fig. 4, the stagnation temperature drops by 5% over the test time.

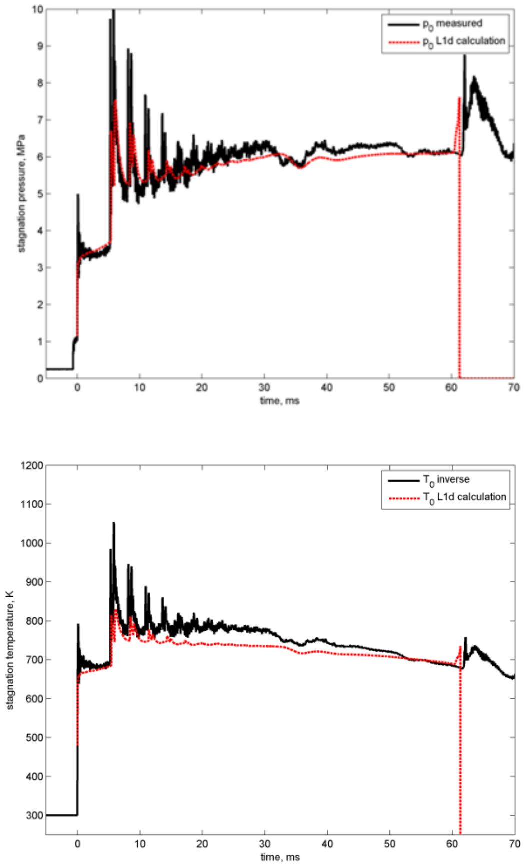


Figure 4. Stagnation conditions for GT7_A flow condition at 148 mm from nozzle throat.

Time histories of both the stagnation pressure and stagnation temperature were also calculated using the 1D simulation code L1D3 [4], using the simulation variables previously validated by Buttsworth *et al.* [5]. The numerically predicted conditions agree with the experimental measurements (derived from an experiment for stagnation temperature). This allows for further confidence in the experimental stagnation conditions, in particular, the stagnation temperature drop over the test period.

A Pitot pressure survey at 10 radial locations was conducted prior to installation of the LAPCAT II model to verify the nozzle Mach 7 nozzle flow. These used shielded Kulite XCL-152 piezoresistive transducers with a max pressure of 170 kPa and 100 kHz bandwidth, with an accuracy of 0.1%. These were shielded in a brass mount and a fine steel mesh to remove any risk of particle damage on the sensors. The sensor signal was amplified by an Analog Devices AD524 amplifier, with a constant gain of 10 and a max bandwidth of 2.5 MHz. This was undertaken at various axial distances from the nozzle to confirm that the core flow would extend to the crotch of the intake. These transducers were calibrated against a Edwards Barocell 658 AB 1000 torr transducer (0.15% accuracy) while in situ from atmospheric pressure to 1 kPa absolute.

Fig. 5 shows three Pitot pressure histories measured at 25 mm from nozzle exit at different radial locations. The three Pitot pressures are in very good agreement, with little time averaged variation. High frequency fluctuations are present throughout which is induced between free stream fluctuations, interaction with the gauge and mechanical noise. These same Pitot measurements are also plotted as normalised by the stagnation pressure history for the shot (time shifted by time of flight between the stagnation pressure transducer and the nozzle), and the Pitot to stagnation pressure remains constant at 0.016. The core flow is seen to be 180 mm at 25 mm from nozzle exit, shrinking to 80 mm at 225 mm from nozzle exit.

