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Interpolation algorithm for internal flow visualization of a supersonic air intake

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Technical Memorandum
DRDC Valcartier TM 2012-067
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Canada

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This work was performed at under WBE 11az01 on plasma discharges for improved aerodynamics.

Abstract

Under the CA/NL MOU IA-6, DRDC Valcartier in Canada and TNO Defence, Security and Safety in the Netherlands jointly work to improve their numerical prediction capability on airbreathing powered missiles. As part of the collaboration program and to fill in the gap on the availability of experimental data in the open literature, wind-tunnel tests were carried out at the DRDC Valcartier tri-sonic wind-tunnel in order to gather internal aerodynamic performance data on a rectangular air intake model in isolation.

The experimental data from the wind-tunnel test campaign aimed to improve the understanding of flow physics inside supersonic air intakes, to validate commercial CFD codes and to serve as input for the ramjet engine performance prediction code developed by DRDC Valcartier and TNO, the DRCORE model.

Mass flow rate, pressure recovery and flow distortion at the combustor face, are outstanding parameters to support assessment of overall engine performance. The evaluation of those performance parameters is strongly dependent on the accuracy of total pressure measurements. In the wind-tunnel test campaign, total pressure measurements were obtained by means of a Pitot rake located in the combustor face of the ramjet, and then averaged in order to define a unique value for determining the performance parameters. However, Pitot rake measurements have limited spatial resolution so as to avoid disturbance to the internal flow.

This study evaluated the ability of the two-dimensional interpolation algorithms implemented in Matlab R2006a to map the flow at the Pitot rake section to overcome the limited spatial resolution of experimental measurements, and to improve flow visualization and the accuracy on the evaluation of total pressure. Additionally, the algorithms allowed calculation of performance parameters (mass flow rate, pressure recovery and flow distortion) of the air intake during the wind-tunnel experiments. Some experimental results using the different algorithms in MatlabR2006a are presented and compared.

Résumé

Dans le cadre de la collaboration CA/NL MOU IA-6, RDDC Valcartier au Canada et le TNO Defence, Security and Safety au Pays-Bas coopèrent pour améliorer leurs capacités de prédiction numérique sur la performance des missiles propulsés par statoréacteurs. Pour combler la manque d’information expérimental disponible dans la littérature ouverte, des essais en souffleries on été effectués à RDDC Valcartier pour la collecte des données sur la performance aérodynamique d’un modèle d’entrée d’air rectangulaire en isolation.

Les données expérimentales acquises durant les essais en soufflerie ont l’objective de améliorer la compréhension sur la physique des écoulements travers une entrée d’air supersonique, et pour ainsi valider les résultats des simulations numériques et servir d’apport pour le modèle DRCORE, soit le code de prédiction de la performance des missiles à statoréacteur développé par RDDC Valcartier et TNO.

Le débit massique, la récupération de la pression totale ainsi que la distorsion de l’écoulement sont des paramètres essentiels pour caractériser les performances globales d’un moteur. L’évaluation de ces paramètres dépend fortement de la précision des mesures de la pression totale. Durant les essais en soufflerie, les mesures de pression totale ont été obtenues au moyen des sondes Pitot situé à l’amont de la chambre de combustion du statoréacteur, ensuite elles ont été moyennées pour définir une valeur unique qui déterminera par la suite les paramètres de performances. Toutefois, l’espace dédié aux sondes Pitot est limité compte tenu de la perturbation qu’il peut apporter à l’écoulement.

Cette étude évalue la capacité des algorithmes d’interpolation en 2D implémentés sur Matlab R2006a pour cartographier la répartition de pression au niveau de la sonde Pitot et subséquemment améliorer la résolution spatiale des mesures expérimentales ainsi que la précision sur l’évaluation de la pression totale. De plus, l’algorithme permet le calcul des paramètres de performance (débit massique, récupération de la pression totale et distorsion de l’écoulement) de l’entrée d’air durant les essais en soufflerie. Quelques résultats expérimentaux utilisant ces différents algorithmes sur Matlab sont présentés et comparés.

Executive summary

Interpolation algorithm for internal flow visualization of a supersonic air intake:

Pimentel, R. Lesage; F., Ghazlani; M. A.; DeChamplain, A.; DRDC Valcartier TM 2012-067; Defence R&D Canada – Valcartier; December 2011.

Introduction or background: In order to fulfill the growing need to accurately predict the performance of air-breathing supersonic missiles, under the Canada-Netherlands Memorandum of Understanding (Implementing Arrangement No. 6) on Missile Propulsion Technologies, DRDC Valcartier in Canada and TNO Defence, Safety and Security in the Netherlands have been working together on the development of a Modelling & Simulation (M&S) capability to assess global performance of advanced high-speed airbreathing missiles and they conceived a model called DRCORE. This model enables the prediction of the thrust of airbreathing missiles during on- and off-design air intake operation using engineering formulae applied to each subsystem of the propulsion unit. The DRCORE model can be fed with results from other studies, such as experimental or numerical data. The M&S capability is used for studies for the mutual Armed Forces, to support operational and threat analyses, and weapon system acquisition processes.

Results: This report evaluated the ability of interpolation algorithms implemented in MatlabR2006a to map the flow quality delivered to the combustor of a rectangular ramjet engine. The technique provided concise temporal and spatial visualization of flow quality at the combustor face necessaries for CFD validation.

Significance: Air intake is an important component of air breathing propulsion systems, since the amount and the quality of the air flow delivered to the combustor strongly influences global ramjet engine system performance and it has been addressed as part of the Canadian-Dutch collaboration program since 2003.Unfortunately, the amount of useful data on air intakes available in the open literature is very limited. Therefore, a wind-tunnel test campaign was carried out at DRDC Valcartier tri-sonic wind-tunnel to gather required experimental data. The tests used a rectangular air intake model based on VOLVO Flygmotor AB design. Besides providing missing data in the open literature, the test campaign aimed to improve understanding on supersonic air intake flow physics, to provide data to be used directly in the DRCORE model, and to validate commercial CFD codes. Once numerical modeling codes are validated, they could generate accurate and larger database for further DRCORE or other simulation tools.

Future plans: The outcomes of this study will be used to evaluate eventual improvement on spatial profile of total pressure upstream the combustor, when the intake will be provided of a plasma flow actuator.

Sommaire

Interpolation algorithm for internal flow visualization of a supersonic air intake:

Pimentel, R. Lesage; F., Ghazlani; M. A.; DeChamplain, A. ; DRDC Valcartier TM 2012-067 ; R & D pour la défense Canada – Valcartier; décembre 2011.

Introduction ou contexte : Dans le but de prédire avec précision la performance d'entrée d'air supersonique pour les missiles aérobieses, dans le cadre du «Canada-Netherlands Memorandum of Understanding (Implementing Arrangement No.6) sur Missile Propulsion Technologies », DRDC Valcartier au Canada et TNO Defence, Safety and Security au Pays-bas ont travaillé en étroite collaboration pour développer leur capacité en modélisation et simulation (M&S) pour évaluer les performances globales des missiles à haute-vitesse, et ont pu concevoir un modèle numérique appelé le DRCORE. Ce modèle permet la prédiction de la poussée des missiles aérobies durant opérations « on et off-design » des entrée d'air en en utilisant des formules d'ingénierie appliquées à chaque partie du système de propulsion. Le modèle DRCORE peut être alimenté de résultats par d'autres études, telles que des données expérimentales ou numériques. M&S est utilisé mutuellement dans les deux armées, pour supporter les processus d'acquisition d'armes et les analyses de menaces.

Résultats : Ce rapport évalue la capacité des algorithmes d'interpolation implémentés sur Matlab R2006a servant à cartographier la qualité d'un écoulement à l'amont d'une chambre de combustion à l'intérieur d'un statoréacteur rectangulaire. Les techniques présentées fournissent une visualisation spatiale et temporelle de la qualité de l'écoulement au niveau de la chambre de combustion et qui est nécessaire pour valider la mécanique de fluide numérique.

Importance : L'entrée d'air est essentielle pour les missiles propulsés par des statoréacteurs, car la qualité de l'air qui rentre dans la chambre de combustion influence fortement la performance globale du moteur et c'est pour cela qu'elle a été adressée au programme de collaboration canadien-hollandais depuis 2003. Malheureusement, des informations détaillées traitant sur les entrées d'air sont très limités dans la littérature ouverte. Par conséquent, des essaies en soufflerie ont effectué à DRDC Valcartier pour collecter des données expérimentales et pourtant combler le manque d'information disponible. Le modèle d'essai consistait d'une entrée d'air rectangulaire basée sur un design de VOLVO Flygmotor AB et avait pour but d'améliorer la compréhension sur l'écoulement interne des entrées d'air supersoniques, et de fournir des données expérimentales qui peuvent être utilisées directement dans le modèle DRCORE, ainsi que dans la validation des codes commerciaux de la mécanique des fluides numérique. Une fois la validation effectuée, ces derniers pouvaient générer de larges bases de données pour être utilisées postérieurement dans DRCORE ou dans autres outils de simulation.

