Series 01 Aerodynamics 15

Base Flow and Exhaust Plume Interaction

Part 1: Experimental Study

M.M.J. Schoones/W.J. Bannink



**Delft University Press** 

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# LIST OF SYMBOLS

## Latin Letters

Α	continuity constant
$C_M$	plume similarity parameter derived by Moran
D	diameter
f(s)	distribution function
f( heta)	density distribution
L	length
m	molecular weight
Μ	Mach number
$N = p_{tj}/p_{\infty}$	ratio of jet stagnation pressure to free stream static pressure
р	pressure
r	spherical radius, radial co-ordinate
Re	Reynolds number
R	radius
Т	temperature
u	Cartesian velocity component in x direction
v	Cartesian velocity component in y direction
w	Cartesian velocity component in z direction
x	axial distance measured from base
У	lateral distance, y=0 at model vertical symmetry plane
Z	co-ordinate pointing upwards, z=0 at model horizontal symmetry plane

## **Greek Letters**

α	flow expansion angle, constant
β	constant
δ	boundary layer thickness
$\delta_N$	nozzle half angle
γ	ratio of specific heat
θ	polar co-ordinate and streamline angle
ρ	density
ν	Prandtl-Meyer angle
$\varphi$	angle between barrel shock and upstream streamline
$\phi$	azimuthal angle at base, $\phi = 0$ at top of model

LIST OF SYMBOLS

## Subscripts

b	jet boundary, base
с	curvature
e	nozzle exit
E	after expansion
j	jet
р	Pitot
pl	jet plume
t	total, stagnation
$\infty$	infinity

### Superscripts

\* nozzle throat

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# Chapter 1

# INTRODUCTION

A combined experimental and computational study of the flow field along an axi-symmetric body with a single operating exhaust nozzle has been made for the FESTIP Aerothermodynamics [3] investigation. This study was carried out in the scope of the Future European Space Transportation Investigations Program (FESTIP) in the Delft University of Technology transonic/supersonic wind tunnel and was part of a joint computational/experimental research program on base flow-jet plume interactions. The model was mounted in supersonic free streams of Mach 1.96 and 2.98, the jet exhausting from the nozzle had an exit Mach number of 4 and operated at various jet stagnation pressures. The Reynolds numbers based on the length of the model were greater than  $5 \cdot 10^6$ . In addition, to ascertain a turbulent boundary layer, the boundary layer on the model was tripped for accurate comparison with numerical simulations. The present investigation embroiders on this theme.

The supersonic jet emanating from the centrally protruding exhaust nozzle in the base interacts with the external main flow around the body. In the interaction zone a turbulent mixing layer, a re-circulation region and a shock system, consisting of a plume shock and a barrel shock, are formed. Flow reattachment at the base, important with respect to heat-transfer, is likely. The present report aims to investigate these different flow phenomena.

In order to explore and explain the before mentioned flow phenomena, experiments have to be conducted to determine the physics of the flow field. To examine the exhaust plume and its influence on the co-flowing supersonic stream, detailed five-hole probe surveys behind the model across the plume will be made. In this way a number of flow quantities can be determined simultaneously at single points in the flow field.

The question arises what the influence of the exhaust plume is on the base pressure. Steady base pressure measurements have been presented in previous studies. However, the base pressure signals might show a dynamic behaviour caused by the exhaust plume and/or the co-flowing supersonic stream. To gain physical insight in the base flow-jet plume interactions, dynamic base pressure measurements will be made. Analysis of the spectrum of a dynamic signal provides insight in the physical behaviour of the flow field. It will be considered whether or not physical phenomena, such as vortex shedding, cause dynamic behaviour.

