Experimental Performance Evaluation of a Streamline Traced Inlet at Off-Design Conditions

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Scramjet engines used as part of a multi-stage space access system must operate efficiently over a wide range of conditions. This paper describes experimental testing undertaken to evaluate the mass-capture performance, self-starting capability and back-pressure limitations of a streamline-traced three-dimensional inlet. Experiments were conducted in the University of Oxford High Density Tunnel. Instrumentation included fast-response surface pressure measurements and a novel back pressure/mass capture device suitable for accurate measurement of mass flow rate in short duration testing. Tests were performed at Mach 7 over a range of unit Reynolds numbers.

Nomenclature

A	=	area (m^2)
ρ	=	density (kg/m^3)
p	=	pressure (kPa)
T	=	temperature (K)
u	=	velocity (m/s)
q	=	dynamic pressure (kPa)
Re_u	=	unit Reynolds number

I. Introduction

Air breathing vehicles that fly much faster than the speed of sound, such as ramjets and scramjets, rely solely upon on the intake geometry to perform compression of the air for combustion. The intake mass capture is a critical parameter that affects the performance of the intake, and thus the entire efficiency of the engine. Van Wie [1] predict that to maintain 1 % accuracy in specific impulse over the range Mach 5 to Mach 10, the accuracy in mass capture must be in the range 1 to 3 %. The ability of an inlet to self-start is also desirable due to the operational simplicity this affords. Both these intake characteristics are highly sensitive to the flow fields produced by any given geometry, so it is vital that numerical predictions of performance must be validated against accurate experimental measurement of these intake characteristics.

One example air-breathing space access system proposed by [2] is shown in Figure 1. This is a three-stage rocket-scramjet-rocket launch system designed for small satellites. The scramjet stage is to accelerate from Mach 5 to Mach 10 and features a conical fuselage with tightly integrated three-dimensional engines. These engines employ a CREST (CRescent to Elliptical Shape Transition) inlet which is designed for high mass capture and low external drag. Although the injector design and combustion performance of this class of engine have been well studied both numerically [3–5] and experimentally (in shock-tunnels) [6, 7], the inlet performance and operability has not yet been

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assessed experimentally.

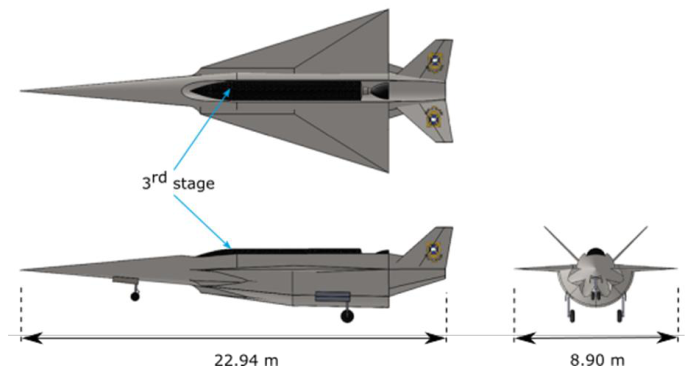

Fig. 1 Airbreathing space-access concept vehicle proposed by [2]. First-stage rocket not shown.

With the prohibitive cost of flight testing, intake performance characterisation is performed in high speed wind tunnels [8, 9] **OTHER NON-UQ REFERENCES**. To ensure simularity, the wind tunnel test condition should reproduce the flight Mach number and Reynold's numbers. Noting that the mass captured by an intake is very sensitive to the back pressure generated from combustion effects, tests are typically conducted over a wide range of back pressures, until unstart occurs.

A schematic of a traditional method of intake mass flow measurement involving a translating cone is shown in Figure 2. In this technique the translating cone restricts the flow exiting a dump isolator and mass flow measurement is made at the choked flow gap between the cone and dump. This type of device also supplies variable back-pressure to the intake. Typically, baffle plates and flow straighteners are used to ensure that the measurements of total pressure and total temperature are representative of the stagnated flow. Devices of this sort have been successfully incorporated in testing in the NASA blowdown tunnels by Ref. [8] and several tests in the H2k facility [10–13]. In the work described in Ref. [11], an accuracy of ±3 % for the mass flow rate was achieved.