Perspectives : Les résultants prévenants de cet étude seront utilisés pour évaluer les éventuels améliorations sur la distribution spatiale de la pression total amont la chambre de combustion, lorsque le modèle d'entrée d'air sera munit d'un actuateur plasma.

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Acknowledgements

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1 Introduction

An increasing interest in airbreathing propulsion systems for tactical high-speed missiles has been observed worldwide due to their improved performance in terms of range, sustained speed and manoeuvrability compared to solid propellant rocket propulsion. Increased speed offers significant improvements in system effectiveness for long range missile applications including decreased time-to-target, increased terminal velocity, and reduced effectiveness of anti-missile systems. Additionally, fewer missiles are required to effectively cover specific area and they can be based farther apart.

In order to fulfill the growing need to accurately predict the performance of air-breathing supersonic missiles, under the Canada-Netherlands Memorandum of Understanding (Implementing Arrangement No. 6) on Missile Propulsion Technologies, DRDC Valcartier in Canada and TNO Defence, Safety and Security in the Netherlands have been working together on the development of a Modelling & Simulation (M&S) capability to assess global performance of advanced high-speed airbreathing missiles and they conceived a model called DRCORE. This model enables the prediction of the thrust of airbreathing missiles during on- and off-design air intake operation using engineering formulae applied to each subsystem of the propulsion unit. The DRCORE model can be fed with results from other studies, such as experimental or numerical data. The M&S capability is used for studies for the mutual Armed Forces, to support operational and threat analyses, and weapon system acquisition processes.

The performance of any airbreathing propulsion system is strongly dependent on the capability of their air intakes to deliver the suitable amount of air required to the combustion process, and to guarantee acceptable flow quality in terms of stability and uniformity, throughout the entire operating envelope.

Total pressure profile at the combustor face is fundamental datum to assess performance of air intakes systems, since it permits evaluation of important performance parameters such as the pressure recovery, mass flow rate, flow distortion and flow stability [1].

1.1 Pressure recovery

Pressure recovery (π) measures the pressure energy available at the combustor entry from the existing pressure energy in the flow at free-stream conditions. It is defined as the ratio of mean total pressure at the combustor face to the free stream total pressure. A classical nomenclature used for pressure measurement stations in the literature is presented in Figure 1.

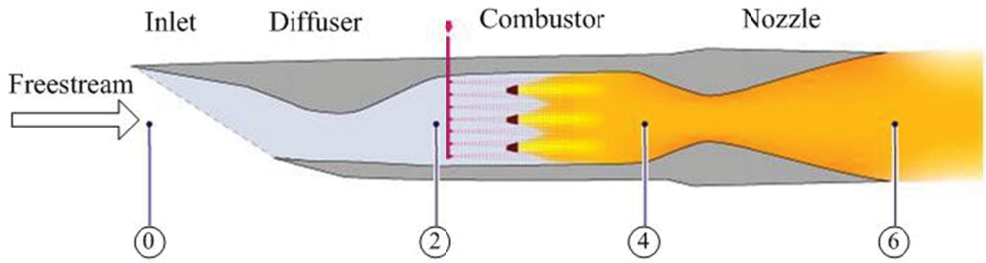


Figure 1: Ramjet engine schematic.

Using the above nomenclature the expression for pressure recovery is derived as follows:

$$\pi = \frac{P_{0,2}}{P_{0,0}} \tag{1}$$

where

$P_{0,2}$: Area averaged total pressure at the combustor face, Pa
$P_{0,0}$: Free-stream total pressure, Pa

It can be shown [2] that the pressure recovery contributes directly to the engine thrust level for which the dimensionless coefficient (C_F) is presented by Equation (2).

$$C_F = \frac{2\left(\frac{A_6}{A_R}\right)}{\gamma_0 M_0^2}\left\{\frac{\frac{P_{0,2}}{P_{0,0}}\cdot\frac{P_{0,4}}{P_{0,2}}\cdot n_N\left[\frac{P_6}{P_{0,6}}\left(1+\gamma_6 M_6^2\right)_{ideal}\right]}{\frac{P_0}{P_{0,0}}} - 1\right\} - 2\frac{A_0}{A_C}\frac{A_C}{A_R} \tag{2}$$

Therefore, higher the pressure recovery index the better is the intake design.

1.2 Flow distortion

Flow distortion (Δ) is another performance parameter that requires the measurement of total pressure at the combustor face. It is a parameter to quantify flow uniformity, which can be calculated differently, depending on the engine maker. The expression used in this study is the following:

$$\Delta = \frac{P_{0,2,max} - P_{0,2,min}}{P_{0,2}} \tag{3}$$

where

$P_{0,2,max}$: Maximum total pressure at the combustor face, Pa
$P_{0,2,min}$: Minimum total pressure at the combustor face, Pa
$P_{0,2}$: Area averaged total pressure at the combustor face, Pa

1.3 Mass flow rate

In this project, mass flow rate crossing the air intake during the experiments was estimated using two different techniques, i.e., the duct-base and the choked valve technique as described in DRDC Valcartier TM 2008-292 [3].

1.3.1 Duct-based technique

By the duct-base technique, mass flow rate is given by the following expression:

$$\dot{m}_d = C_{D,d} A_{d,geo} \sqrt{\frac{\gamma}{R_{air}}} \frac{P_{0,2}}{\sqrt{T_0}} \frac{Ma_d}{\left(1 + \frac{\gamma - 1}{2} Ma_d^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad (4)$$

where

$C_{D,d}$: Discharge coefficient

$A_{d,geo}$: Area of the chocked nozzle, m^2

γ : Ratio of specific heats, 1.4 for air

R_{air} : Gas constant, 287 J/kg.K for air

$P_{0,2}$: Area averaged total pressure at the combustor face, Pa

T_0 : Total temperature, K

Ma_d : Mach number

and the Mach number, Ma_d, is given by the following expression:

$$Ma_d = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P_{0,2}}{P_d}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \quad (5)$$

where

P_d : mean static pressure at the combustor face, Pa

1.3.2 Choked valve technique

By the choked valve technique, mass flow rate is given by the following expression:

$$\dot{m}_v = C_{D,v} \frac{P_{0,2}.A^*}{c^*} \quad (6)$$

where

$C_{D,v}$: discharge coefficient

$P_{0,2}$: mean total pressure at the combustor face, Pa

A^* : area of the chocked nozzle, m^2

c^* : characteristic velocity, m/s

The characteristic velocity is calculated by the following expression:

$$c^* = \frac{\sqrt{\gamma . R_{air} . T_0}}{\gamma . \sqrt{\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}} \tag{7}$$

where

γ : ratio of specific heats, 1.4 for air

R_{air} : gas constant, 287 J/kg.K for air

T_0 : total temperature, K

The discharge coefficients compensates for inaccuracies of the mean total pressure determination due to the limited spatial resolution of the Pitot rake shown in Figure 6 and the fact that Equations (3) and (4) are based on the assumption of 1-dimensional isentropic flow. In reality, the flow is 3-dimensional with viscous and non-isentropic effects (i.e. boundary layers). The discharge coefficients $C_{D,d}$ and $C_{D,v}$ in Eq. 4 and 6 were determined by separate tests as presented in the DRDC Valcartier TM 2008-292[3].

2 Experimental set-up

The wind-tunnel test campaign used a rectangular supersonic air intake model in isolation based on a VOLVO Flygmotor AB design [4],[5]. The model was provided of a translating prismatic valve at the rear end to allow variation in the back pressure, for simulating different operating condition of the combustor.

During the wind-tunnel test campaign, the effect of Mach number, AoA, ramp bleed block openings, and backpressure on air intake performance was evaluated. No force balance measurement was taken, and the bleed holes at the cowl side were kept open during the experiments. Total pressure at the combustor face can be obtained experimentally using a Pitot tube rake.

2.1 Wind-tunnel

The experimental tests were carried out at DRDC Valcartier tri-sonic wind-tunnel. It is an intermittent in-draft-type wind-tunnel with a test section of 60 cm x 60 cm and a useful run time of about 8 seconds depending on the operating Mach number.

In the facility, air is drawn in an evacuated tank from an atmospheric pressure reservoir. Supersonic flow is achieved by using different interchangeable nozzle blocks. Seven blocks are available at DRDC Valcartier, permitting operating in the following Mach numbers: 1.5; 1.75; 2.0; 2.5; 3.0; 3.5 and 4.0. Transonic flow is obtained by the use of a perforated chamber with boundary layer control through suction. Subsonic flow is obtained with one nozzle block and a downstream choke valve. It is very flexible and relatively low cost facility, which permits up to 10 tests per day. Schematic of the experimental facility is presented in the Figure 2.