## **Chapter 2**

# THE STRUCTURE OF UNDER-EXPANDED JETS IN A CO-FLOWING SUPERSONIC FREE STREAM

#### 2.1 Description of Under-expanded Jets

The structure of under-expanded jets has, among others, been investigated in detail by Adamson & Nicholls [1], Moran [12], and Peters & Phares [15]. These three studies are restricted to plumes exhausting into quiescent media. In the present (two-dimensional) description the results of these studies are extrapolated to under-expanded jets in a co-flowing supersonic free stream.

The pressure at the exit of an isentropic supersonic nozzle is a function of the upstream stagnation pressure and the nozzle to throat area ratio. The ambient pressure and the static pressure at the nozzle exit will generally show a difference in magnitude. The jet is called under-expanded when the exit pressure of the exhaust gas,  $p_e$ , is higher than the ambient pressure. The following description is based on the under-expanded jet.

When the nozzle operates at design conditions, i.e., the Mach number  $M_e$  at the nozzle exit has reached its design value, the exhaust air expands in a fan centred at the nozzle lip (Fig. 2.1). Streamlines close to the nozzle wall are deflected through an angle  $\alpha$ , sufficient to expand the gas to the ambient pressure. More inside the jet the flow is expanded more and causes the gas to fall to pressures below the ambient pressure. Recompression to the ambient pressure partly takes place through compression waves, formed at the intersection of expansion waves with the jet boundary, coalescing into the barrel shock. The barrel shock is a line of demarcation between the interior region, which is independent of the ambient pressure, and the outer region, which is influenced by the ambient pressure.

The jet flow upstream of the barrel shock assumes a source-like nature, and can be described by the source-flow-model. The barrel shock is an oblique axi-symmetric shock that is being driven towards the nozzle axis by the external pressure further downstream. Through the expansion at the nozzle lip the exhaust gas acquires a velocity of which the radial component initially sweeps the barrel shock away from the nozzle axis. The flow downstream of the barrel shock is rotational as the barrel shock strengthens with distance from the nozzle exit (compression waves coalesce into the barrel shock) producing an entropy gradient across the shock layer. The 'inner shock layer' covers the region between the jet boundary and the barrel shock and contains the jet boundary and the shear layer growing along the jet boundary. To allow the gas to follow the



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Figure 2.1: Schematic Geometry of an Under-expanded Jet

curvature of the barrel shock a significant static pressure gradient across the shock layer due to the centrifugal acceleration is also required. The under-expanded jet in a co-flowing supersonic stream has got, in contrary to an under-expanded jet issuing into a quiescent gas, a boundary of inconstant pressure.

The external flow, which has been deflected by the centered expansion at the end of the model, again changes direction because of the expanding jet and an oblique shock, called the plume shock, develops in the supersonic external stream. Consequently the pressure at the jet boundary is increased. Compared to its quiescent counterpart the expansion of the plume is significantly reduced this way. When the plume jet boundary turns back towards the nozzle axis, the free stream expands and as a result the ambient pressure drops. This in turn tends to reduce the contraction of the jet. Both processes help to adjust the jet pressure to the ambient pressure and tend to dampen the formation of downstream shock cells, which are evidently present in the flow field of under-expanded jets issuing into quiescent media. The mechanism of adjusting the jet pressure to the ambient pressure is called the 'supersonic pressure relief effect'.

In the case of moderately and highly under-expanded jets the barrel shock is too strong to reflect in a regular manner from the axis of symmetry. A Mach stem is formed which in the axisymmetric case is known as a Mach disc. Cain [8] clearly describes this phenomenon. Peters & Phares [15] showed that in the case of slightly under-expanded jets, like in the cases studied in the present investigation, the barrel shock reflects in a regular manner from the axis of symmetry.