2.3. Intake Model

The main objective of the Oxford experiments in the LAPCAT II programme was to test for start/unstart capability of the MR2 vehicle. Thus, the model was cropped from the full scramjet configuration to be just the intake and the isolator geometry (Fig. 6), with the injection struts removed from the geometry. An additional elliptical to circular transition was added to the model to allow symmetric area blockage to be achieved. The geometry used in the Oxford LAPCAT II model was scaled from the DLR Koln model CAD [1] to give nominal elliptical intake geometry of 120 x 40 mm. This is a 1:100 scale from the flight vehicle, which

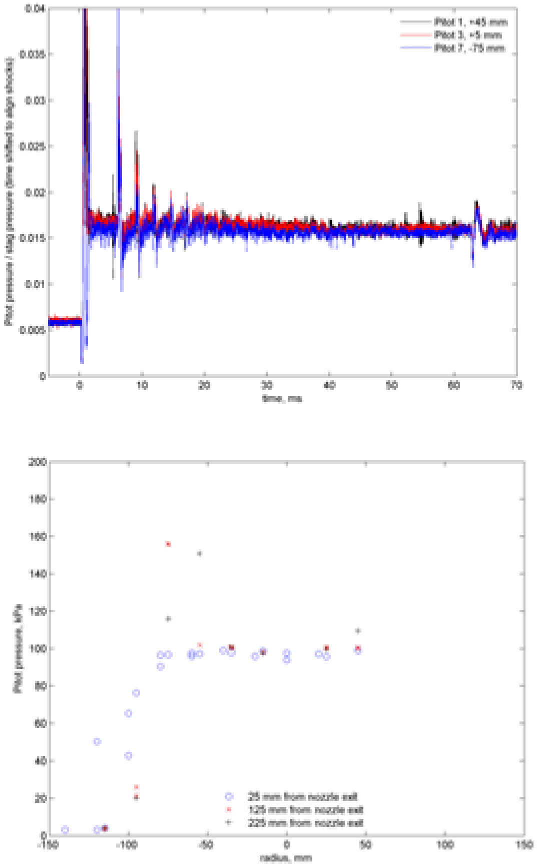


Figure 5. Pitot pressure histories and radial distribution for GT7_A flow condition.

was altered through Mach number scaling making a contraction ratio of 8.6 [2]. Both the crotch 1 and 4 design was manufactured. The total length of the model is 562 mm, with the general dimensions of the model are shown in Figure 5 and detailed in Tab. 2 from the leading edge of the model centreline. Note in this view, the x direction is the horizontal direction, y is into the page, and z is the vertical direction.

Table 2. Positions noted in CAD schematic of Oxford test model.

Position	**x - streamwise (mm)**	**z – vertical (mm)**
A	109.8	0.5
B	260.9	26.0
C	243.3	40.0
D	276.7	26.0
E	276.7	39.9

The intake was manufactured from GP Sterolithography by Puckett & associates. The model was originally made in two halves, with a replaceable leading edge/crotch which could be replaced if damaged from particle strike or heating. The leading edge resulted in a radius of less than 0.1 mm. Initial experimentation resulted in damage to the model, thus the front end of the model needed to be replaced and was manufactured in one part (including leading edge), with the crotch now as replaceable part. This part was manufactured by CDRM.

The effective back pressure was set using a blunted cone (15 degree half angle, 4 mm radius, 24 mm diameter base) translating into the circular intake exhaust. The position is given as the distance the tip has entered into the exhaust (x_{cone}), as seen in Fig. 7. A similar method is generally used in other scramjet intakes to set the back pressure once the flow has reached a subsonic state. The exit diameter from the scramjet has a diameter of 28.2 mm, which relates to an area of 624.6 mm^2. Fig. 7 shows the variation of area blockage with different axial positions of the cone.