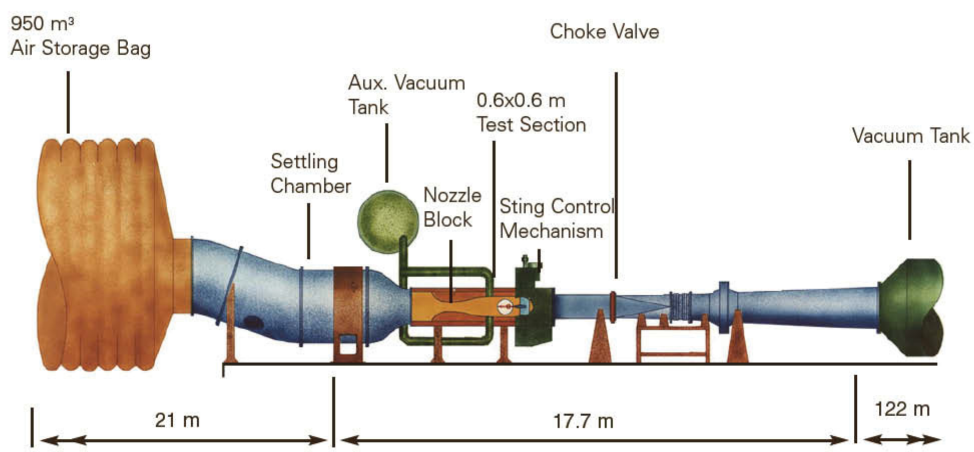


Figure 2: The DRDC Valcartier tri-sonic wind-tunnel.

Because its in-draft characteristic, Reynolds numbers in the test section are lower than real free-flight conditions. The range of Reynolds numbers for the test campaign varied between 12.8 x 10^6/m at Mach number 2.0 to 7.8 x 10^6/m at Mach number 3.0.

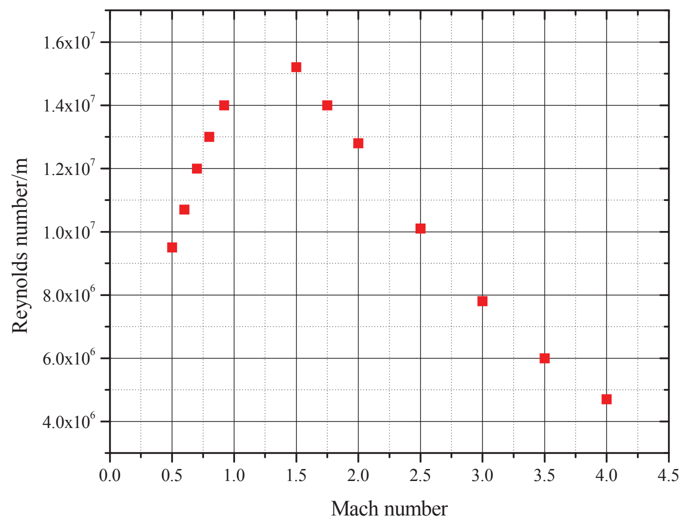


Figure 3: Reynolds number par meter in the DRDC Valcartier tri-sonic wind-tunnel.

Standard instrumentation, such as Pitot tubes, wall pressure taps and temperature probes, located in the settling chamber and in the test section were used to monitor the wind-tunnel freestream conditions.

2.2 The air intake model design

The model used in the wind-tunnel test campaign was a rectangular air intake with a design Mach number of 2.5 and an internal cowl lip angle of 12 deg based on VOLVO Flygmotor AB design [1],[5], which schematic is presented in Figure 4.

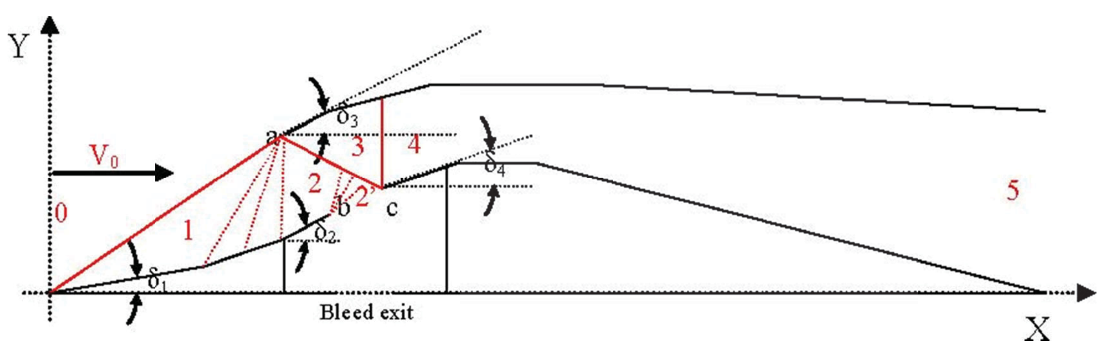


Figure 4: Sketch of internal ramjet air intake geometry

In Figure 4, the red lines represent compression and expansion waves; the normal shock is put in the critical position. The air intake design has the following characteristics:

- Design Mach number equal to 2.5.
- Mixed-compression rectangular air intake type.
- External compression wedge angle of 5 deg at the tip, δ_1, followed by an isentropic compression shape.
- From flow area 2 to 3, the air intake duct cross-sectional area decreases. Downstream of flow area 4, the air intake cross-sectional area is constant over a certain length followed by the subsonic diffuser that is characterized by an increasing cross-sectional area.
- Internal cowl lip angle equal to 12 deg, δ_3.
- Boundary layer bleed system.

The boundary layer bleed system consisted of a bleed block at the end of the isentropic ramp and two rows of 19 bleed holes, 3.0 mm diameter, close to the cowl lip. A prismatic valve with a variable position at the outlet of the air intake was used to simulate different operating conditions of the combustor. Figure 5 presents the ramjet air intake model manufactured at DRDC Valcartier workshop.

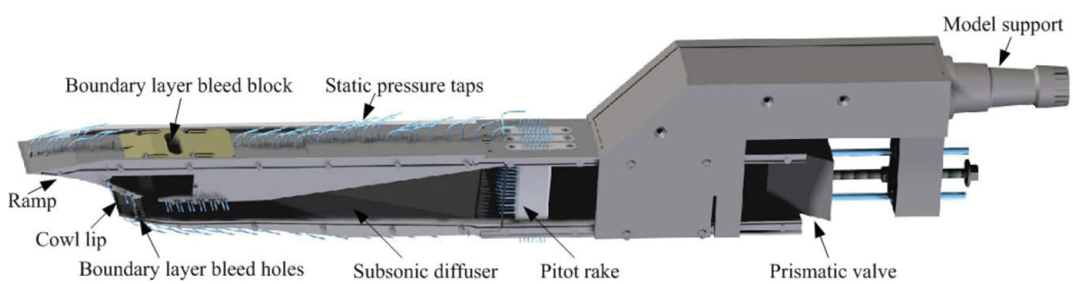


Figure 5: The air intake wind-tunnel model design.

The model is provided with 125 static pressure taps to gather flow physics associated with the internal flow, to locate shock impingement points as well as regions of flow separation, and to support the validation of CFD codes. A longitudinal row of wall static-pressure orifices extends from the leading edge of the air intake ramp down to the end of the subsonic diffuser. This allows a good evaluation of the supersonic and subsonic diffuser performance. An additional row of static taps along the centerline of the cowl in the longitudinal direction is used to locate shock waves in the throat or subsonic diffuser region.

In order to avoid influence of adjacent holes, the static pressure taps are spaced 50 tap diameters apart, following recommendation in previous studies [6].

Total pressure profile at the combustor face is an important parameter to evaluate performance of air intakes, such as the mass flow rate, pressure recovery and flow distortion. In the wind-tunnel test campaign, total pressure profile was obtained from a Pitot rake station provided with 49 probes. This limit the spatial resolution of total pressure profile obtained from the experiments. Additionally, four wall pressure taps are used to measure static pressure at the center of each face in the Pitot tube rake plane. Detail of the static and total pressure station is illustrated in Figure 6.

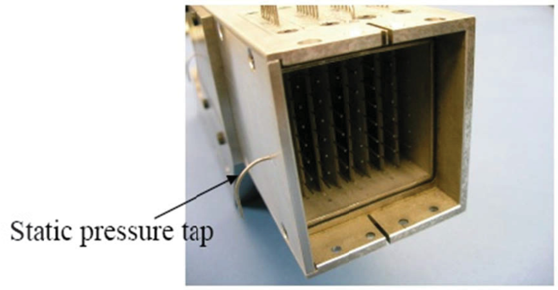


Figure 6: Pitot rake station.

Using the average of these four static pressure measurements and the total pressure obtained with the Pitot tube rake, the Mach number necessary to evaluate mass flow rate by the duct-based method (Equation (4)(5)) can be calculated.