#### 2.2 Plume Similarity

The plume length  $L_{pl}$ , representing the axial distance from the nozzle exit plane to the Mach disc or the reflection point of the barrel shock at the axis of symmetry, may serve to describe a plume similarity quantity.  $L_{pl}$  increases with increasing pressure ratio  $N = p_{tj}/p_{\infty}$ . Morris *et al.* [14] expressed the plume length as

$$L_{pl} = \sqrt{N}D^* \tag{2.1}$$

where  $D^*$  is the nozzle throat diameter. Due to slight differences in derivation or for convenience in analysis  $\sqrt{N}D^*$  is often multiplied by a weak function of  $M_e$  and  $\gamma_e$  that has a value of the order 1. Moran [12] derived a plume length similarity parameter for a cold under-expanded jet, which is invariant for a fixed nozzle and a constant free stream Mach number. It is expressed as

$$C_M = \frac{L_{pl}}{D_e \sqrt{\frac{p_e}{p_\infty}}} \tag{2.2}$$

 $C_M$  can be found by substituting the plume length equation of Morris *et al.* (2.1) into the plume length equation of Moran (2.2).

The extent of the shear layer (Fig. 2.1) is influenced by the ratio of the inner shock layer thickness  $\delta$  to the plume length  $L_{pl}$ , since the length over which the shear layer grows varies with  $L_{pl}$ . The Mach number at the barrel shock may also influence the growth rate of the shear layer, and since it is a function only of  $\gamma$  and N, N is also an important similarity parameter, see Moran [12].

#### 2.3 Models of Under-expanded Jets

#### 2.3.1 Initial Expansion

In the literature some approximate models of the exhaust plume flow field exist. Here we will adopt a two-dimensional description in order to obtain a first insight in the flow physics. The initial expansion at the nozzle lip may be solved starting from the characteristic (in this case a Mach line) running from the nozzle lip to the centerline. The Prandtl-Meyer expansion close to the nozzle lip generates additional right running characteristics. Intersections of these right running characteristics with left running characteristics from arbitrary points along the starting line are found by assuming straight Mach lines between each successive point. From the compatibility equations the properties at an intersection point are found.

#### 2.3.2 Source Flow Model

The (two-dimensional) model by Simons [18] analytically approximates the jet core flow. It is assumed that far from the nozzle the static pressure is very low compared to the dynamic pressure. Now, the approximation is made of the zero pressure limit in the Euler equations. Then,

the velocity takes the value of the limiting velocity and its direction is along a ray emanating from a source point near the exit of the nozzle (Fig. 2.2). The density at the co-ordinate  $(r, \theta)$ 



Figure 2.2: Barrel Shock and Plume Boundary

is related to the density at the sonic line by

$$\frac{\rho}{\rho^*} = \frac{R^*}{r} f(\theta) A \tag{2.3}$$

where r is the spherical radius,  $R^*$  is the radius of the nozzle throat,  $\theta$  is measured from the plume centreline, and A is a constant obtained from continuity of the rocket-mass flow.

The density distribution  $f(\theta)$  is an unknown function. Boynton [5] suggested that  $f(\theta)$  was best duplicated by a cosine law

$$f(\theta) = \cos^{2/(\gamma-1)} \frac{\pi\theta}{2\theta_{\infty}}$$
(2.4)

where  $\theta_{\infty}$  is the limiting turning angle in case of inviscid supersonic flow. Boynton derived this cosine law from a formula for the density distribution, which is found by considering a two-dimensional expansion at the nozzle lip. The density distribution may be approximated by a series expression or a cosine law. The density profile, suggested by Boynton, provides a reasonable fit to numerical results. Integrating the profile over the exhaust plume shows that in case of a cold jet ( $\gamma = 1.4$ ) the plume axial moment is very accurate indeed (within a few percent of numerical results, see Cain & Jones [6] & [7]).

However, the density distribution  $f(\theta)$  does not accurately represent the density near the limiting angle  $\theta_{\infty}$  (Simons [18]). Therefore, Simons extended the source flow model to obey an exponential decay law,

$$f(\theta) = \cos^{2/(\gamma-1)} \frac{\pi\theta_0}{2\theta_\infty} e^{-\beta(\theta-\theta_0)}$$
(2.5)

where  $\theta_0$  and  $\beta$  are based on a mass flow balance for a given boundary layer profile.