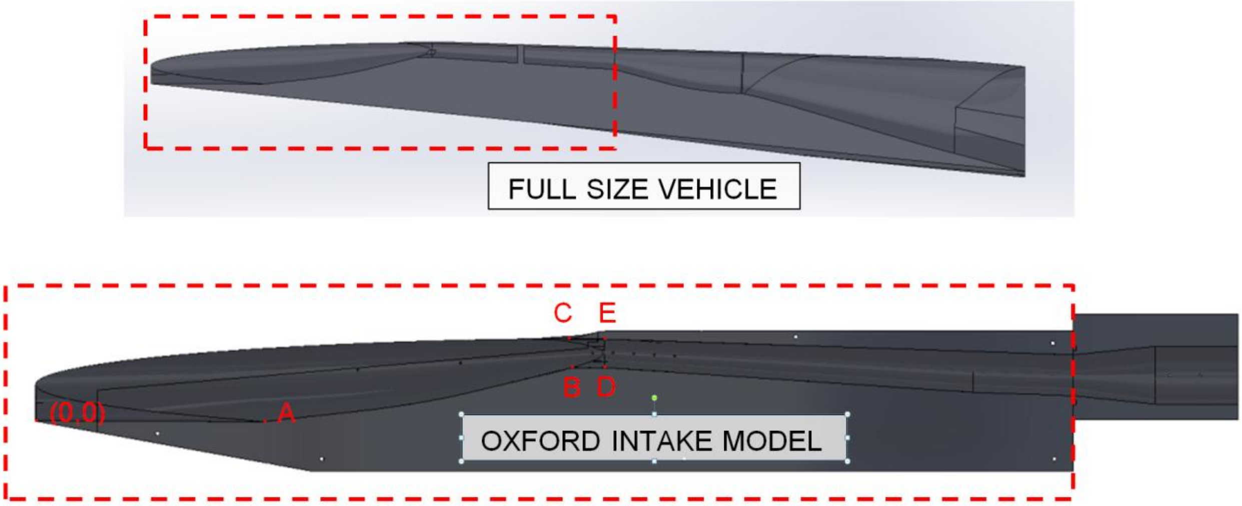


Figure 6. Mid-plane slice of full vehicle and Oxford Intake model.

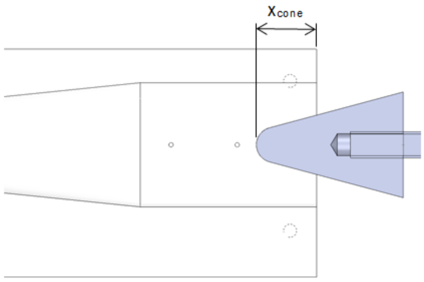


Figure 7. Schematic of back pressure cone showing position relative to exit.

Table 3. Area blockage as a function of cone position.

Cone position x_{cone} (mm)	Diameter blockage (mm)	Area blockage (mm^2)	Percentage blockage (%)
0	0	0	0
5	8.8	61.1	9.8
10	11.5	103.8	16.6
15	14.2	157.9	25.3
20	16.9	223.2	35.7
21	17.4	237.6	38
22.5	18.2	260	41.6
25	19.5	299.8	48

2.4. Instrumentation

Wall pressure was measured at 60 discrete locations within the scramjet model. The pressure lines were manufactured into the model, normal to the surface, and plumbed through to the transducers. The pressure transducers were located on the exterior of the model either in the front or mid instrumentation bays (Fig. 8). The transducers were connected to the internal surface either directly through 1 mm diameter lines in the model, or similarly with 1 mm holes through the model and then 1.6 mm flexible scani-tube. Four different types of transducers were used in the model, to ensure that the low to high pressures could be measured. These were the Silicon Microstructures SM5812 (0-35 kPa, 2 ms response time, 2.5% accuracy), the Freescale MPXA6115A (15-115 kPa, <1 ms response time, 1.5% accuracy), the Freescale MPXA6250A (15-250 kPa, <1 ms response time, 1.5% accuracy) and the MPXA6400A (20-400 kPa, <1 ms response time, 1.5% accuracy). All the transducers were powered from a common 5V power source, and each were temperature compensated and amplified on-board. Calibration and zero offset levels were measured against the Edwards Barocell 658 as used for the Pitot calibrations, from atmospheric pressure to 1 kPa absolute. The gauges were recorded at two different speeds depending on location, 30 channels at 4 kHz and 31 channels at 100 kHz.

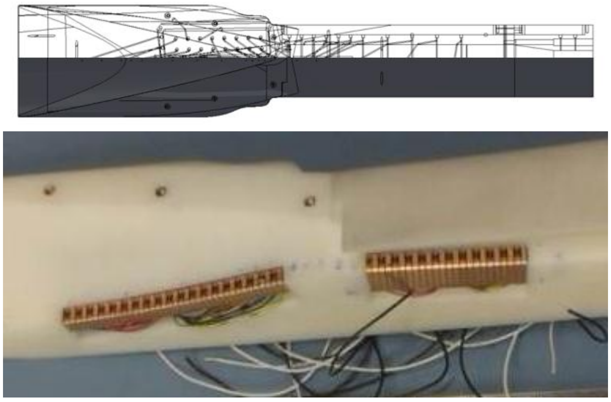


Figure 8: CAD picture showing pressure tap line and photo of thin film and surface pressure taps.