2.3 Pressure measurements

The pressure instruments used in the experiments and their specific applications are described in Table 1.

Table 1: Pressure instruments.

Measure	Equipment	Accuracy
Wind-tunnel static pressure	Rosemount model 1301-A-4-A	0.11%F.S.
Wind-tunnel total pressure	Rosemount model 1201F1A14A1B	0.11%F.S.
Model static/total pressure	ESP miniature pressure scanner ± 1.0; 2.5; 5.0 and 2 x 15.0 psid	0.15% F.S.

Figure 7 presents the ramjet air intake model in the test section of the DRDC Valcartier wind-tunnel.

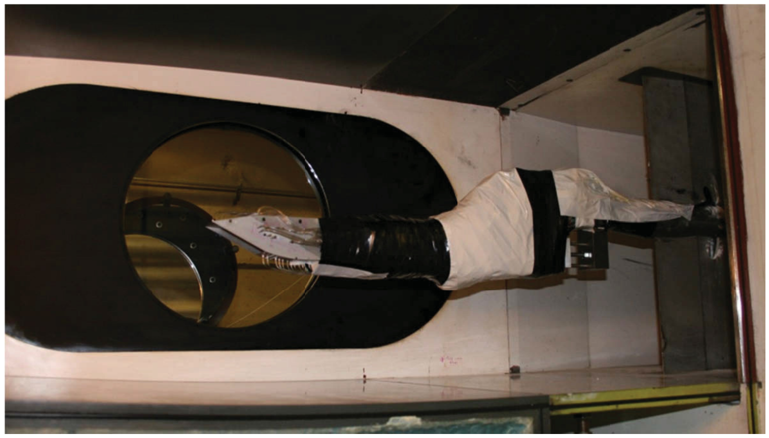


Figure 7: Ramjet air intake model in the wind-tunnel.

Measurements of wind-tunnel static pressure are required to permit calculation of Mach number in the test section, Ma, from Equation (5).

$$Ma = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P_0}{P_s}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{8}$$

where

P_s : mean static pressure at wind-tunnel wall, Pa

P_0 : total pressure at the settling chamber, Pa

3 Experimental results

The model was tested at three different Mach numbers (2.0; 2.5 and 3.0), four AoA (-2.5; 0; 5 and 10 deg) and several positions of prismatic valve insertion and bleed opening.

As shown in Figure 8, the Pitot rake data obtained could not provide us with concise spatial and temporal diagnostics of the flow physics inside the air intake, as illustrated by a typical pressure measurement from such a system.

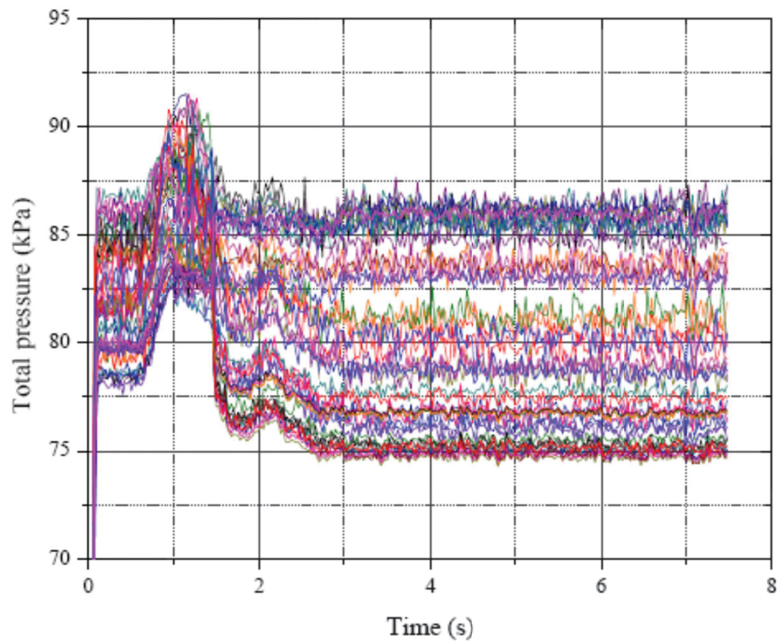


Figure 8: Typical pressure measurements at Pitot rake station.

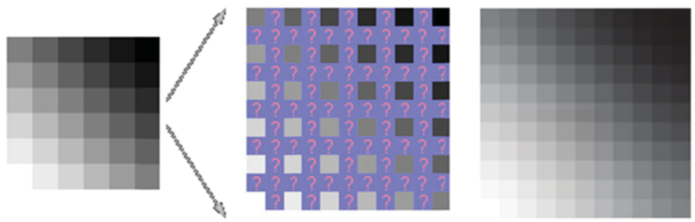
Therefore, a flow mapping technique using an interpolation algorithm implemented in Matlab was developed in order to facilitate the diagnostics of the internal aerodynamics of the air intake. Note that the first three seconds show the start-up of the wind-tunnel.

In order to improve the visualization of total pressure data in the combustor face, and to overcome the limited spatial resolution of the Pitot rake, a two-dimensional flow mapping was implemented using the 49 total pressure readings from the Pitot rake station. The four wall pressure measurements at the Pitot rake section were used as the boundary condition.

4 Interpolation algorithms

Interpolation is the method that allows to build up a new dataset from a discrete set of data previously known. Unlike smoothing, interpolation techniques estimate curves or surfaces passing through all data points. In fact, interpolation is a particular case of curve fitting, in which the function must go through all data points. Interpolation is also largely used when it comes to image scaling in computer graphics. Such process allows pictures to be resized or remapped to maintain their best quality and smoothness.

As shown in Figure 9, each pixel represents in this case a pressure measurement and the interpolation tries to provide best pressure value based on the surrounding pressures. One has to consider that the result of the interpolation depends on how much information is available. MatlabR2006a was the software suite available for the study.



Time averaged data   Before   Interpolated

Figure 9: 2D interpolation.

4.1 2-D Interpolation algorithms in MatlabR2006a

There are three interpolation algorithms in MatlabR2006a for two-dimensional data: the nearest neighbour, bilinear and bi-cubic algorithms [7]. All of these methods require that x and y be monotonic, that is, either always increasing or always decreasing from point to point.

The particular difference between these algorithms above is how they analyze a value of a matrix's element and use it to determine a new value for the new element next to the previous one.

4.1.1 Nearest neighbour interpolation

It fits a piecewise constant surface through the data values. The value of an interpolated point is the value of the nearest point.

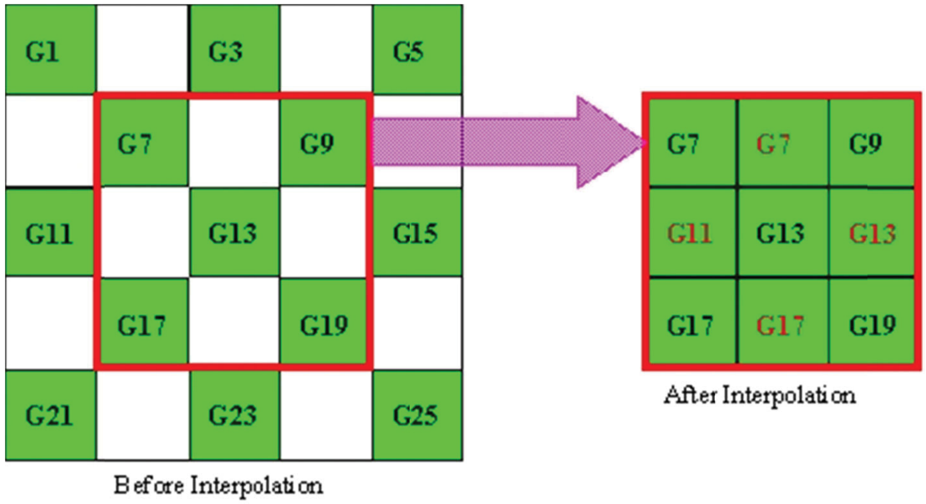


Figure 10: Nearest neighbour interpolation.