#### 2.3.3 Jet Boundary

The structure of the jet boundary has been investigated into detail by Adamson and Nicholls [1], and Korst *et al.* [11]. Adamson and Nicholls investigated plumes exhausting into quiescent

media, whereas Korst et al. investigated plumes exhausting into a co-flowing supersonic free stream. An analytical approach is used.

The ideal two-dimensional fluid jet boundary can be calculated using characteristic theory. This gives a good approximation to the real jet boundary, although there is actually a viscous mixing region along the boundary. However, the work involved for each nozzle and pressure ratio is considerable and is still only approximate for the above reason and because there is some question about continuation of the characteristic net beyond the intercepting shock.

The initial expansion angle at the nozzle can be found by considering the flow at the lip of a nozzle with half angle  $\delta_N$ . At the nozzle lip, before expansion, the Mach number is  $M_e$  and the corresponding Prandtl-Meyer angle is  $\nu_e$ . After expanding the Mach number is  $M_E$  with a corresponding Prandtl-Meyer angle  $\nu_E$ . Thus, the flow at the nozzle lip turns through an angle of  $\nu_E - \nu_e$  relative to the nozzle wall, and the overall flow expansion angle with respect to the flow axis is  $\alpha$ , where

$$\alpha = \nu_E - \nu_e + \delta_N \tag{2.6}$$

The flow is turned from this initial expansion angle by the intersection of expansion waves of the opposite nozzle lip with the boundary; the expansion waves are reflected as compression waves, which eventually coalesce into the barrel shock.

A two-dimensional physical description of the plume boundary up to its maximum diameter was formulated Albini [2] and Hubbard [10]. The source model of the core flow is the basis of their solutions. Determination of the boundary is done by equating the pressure required to balance the centrifugal acceleration of the shock layer gas along the curved barrel shock and the external pressure to Newtonian pressure of the core flow, which results in the following equation:

$$p_b = \rho_j u_j^2 \sin^2 \varphi + \int_0^\delta \frac{\rho u^2}{R_c} dy$$
(2.7)

where  $p_b$  is the pressure at the boundary,  $\varphi$  the angle between the barrel shock and the ray emanating from the source, and  $R_c$  the radius of curvature of the streamline. The first term on the right hand side of the equation describes the Newtonian term, whereas the second term on the right hand side of the equation describes the centrifugal correction. It is assumed that  $\delta$ , the inner shock layer thickness, is small compared to  $R_c$  and y such that during integration the radii may be assumed constant and the integral becomes

$$\frac{1}{R_c} \int_{\dot{m}_{core}}^{m^*} u d\dot{m}$$
(2.8)

The difference between the methods of Albini and Hubbard is that Albini assumed u to be constant across the shock layer and equal to the local tangential jet velocity component at the barrel shock, whereas Hubbard assumed u to be constant along a streamline in the shock layer and equal to the tangential jet velocity component at the point the streamline crossed the barrel shock. The boundary pressure  $p_b$  is constant if the jet exhausts into a quiescent medium. In the case of a co-flowing stream with a high Mach number the boundary pressure  $p_b$  may be calculated from an equation similar to equation (2.7) for the outer shock layer, but Boynton [5] found it better to neglect the centrifugal term in this case. Chernyi [9] showed that on convex bodies the pressure distribution is better approximated by Newtonian theory without a centrifugal correction. This is a well-known result for the Busemann centrifugal correction in hypersonic flows.

Using this method the problem is reduced to a set of integral-differential equations that are numerically integrated. Boynton [5] showed that the approach of Hubbard agrees quite well with CFD calculations if the density distribution function suggested by Boynton (equation (2.4)) is used and the centrifugal term is neglected for the outer shock layer. The calculations were not overly sensitive to the core flow model and firm conclusions about the core flow cannot be drawn from comparisons of boundary positions alone.