Two strips of thin film heat transfer gauges, 32 in total with 24 connected to the data acquisition, were mounted to the body side of the model on the upper intake and the beginning of the isolator section 4 mm off the centreline of the model (Fig. 8). These were manufactured at the University of Oxford, with a 0.04 µm platinum gauge, with copper leads etched onto a Kapton/glue substrate which was 0.5 mm thick, allowing for a semi-infinite assumption to be applied. The thermal product ($\sqrt{\rho c k}$) of the Kapton/glue combination has been experimentally calibrated (Theret, 98) to be 504 J/m.K.s$^{0.5}$. The gauges used have a 95% response at 100 kHz, with readings up to 1 MHz capable to be recorded. The gauges were individually calibrated in a water bath in situ under isothermal conditions over a temperature range of 10-40 degrees C. The gauges were taken from the model on twisted pair shielded wires, to the in-house designed HTA3 signal conditioning/constant current power supply electronics [6]. For the most part, the AC component of the gauges was recorded with a flat gain response with frequency of 4.7 (AC low, 20 mV baseline noise). The DC component was recorded over 100 samples pre-test to include the DC offset. The gauges were typically set to have an initial voltage of 0.25 V, driven with a constant current dependent on the particular gauges resistance. The impulse response method was applied in processing assuming a semi-infinite substrate [8]. These were recorded at either 1 MHz (8 gauges) and 100 kHz (16 gauges).

A video Schlieren system was setup to mainly visualise the crotch area, to give a visual check of start/unstart. This also allowed for flex in the model support to be diagnosed and rectified. The illumination was provided by a CREE-XTL LED, with an iris to establish an appropriate cone angle from the extended light source. The mirrors were setup in a Z-style arrangement (Fig.

9), with two 8” parabolic mirrors (focal length of 12”) and two flat mirrors. A horizontal knife edge was placed at the focal plane, and the video was captured on a Photron 1024 at 6000 fps, with a resolution of 512 x 256 pixels and a gate width of 10 ms. Fig. 10 shows a composite of Schlieren images captured during two different tests. The images have been scaled and positioned against the CAD drawing taken at the split line of the model.

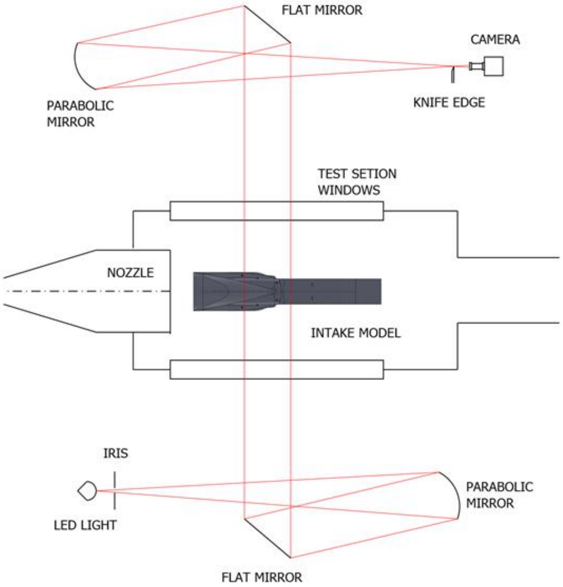


Figure 9: Schematic of Schlieren setup used in testing.

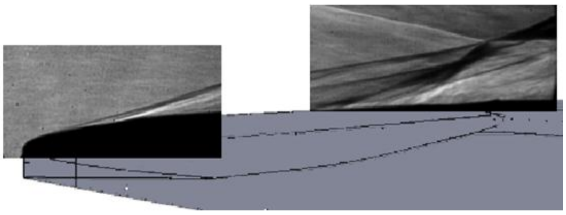


Figure 10: Composite image of Schlieren images taken at leading edge and crotch overlaid on CAD of intake.