The difficulties with such a device are (1) the sensitivity and non-linearity of the back pressure to the position of the rear cone, (2) large response times of the device, specifically the temperature measurement and fill times when tested in short duration facilities, (3) coupling of the back pressure with the mass flow rate, and (4) the use of non-ISO standard measurement geometry decreases accuracy over wide ranges of Reynolds numbers. Van Wie [1] proposed the application of measuring the increase in pressure in a sealed reservoir for impulse facility operation, with accuracies of 5 % and response times of 2–3 ms.

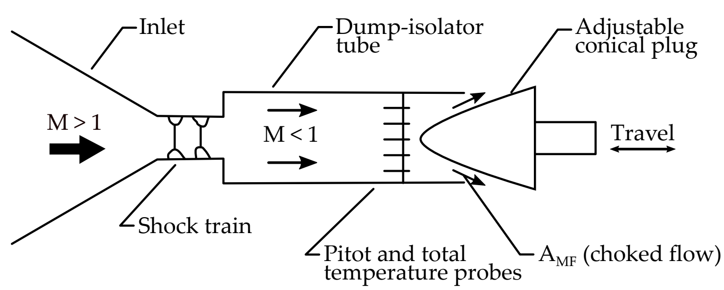

Fig. 2 Schematic of a typical Intake Mass Capture Device. Taken from [14].

This paper describes testing of a CREST intake using a novel mass capture device in the University of Oxford's High Density Tunnel (HDT) [15]. Section II of the paper describes the design principles of the highly three-dimensional intake and the instrumentation used. Section III provides details on the novel mass capture device, including describing its principle of operation, design, instrumentation and benchtop calibration against a reference orifice plate. Section IV then describes the experimental facility, the HDT, before the experimental results for are presented in Section V.B. Some conclusions are provided in Section VI.

II. Streamline Traced Inlet

A. Inlet Design

In the current experiments a small-scale CREST intake with geometric capture width of 100 mm was tested. Figure 3 shows an isometric CAD drawing of the model attached to the mass capture device.

In the final paper the design of the inlet will be discussed.

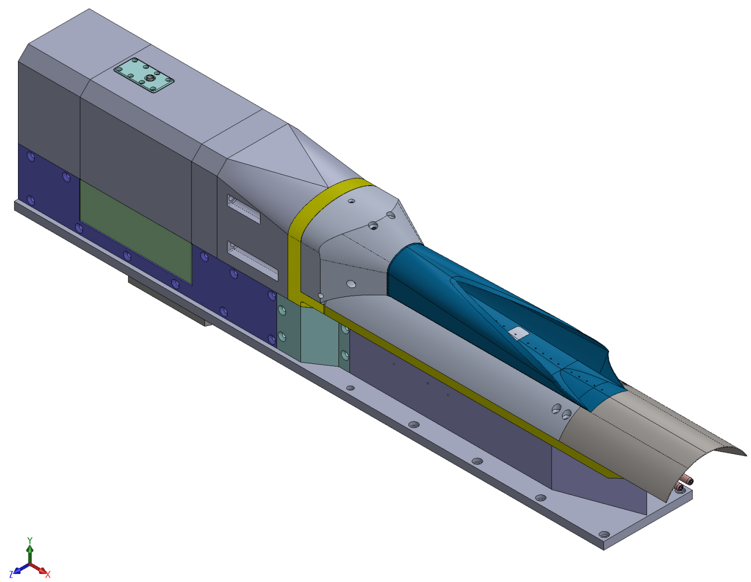

Fig. 3 CAD rendering of the intake model attached to the MCD

B. Instrumentation

The intake can be seen to be mounted to a cylindrical forebody. The model includes 14 pressure transducers on the body side of the intake. These were a mixture of six Kulite® XTL-140M sensors and eight Honeywell HSC sensors of various ranges. The freestream Pitot pressure and total temperature are measured using probes mounted below the intake forebody.

Further information regarding the intake instrumentation will be given in the final paper.

III. Novel Mass Capture Device

A. Principles of Operation

A new back pressure/mass flow measurement device developed by Ref. [14] was used in the intake testing. Shown schematically in Figure 4, the device sparates mass flow measurement and back-pressure capability. The device consists of a dump-isolator and secondary isolator downstream of a variable area restrictor. The variable area restrictor consists of two perforated, circular plates that rotate relative to each other in a controlled manner. The upstream plate is held fixed while the downstream plate is rotated by a stepper motor, housed outside the main flow path, via a spur gear mechanism. Because the plate is driven perpendicular to the flow, the motor experiences far less load than the translating cone device in Figure 2. Rapid, controlled changes in restriction area are possible, potentially allowing the mass capture characteristics during a complete start-unstart event of an inlet to be recorded in a single experiment. Furthermore, the hole patterns may be specified so as to optimise the back pressure profile relative to the actuation. The flow exits the device through a fixed, calibrated venturi nozzle, enhancing the accuracy of the device.