#### 2.3.4 Viscous Solutions and Instability

The laminar shear layer of a plume was subject of an analytical study by Moran [13]. The inviscid flow in the inner shock layer, consisting of the barrel shock, and the jet boundary including the shear layer, had a higher velocity and density than the adjacent inviscid flow in the outer shock layer, consisting of the plume shock and the region between the plume shock and the shear layer. Moran concluded that this was an unstable process. A pressure gradient sufficient to balance the centrifugal acceleration of the low velocity, low-density gas in the outer shock layer is too low to constrain a high velocity, high density gas particle from the inner shock layer. A gas particle will therefore not be drawn back when migrating outwards from the inner shock layer. Likewise, migration into the inner shock layer by gas in the outer shock layer is not prevented.

A jet issuing into a quiescent medium only has an inner shock layer with a shear layer growing in its outer edge. The shock layer would be stable without the shear layer since the entropy decreases from the inner edge (near the barrel shock) to the outer edge. Hence if a heavy outer gas particle were to begin travelling towards the inner edge and expanding isentropically to the local pressure it would always be heavier than the surrounding gas. This prevents migration across the shock layer by particles, in a manner analogous to a meteorological inversion layer. The gas at the outer edge of the shock layer is slowed down by the shear layer and decreased in density as kinetic energy is turned into an increase of internal energy and temperature at constant pressure. The low density and velocity of the particles in the shear layer makes them unstable in the shock layer pressure gradient, because the migration is no longer prevented.

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# **Chapter 3**

# EXPERIMENTAL APPARATUS

### 3.1 Wind Tunnel

The supersonic and transonic wind tunnel TST-27 of the Aerospace Department of the Delft University of Technology (see Figures 3.1 & 3.2) is a blow-down facility with a test section of 280mm width and of a height varying from 250mm to 270mm depending on the Mach number (see Fig. 3.3). Test Mach numbers range from 0.5 to 0.85 in the subsonic test region and



Figure 3.1: Photograph of the TST-27 Wind Tunnel

from 1.15 to 4.2 in the supersonic test region. Supersonic Mach numbers are set by means of a continuously variable throat and flexible upper and lower nozzle walls; the Mach number may be varied during a run. Subsonic Mach numbers are controlled using a variable choke-section in the outlet diffuser. Small deviations of the Mach number during a run are corrected by auto-



Figure 3.2: Schematic Layout of the TST-27 Wind Tunnel

matic fine adjustment of the choke. Downstream of the nozzle and supersonic test section the wind tunnel may be equipped with separate modules, supported on wheels. The modules can be connected by quick-lock couplings to the nozzle part. This allows using the wind tunnel in several configurations. For transonic tests, a transonic test section with either slotted or perforated walls may be inserted downstream of the closed- wall test section. Either of two different model carts may be used, one of which is equipped with an angle of incidence mechanism for sting-mounted models, and the second with a mechanism for traversing probes in three directions through the flow field. The comparatively long running time of the wind tunnel (up to 300s) allows exploring the flow field over a model in detail. The wind tunnel has been designed for operation at high stagnation pressures; the maximum unit Reynolds number varies from 38 million per meter in the transonic range to 130 million per meter at Mach = 4.

#### 3.2 Model Geometry

The selected geometry is axi-symmetric having a spherically blunted cone as forebody and a cylinder of about the same length as the cone as afterbody. The model is supported at the lower side of the aft part and has a free base. From the centre of the base a nozzle protrudes; its outside shape is a circular cylinder. The nozzle itself is conical with a total divergence of 15°. This angle has been chosen to obtain a satisfactory radial flow at the nozzle exit and to minimize the possibility of flow separation. The exit diameter of the nozzle is about one third of the model base diameter. The maximum mass flow through the nozzle was restricted to 1 kg/s because of structural design reasons. An external high- pressure supply was used to supply the gas for