The nearest neighbour interpolation is the simplest and the less time consuming method. It simply takes a value of a matrix's element and assigns it to the new closest element. Therefore, this method does not create an anti-aliasing effect when the matrix is plotted and will not be considered further in this paper. The syntax of this interpolation method in Matlab is:

ZI = interp2(X,Y,Z,XI,YI, 'nearest')

4.1.2 Bilinear interpolation

This method fits a bilinear surface through existing data values. Bilinear interpolation is an extension of linear interpolation for interpolating functions of two variables. The value of an interpolated point is a combination of the four closet points. This method is piecewise bilinear, and generally it is faster and less memory-intensive than bi-cubic interpolation. The key idea in this method is to perform linear interpolation first in one direction:

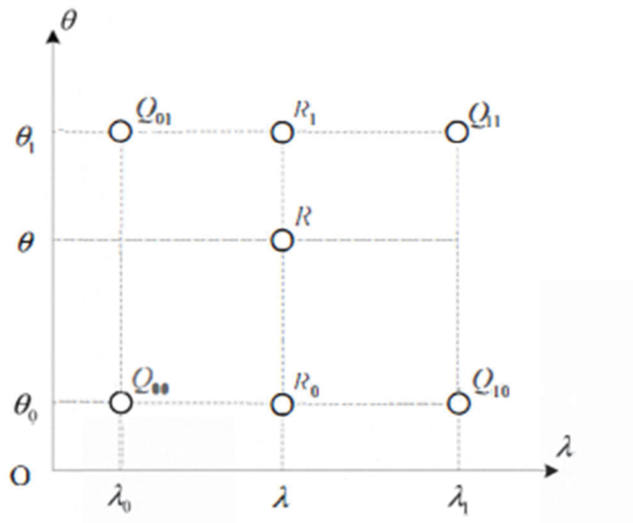


Figure 11: Coordinates for bilinear interpolation.

$$f(R_0) = \frac{\lambda_1 - \lambda}{\lambda_1 - \lambda_0} f(Q_{00}) + \frac{\lambda - \lambda_0}{\lambda_1 - \lambda_0} f(Q_{10})$$

$$f(R_1) = \frac{\lambda_1 - \lambda}{\lambda_1 - \lambda_0} f(Q_{01}) + \frac{\lambda - \lambda_0}{\lambda_1 - \lambda_0} f(Q_{11})$$

and then in the other direction:

$$f(R) = \frac{\theta_1 - \theta}{\theta_1 - \theta_0} f(R_0) + \frac{\theta - \theta_0}{\theta_1 - \theta_0} f(R_1)$$

The syntax of this interpolation method in Matlab is:

ZI = interp2(X,Y,Z,XI,YI, 'linear')

4.1.3 Bi-cubic interpolation

This method fits a bi-cubic surface through the measured pressure data points and the value of an interpolated point is a combination of the closest 4x4 neighbourhood for a total of sixteen closest points. Since these points are at different distances from the interpolated point, closer neighbours are given a higher weighting in the calculation. This method is piecewise bi-cubic, and produces a much smoother surface than bilinear interpolation. Bi-cubic interpolation is used when the interpolated data and its derivative are continuous. The bi-cubic algorithm produces sharp images and is less time-consuming compared with higher order interpolation techniques, which make it one of the most common interpolation methods in two dimensions.

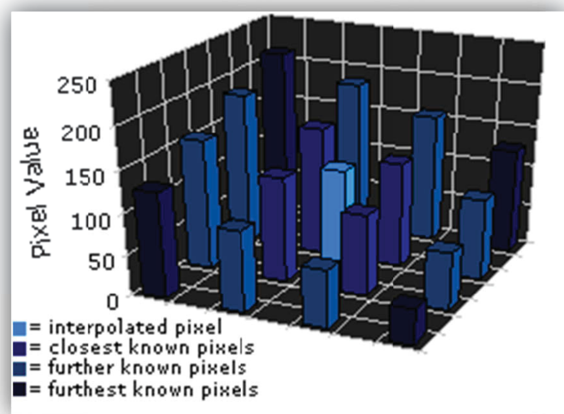


Figure 12: Bi-cubic interpolation.

The syntax of this interpolation method Matlab is:

ZI = interp2(X,Y,Z,XI,YI, 'cubic')

4.2 Interpolation of wind-tunnel data

The operating condition presented in this section refers to Mach number 2.5, prismatic valve insertion of 20.57 mm, ramp bleed opening of 5.15 mm and zero angle-of-attack. Figure 13 shows the averaged total pressure profile at Pitot rake station without interpolation, after filtering high-frequency noise in the measurements shown in Figure 8.

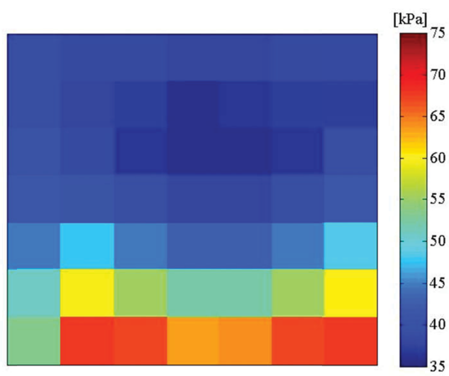


Figure 13: Averaged total pressure profile without interpolation.

Figure 14 to Figure 16 illustrate the improvements on the interpolation of the averaged total pressure profile as function of the mesh size for the three interpolation algorithms in Matlab. During each pass of calculation, the distances between two neighbour points are reduced by half.

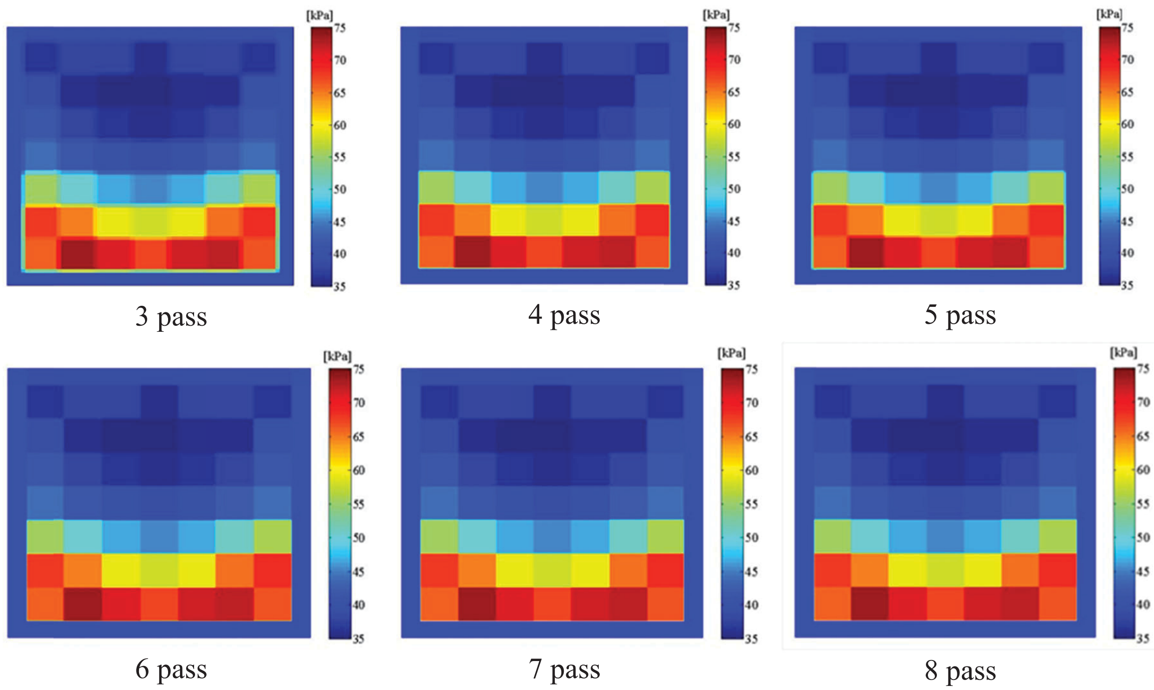


Figure 14: Averaged total pressure profile with nearest neighbour interpolation.

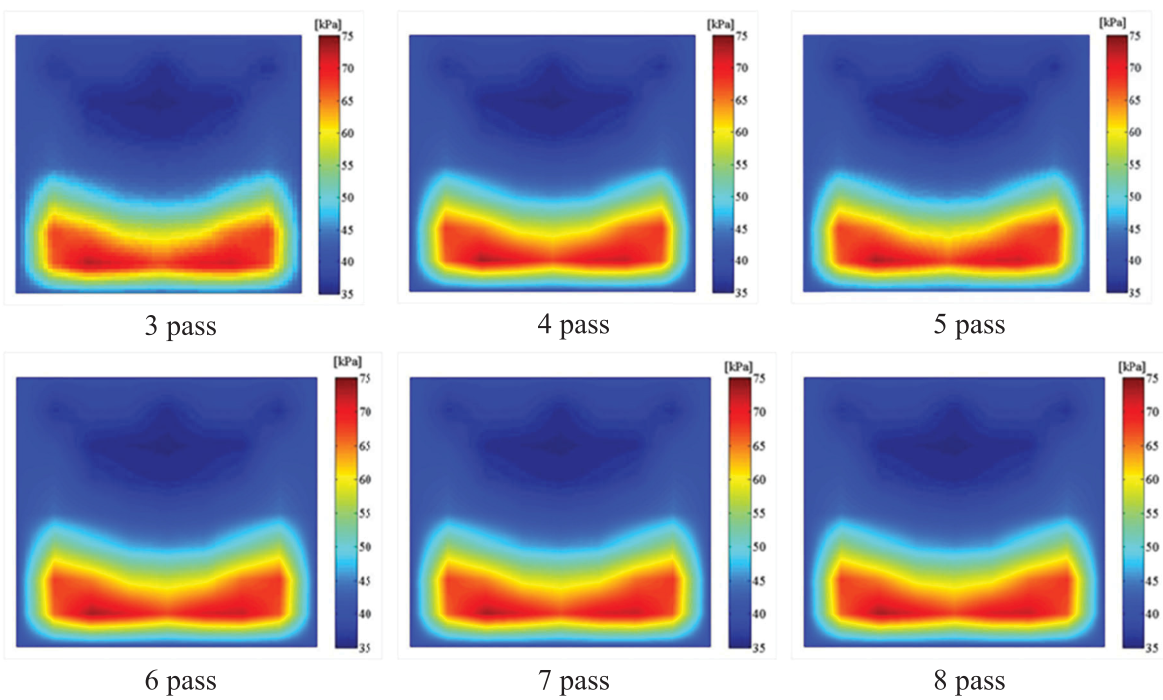


Figure 15: Averaged total pressure profile with bilinear interpolation.