3. TESTING RESULTS

Fig. 11 presents a summary of the collected data for base condition and zero area restriction where the AoA was varied. The test period taken for all averages is between 50 ms and 55 ms. The pressure distribution throughout the engine during the test time is as would be expected, an increase to the throat to 45 times the freestream pressure and a relaxation with weak waves in the isolator to approximately 20 times the freestream pressure level. The heat flux follows a similar trend with a peak of 300 kW/m^2 measured in the isolator. The test time averaged Schlieren shows the intake started, with significant spillage occurring for this crotch design and off-design condition. The wave coming from the top left is the nozzle Mach cone, which indicates the model is well within the test flow up to the crotch. Going to a negative AoA increases the mass capture capability and increases the initial shock angle, resulting in a higher body wall pressure both on the intake and in the isolator. As the intake was moved to positive AoA (decreasing the mass capture), a large decrease is seen in the wall body pressure, coupled with a downstream shift of peak pressure due to a shift in the return cowl shock. At the very high AoA (+4° and above) , the intake pressure is very low due to the entire body side of the intake surface having a negative gradient in relation to the freestream flow. Generally, the heat transfer drops on with increasing AoA, though the distribution shifts due to re-positioning of the waves.

The translation of the cone into the model has very little effect on either the pressure distribution or the wall heat flux as summarised in Fig. 12 for 0° AoA. For the highest area blockage achieved in the testing without intake buzz (25.3%), a large difference is seen in the isolator, caused by a shock settling half way down the isolator and creating subsonic conditions for the downstream half of the isolator. There is slightly more difference seen in the heat transfer, which is more sensitive to freestream behaviour, turbulent spots and

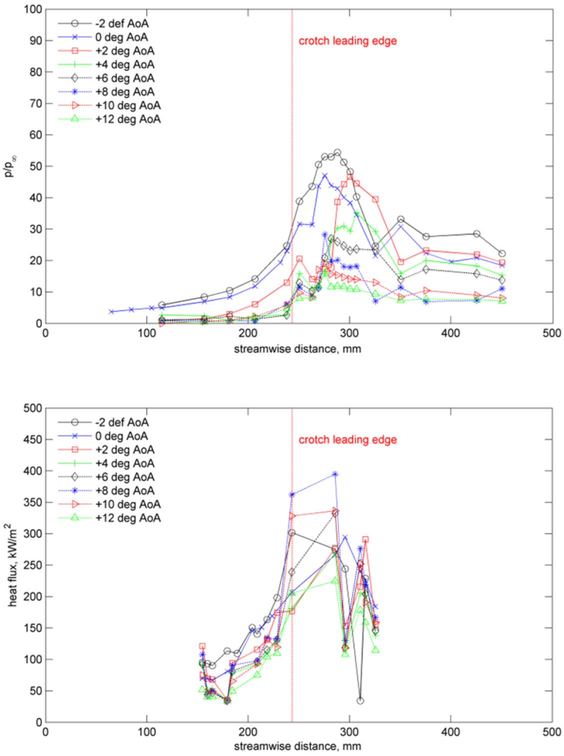


Figure 11: Comparison of wall pressure and heat flux for different area restrictions at 0° AoA.

any movement of the model. The differences seen between the 0% blockage and the higher are blockage is suspected to be caused by repairing the crotch after gt_0020.