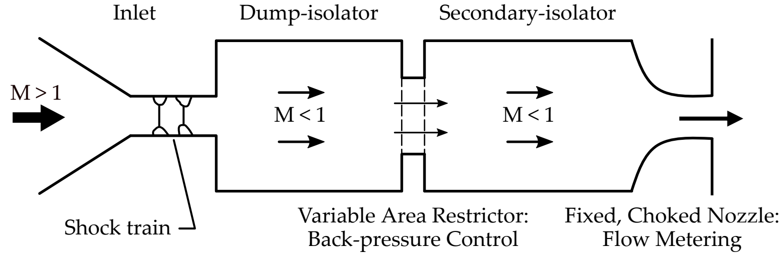

Fig. 4 Schematic of Intake mass capture device with separated back pressure and mass capture function. Taken from [14].

B. Design and Instrumentation

The mass capture device used in this work is shown in Figure 5. Also shown is a simple Pitot Intake that was used for validation experiments detailed in Section V.A. The MCD features a 120 mm diameter bore that is 410 mm in length. The flow exits through a 60 mm diameter, 120 mm length venturi nozzle that has an internal profile similar to that defined by ISO9300:2005(E). The variable area restrictor was located 204 mm downstream of the entrance to the MCD. In the current configuration both the static and dynamic circular plates featured four circumferential slots. The dynamic plate was driven using a Zaber NEMA stepper motor via. an anti-backlash gear.

Shown in Figure 5, the MCD was instrumented with five absolute pressure transducers: two upstream of the variable area restrictor (P_{MC1} and P_{MC2}), two upstream of the venturi (P_{MC3} and P_{MC3A}) and one at the exit of the MCD on the backward facing step (P_{MC4}). P_{MC3A} was used for calculation of the venturi mass flow. It was a Kulite® XTL-140-100A with range 0 to 100 psi, all other sensors within the MCD were Kulite® XT-190(S)M transducers with range 0 to 3500 kPa. P_{MC4} was used in combination with P_{MC3} to monitor the pressure ratio across the venturi nozzle.

The temperature upstream of the venturi was measured using two bespoke mounted thermocouples, T_{MC2A} and T_{MC2B} (Figure 5). Both were 0.003 inch diameter Omega™ K-Type thermocouples (PNo. 5TC-TT-KI-40). The bespoke mounting for T_{MC2A} positioned the bead approximately 25 mm proud of the internal surface such that it was within the outer third of the MCD cross-section. Similarly, the bead of T_{MC2B} was positioned approximately 45 mm proud such that it was within the middle third of the cross-section.

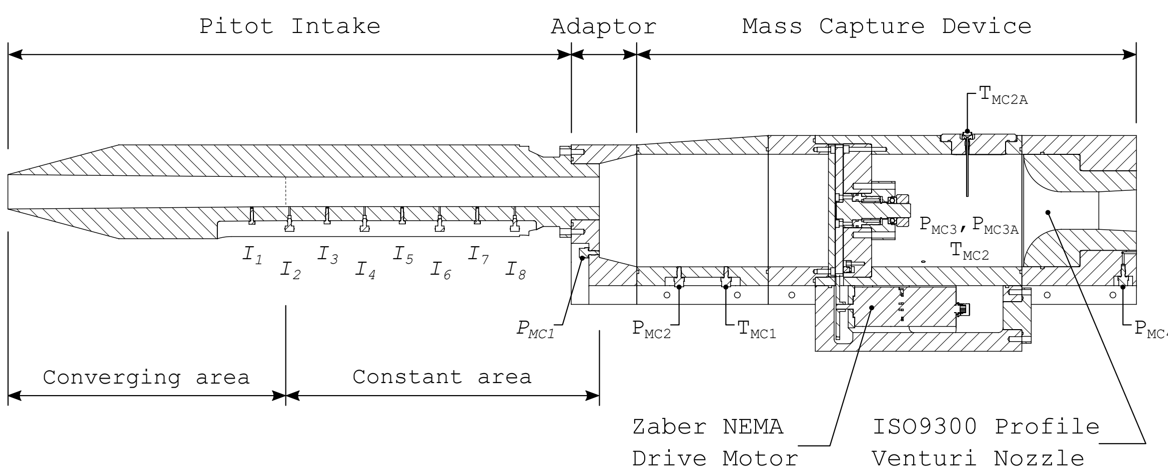

Fig. 5 Updated from [14].