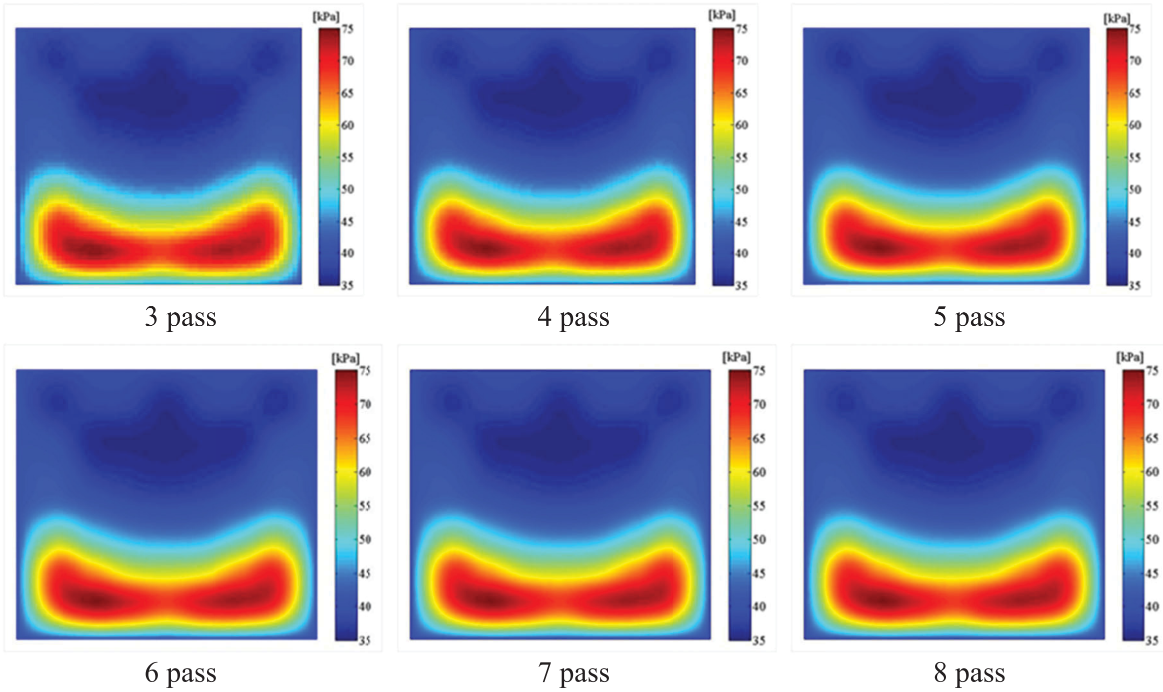


Figure 16: Averaged total pressure profile with bi-cubic interpolation.

Figure 17 demonstrates that, independent of the interpolation method; the solution converges after four pass meshes.

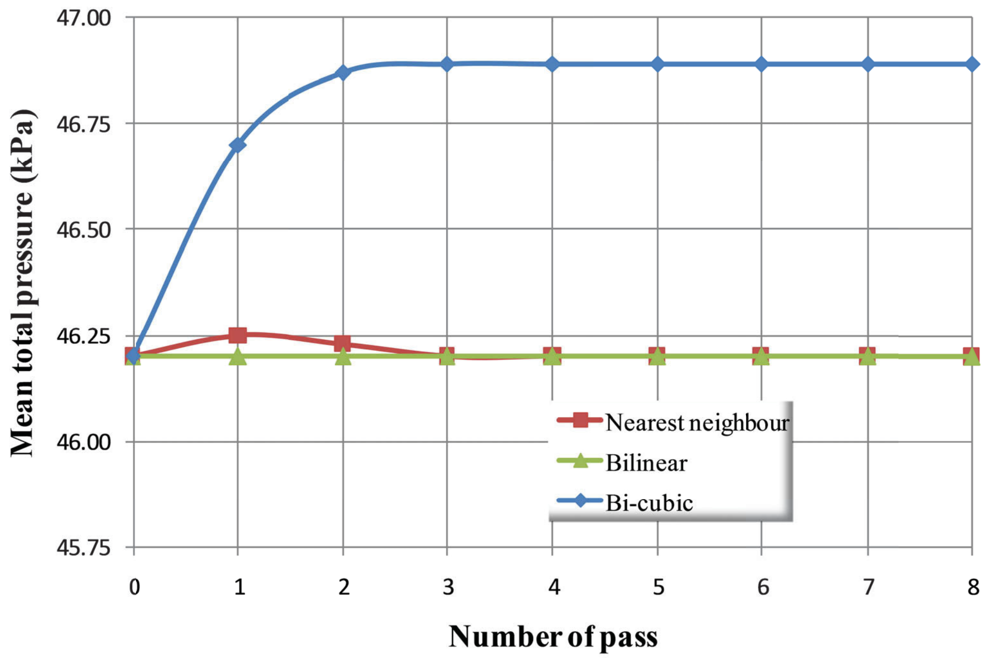


Figure 17: Interpolation of mean total pressure.

Ones could also note from Figure 14 to Figure 16 that no significant improvements are obtained on the total pressure mapping when the number of pass is higher than six. Additionally, bi-cubic interpolation provided smoother total pressure profile.

Results presented on Figure 18 show the computation time on an Intel Core Duo CPU U9400 (1.4 GHz) needed to perform the interpolation. The figure indicates no relevant difference on computation time between the three interpolation methods. Best trade-off between processing time and output quality leads us to use six pass meshes. The bi-cubic interpolation with six passes was therefore selected.

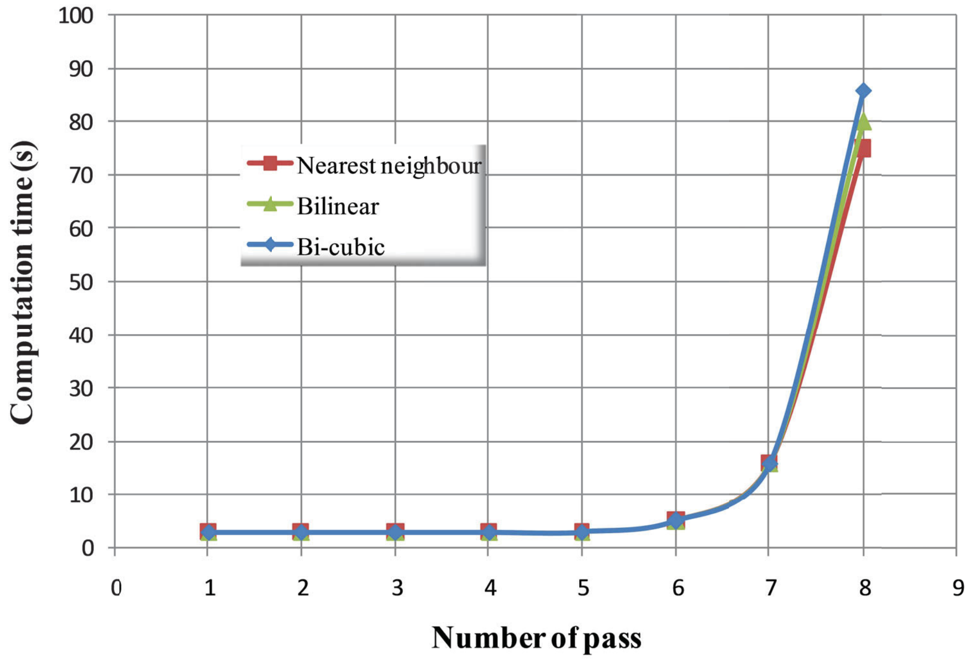


Figure 18: Time of computation for bi-cubic interpolation.