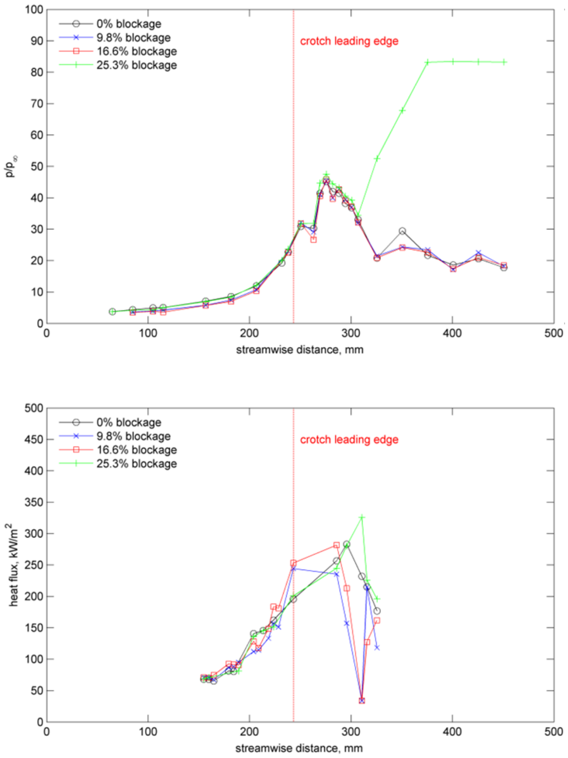


Figure 14: Comparison of wall pressure and heat flux for different AoA.

Intake buzz was recorded for both 0° AoA and 12° AoA when sufficient area restriction was applied. As the nozzle is pushed into an un-start state and then recovers to a fully started regime, this implies that the intake can self-start. The development of this unsteady process is presented in Fig. 15. Initially, the flow down the intake and isolator looks similar to that previously presented (t = 47.33 ms). As the flow becomes subsonic in the area transition piece, this propagates back upstream resulting in higher wall static pressure and heat transfer. This eventually reaches the crotch, where an additional shock is seen originating from the upstream of the cowl location. This then reduces the mass flow rate in the engine allowing the back pressure to drop. If the intake did not self-start, it would remain in this state, however, it returns to a started state.

4. COMPARISON TO PREVIOUS RESULTS

Cain [9] performed post-test analysis of the experiments and numerical simulations of the LAPCAT MR2 intake. This highlighted that the Oxford testing had higher body side pressure than observed in DLR CFD, F4 testing and H2K (runs #4 & #5) for the same nominal condition (Fig. 13). When the Oxford testing was compared to the initial H2k tests where a pitot rake in the isolator was causing boundary layer separation at start of the intake, the Oxford pressure and shock pattern (Fig. 14) show good agreement. As the intake had boundary layer separation in three out of four tunnels it was tested in, it showed a lack of robustness. Cain highlights the likely cause was in the design of the intake underestimating the growth of the boundary layer. The analysis was validated by using the heat transfer data recorded in the Oxford model.

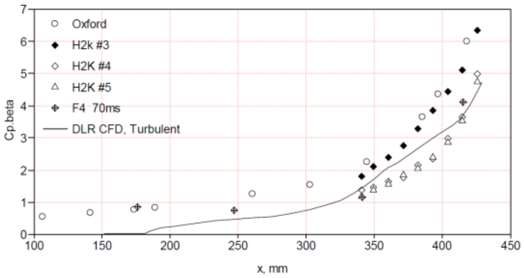


Figure 12: Measured pressure coefficients from different facilities and simulation, indicating separation in Oxford tests. Taken from [9].