C. Benchtop Calibration

Following Ref. [14], the discharge coefficient for the MCD was determined prior to the wind tunnel campaign via. a benchtop calibration against an BS EN ISO 5167-2 standard orifice plate. The calibration rig was connected to a large reservoir of 100 psi air via a full-bore ball valve and regulator. Downstream of the MCD the exhaust was vented to a **XX m3** vacuum vessel, allowing calibrations at relatively low mass flow rates of 100 g/s. The differential pressure across the orifice was measured using an Omega™ PX419-100DDU5V differential pressure sensor with range 0 to 100 psid and uncertainty ±0.08 % FS BSL. The static pressure upstream of the orifice was measured using an Omega™ PX419-100A10V-EH absolute pressure sensor with range 0 to 100 psi and uncertainty ±0.05 % FS BSL.

The static temperature downstream of the orifice plate was measured using a 0.005 inch diameter Omega K-Type thermocouple (PNo. TT-K-36-SLE) mounted ≈5 mm from the centreline. As per BS EN ISO 5167-2 this temperature measurement was used to infer the temperature upstream of the orifice.

In the final paper a picture of the calibration rig with MCD installed will be provided. Calibration results will be presented and discussed and the calibration uncertainty quantified.

IV. Experimental Facility

The experiments were carried out in the University of Oxford's High Density Tunnel (HDT). This facility was originally developed by the RAE (then Qinetiq) in the United Kingdom in the 1960's. Constructed from 6-inch gun barrels, the facility was initially operated as a cold hydrogen driven shock tube and tunnel. The HDT was acquired from Qinetiq in 2012 by the Univeristy of Oxford to widen the portfolio of hypersonic ground-test facilities within the Oxford Thermo-Fluids Institute [15]. The facility has been installed and is now fully operational in its Ludwieg Tube mode. More details of its performance during commissioning are presented in Ref. [16]. It is capable of generating relatively long duration flows at high Reynolds number, and is suitable for both steady and unsteady aerothermodynamic testing of hypersonic configurations. Figure 6 shows the HDT on the right, along with the new T6 Stalker Tunnel on the left.

Fig. 6 Hypersonic lab at the Oxford Thermofluids Institute. The T6 Stalker Tunnel [17] is on the left and the High Density Tunnel is on the right.

A. Test Conditions

A test condition is to be conducted in the Oxford High Density Tunnel using the Pitot Intake shown in Figure 5. This intake ensures a 100 % mass capture is achieved, thereby allowing the performance of the MCD to be evaluated. A nominal condition of Mach 5, unit Reynolds number of 53×10^6/m and total temperature of 400 K has been chosen however it is expected that during testing the following ranges of these parameters will be explored:

In the final paper full details of the test flow properties achieved during the experimental campaign will be provided.

V. Results and Discussion

A. In-tunnel Calibration of MASSCAP

Further to the benchtop calibration of the MCD (Section III.C), the device was tested in the HDT with the 100 %-capture Pitot intake shown in Figure 5. These tests served as a further calibration and check of the MCD under realistic flow conditions. The Pitot intake featured an inlet diameter of (70.00 ± 0.05) mm and an exit diameter of (60.00 ± 0.05) mm, giving a contraction ratio of 1.36. This contraction ratio is small so as to ensure that the intake properly started. The overall length of the intake was 600 mm. Instrumentation consisted of four Honeywell HSC absolute pressure sensors with measurement ranges 0 to 15 psi (I_2, I_4) and 0 to 15 psi (I_6, I_8). **CHECK SENSOR DETAILS**

In the final paper the results will be presented in full.

B. Inlet mass capture performance

In the final paper, results from the experiments of the CREST intake at a range of Reynolds numbers will be presented and discussed.

VI. Conclusions

This section will be completed in the full paper.

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