Besides providing graphic output of total pressure data at the combustor face, the algorithm calculates the mean total pressure ($P_{0,2}$) using the area averaged method [3], and evaluates the air intake performance parameters, such as pressure recovery (π), flow distortion (Δ) and mass flow rate, $\dot{m}$. When using time dependent pressure data, the technique permitted visualization of eventual flow instabilities in the internal flow conveyed to the combustor.

4.3 Time resolved interpolation of wind-tunnel data

Figure 19 shows six instants of a typical animation for the Ma 2.5, prismatic valve insertion of 29.57 mm, bleed block opening 5.15 mm and 0 deg AoA operating condition.

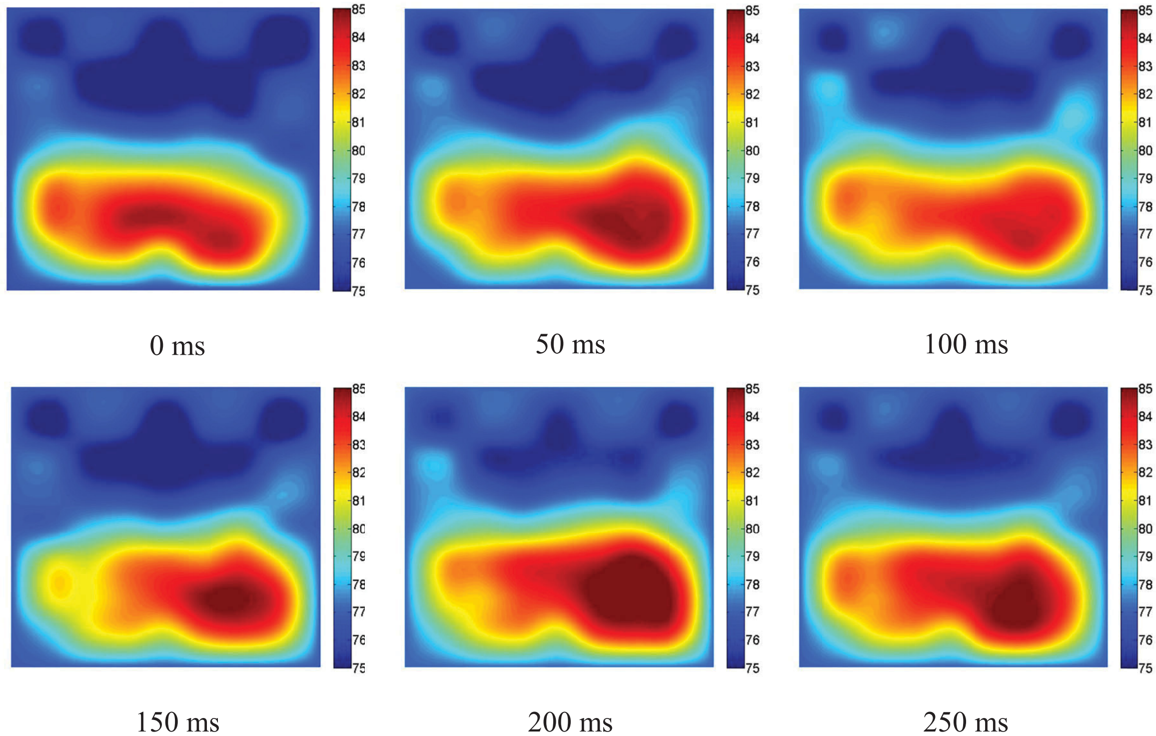


Figure 19: Total pressure in kPa at Pitot rake station as a function of time.

With interpolation, it is now possible to observe significant spatial and temporal variations that are taking place at the combustor face (Pitot rake station). It now becomes possible to characterise flow distortion (Δ) with animations depicting the physical process instead of the straight values (minimum, maximum and average) used previously.

Examples of the flow patterns at the Pitot rake station at different operating conditions, using six-pass meshes are presented in Figure 20 to Figure 22.

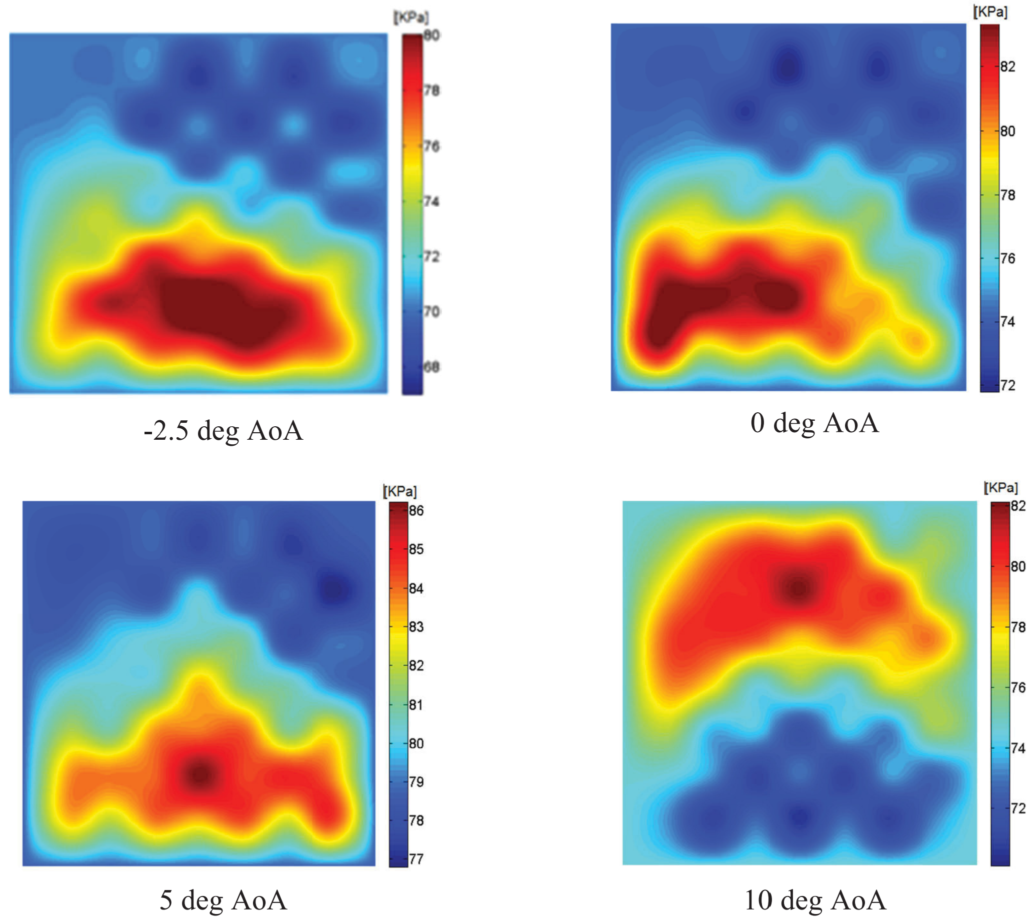


Figure 20: Total pressure profile at Pitot rake station – Ma 2.5, Wedge 29.57 mm, Bleed 2.53 mm.