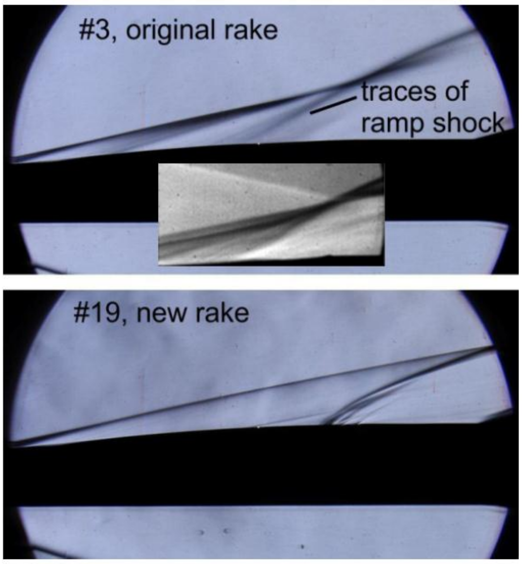
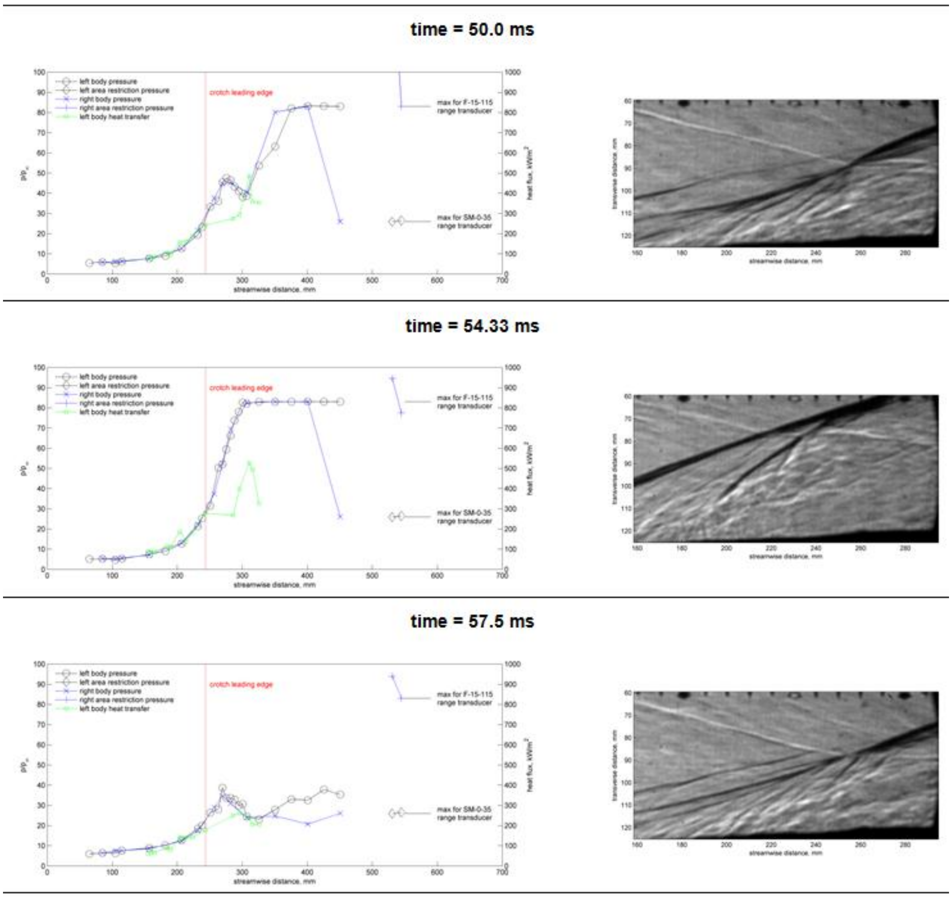


Figure 13: Schlieren images from DLR H2K tests (top & bottom, [1]) and Oxford (middle).

5. CONCLUSION

The LAPCAT II Mach 8 intake and isolator has been tested in the Oxford Gun tunnel to explore if the intake is self-starting at off-design angles of attack and the effects of back pressure on the intakes wall pressure and heat transfer distribution. The model was a 1:100 scaled


time = 50.0 ms

time = 54.33 ms

time = 57.5 ms

Figure 15: Centreline body side pressure distribution at several test times at 0° AoA.

model, with an intake of 120 x40 mm, and tested at Mach 7 with a unit Reynolds number of 20 million/m. This model was instrumented with 61 pressure transducers , 24 thin film heat transfer gauges and video Schlieren was captured in the crotch region. A comparison of the intake wall pressures showed that the LAPCAT II intake performs in a similar fashion to the DLR tests. The intake showed self –start capability at 0° and +12° AoA, implying that the intake will self-start at any AoA less than 12°. With a reduced exit area 25.4%, which is analogise to increased back pressure, a normal shock formed in the isolator. With further area reduction to 40%, intake buzz was observed.

6. REFERENCES

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