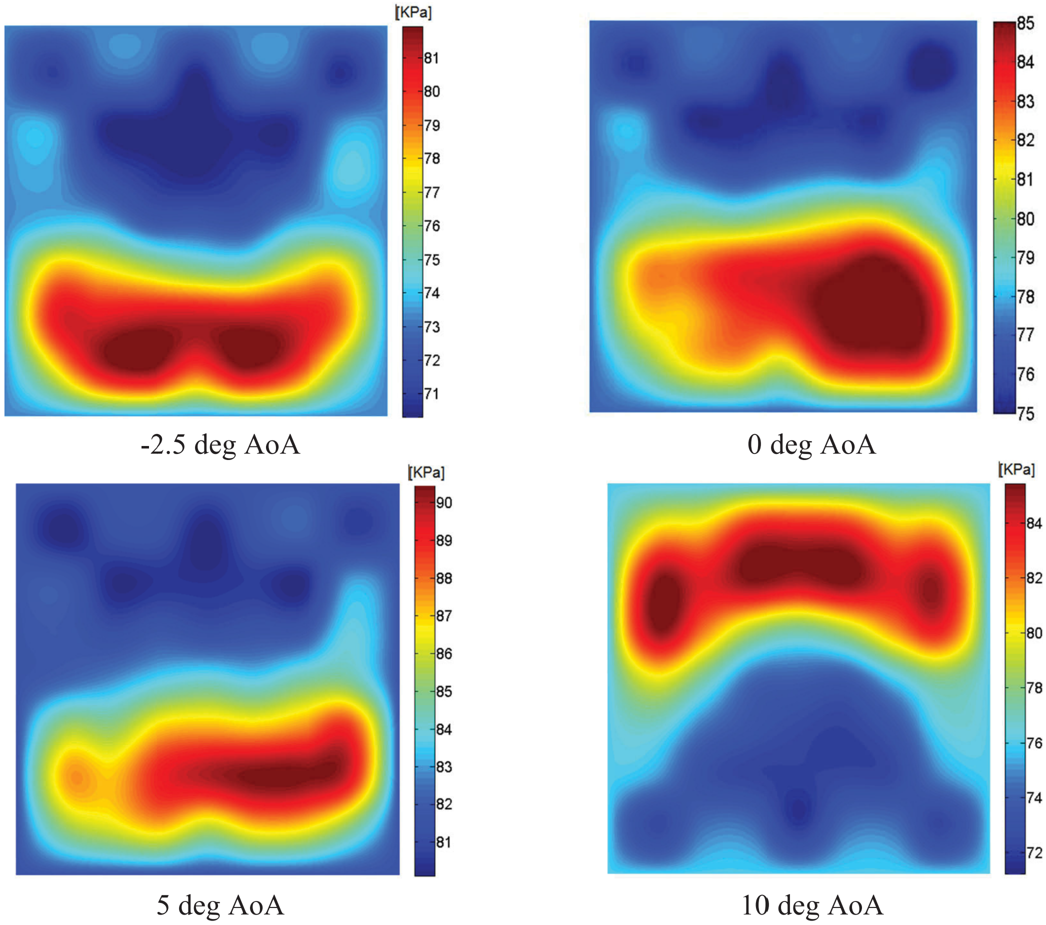


Figure 21: Total pressure profile at Pitot rake station – Ma 2.5, Wedge 29.57 mm, Bleed 5.15 mm.

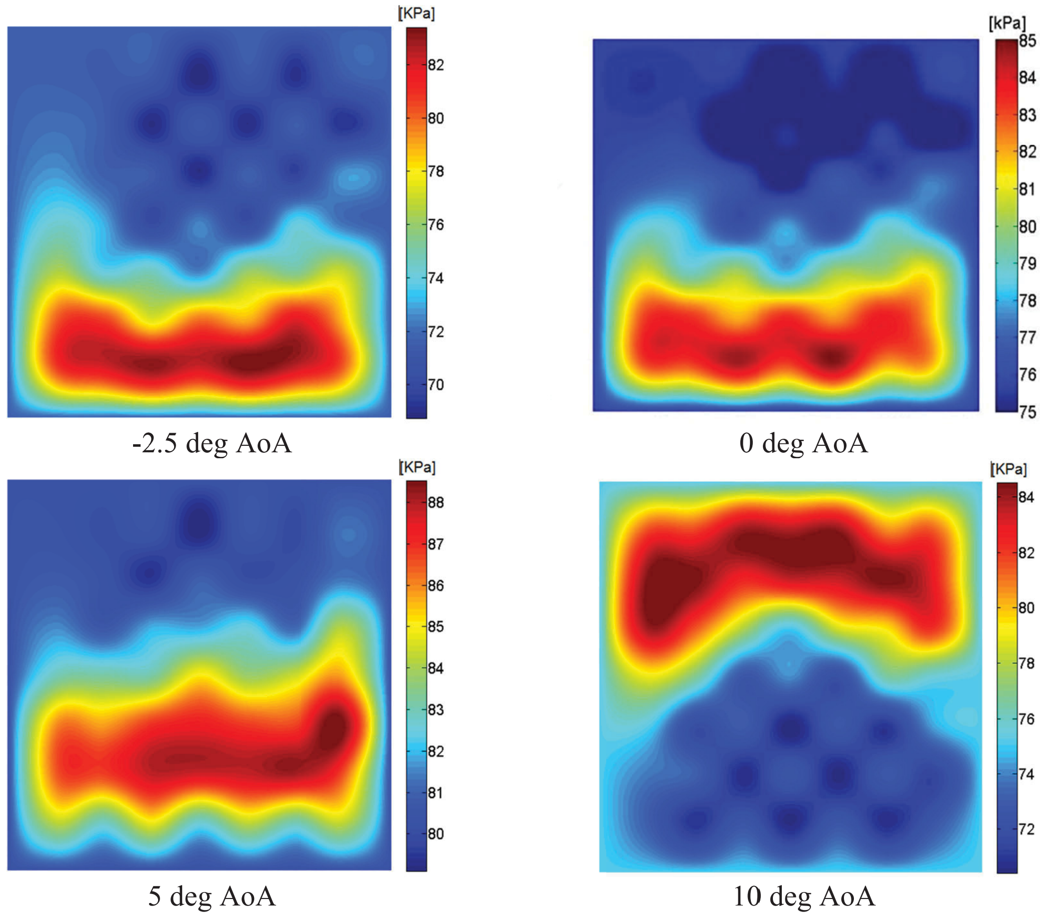


Figure 22: Total pressure profile at Pitot rake station – Ma 2.5, Wedge 29.57 mm, Bleed 7.59 mm.

In the figures, it is possible to observe interesting flow features such as well defined cores, secondary flows, or symmetry planes. Correspondence of these pictures with CFD results would be very valuable.

5 Conclusions and recommendations

This study evaluates the 2D interpolation algorithms available in Matlab to improve flow visualization and to estimate the mean total pressure at the combustor face, which is necessary for calculation of pressure recovery, flow distortion and the mass flow rate of air intakes during wind-tunnel test campaign.

There are three interpolation algorithms in MatlabR2006a for two-dimensional data, which were evaluated in this study: the nearest neighbour, bilinear and bi-cubic algorithms. The bi-cubic algorithm produced sharper images and no relevant difference on computation time between the three interpolation methods was observed. The quality of those interpolation methods could be validated using CFD solutions of simpler test cases. Best trade-off between processing time and output quality leads us to use six pass meshes.

The algorithm can now be used to treat all the existing wind-tunnel data of the DRDC/TNO supersonic intake for better characterisation of the physical process for all operating conditions. This new information, combined with further CFD solutions, will provide a good data set to help evaluation of supersonic airbreathing missiles performance. The effect of distortion at the combustor face on the engine performance should be further investigated now that more detailed information on the flow is available. Additionally, the algorithm will be used for evaluation of eventual improvement on air intake performance due to use of plasma actuators in the framework of the TIF 11az01 “Plasma discharges for improved stealth and aerodynamics”.

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List of symbols/abbreviations/acronyms/initialisms

A	Area, m^2
A^*	Area of the chocked nozzle, m^2
AoA	Angle of attack, deg
CFD	Computational Fluid Dynamics
c^*	Characteristic velocity, m/s
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
$\dot{m}$	Mass flow rate, kg/s
Ma_b	Mach number at the bellmouth
Ma_w	Mach number at the wedge
P_{02}	Mean total pressure at the Pitot rake station, Pa
P_{00}	Free stream total pressure, Pa
P_{0d}	Total pressure in the duct, Pa
P_b	Static pressure bellmouth, Pa
R	Gas constant, 287 J/kg.K for air
Re	Reynolds number
R&D	Research & Development
$T_{0\infty}$	Total ambient temperature, K
x	Wedge insertion depth, mm
Δ	Flow distortion
γ	Ratio of specific heats, 1.4 for air
π	Pressure recovery
θ	Angle of the wedge, deg

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Under the CA/NL MOU IA-6, DRDC Valcartier in Canada and TNO Defence, Security and Safety in the Netherlands jointly work to improve their numerical prediction capability on airbreathing powered missiles. As part of the collaboration program and to fill in the gap on the availability of experimental data in the open literature, wind-tunnel tests were carried out at the DRDC Valcartier tri-sonic wind-tunnel in order to gather internal aerodynamic performance data on a rectangular air intake model in isolation.

The experimental data from the wind-tunnel test campaign aimed to improve the understanding of flow physics inside supersonic air intakes, to validate commercial CFD codes and to serve as input for the ramjet engine performance prediction code developed by DRDC Valcartier and TNO, the DRCORE model.

Mass flow rate, pressure recovery and flow distortion at the combustor face, are outstanding parameters to support assessment of overall engine performance. The evaluation of those performance parameters is strongly dependent on the accuracy of total pressure measurements. In the wind-tunnel test campaign, total pressure measurements were obtained by means of a Pitot rake located in the combustor face of the ramjet, and then averaged in order to define a unique value for determining the performance parameters. However, Pitot rake measurements have limited spatial resolution so as to avoid disturbance to the internal flow.

This study evaluated the ability of the two-dimensional interpolation algorithms implemented in Matlab R2006a to map the flow at the Pitot rake section to overcome the limited spatial resolution of experimental measurements, and to improve flow visualization and the accuracy on the evaluation of total pressure. Additionally, the algorithms allowed calculation of performance parameters (mass flow rate, pressure recovery and flow distortion) of the air intake during the wind-tunnel experiments. Some experimental results using the different algorithms in MatlabR2006a are presented and compared.

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Flow visualization; Air intakes; Interpolation algorithm

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