Figure 3.3: Test Section of the TST-27 Wind Tunnel with the FESTIP-model

Nr.	y (mm)	z (mm)	r (mm)	$\phi[^{\circ}]$
15	6.96	16.81	18.20	22.50
23	-5.92	14.30	15.48	-22.50
26	-4.36	10.53	11.40	-22.50

Table 3.1: Positions of Pressure Taps

the exhaust jet. For a realistic jet Mach number of 4 at the nozzle exit, taking into account the requirements imposed by the interior construction length of the nozzle, a nozzle throat diameter of 5mm resulted and an internal exit diameter of 16.4mm. The conical forebody has a semi apex angle of 11° and a fair amount of bluntness in a nose radius of 7.5mm. The cylindrical afterbody has a length of 90mm and the total length of the model is 186.81mm. The model configuration in the TST-27 wind tunnel is depicted in Figures 3.4 & 3.5. Details of the model are shown in Fig. 3.6. Fig. 3.7 shows the distribution of the pressure taps. The distribution of the pressure taps 1 through 27 was used for the FESTIP Aerothermodynamics [3] investigation. In the present investigation the pressure taps 15, 23, and 26 are used. The exact location of the taps is given in Table 3.1. The base pressures were measured using three ENDEVCO high sensitivity piezoresistive pressure transducers of the model 8507C-5, which are mounted in the base of the model.



Figure 3.4: Schlieren Photograph of the FESTIP-model During a Run

#### 3.3 Five-hole Probe

To determine flow quantities in a three-dimensional flow field, for example flow fields containing vortices, five-hole probes can be employed. If the direction of flow is not known five-hole probes can be used to determine the total pressure, static pressure and the direction of flow. This kind of probe consists of a cylindrical tube with a small diameter and a specific shape of the head of the tube. The shapes mostly used for the head of the tube are the frustrated cone shape and the spherical shape. The head is provided with one central orifice and four orifices equally divided along the head, 90° apart.

For the present investigation a five-hole probe with a spherically shaped head has been utilized. The diameter of the cylindrical tube is 1.65mm and the internal diameter of the pressure holes is 0.2mm. Calibration-coefficients for a probe with a spherically shaped head can be derived by means of the theoretical pressure distribution around a sphere. This provides the possibility to develop calibration-coefficients, which are in theory merely depending on the flow quantity for which the coefficient is valid. Spherical probe-head shapes are Mach-insensitive.

The principle of the measuring technique employing five-hole probes is as follows. At first the five-hole probe is being calibrated in a known uniform parallel flow and a known probe disposition with respect to that flow field. Then pressures, velocities and direction of flow at the head of the probe are also known. The relationship between the flow quantities and measured pressures is determined through calibration- coefficients. Once the relationship between the flow quantities and measured pressures has been established, the five-hole probe can be used for measurement in a flow field of which the flow quantities are unknown. Through interpolation in the calibration data the flow quantities were determined.

Because of the fact that employment of a five-hole probe in the jet region involves high risks of damaging the probe, calibration-coefficients of an identical five-hole probe were used. As a result only the Pitot-pressure and the direction of flow could be determined.

#### 3.4 Set-up for Base Pressure Measurements

The base pressures were measured using three ENDEVCO high sensitivity piezoresistive pressure transducers of the model 8507C-5, mounted in the base of the model. It has a 2.34mm cylindrical case and features an active four-arm strain gage bridge diffused into a sculptured silicon diaphragm for maximum sensitivity and wideband frequency response. The resonance frequency is 85,000 Hertz. Pressure ranges can be considered bi-directional. The model 8507C-5 can be used to measure + or - 0.345 bar. Sensitivity in the positive direction is typically within 1% of sensitivity in the negative direction.

The pressure transducers were connected to a Philips and Fluke PM3335 oscilloscope, which can be used to transfer data to a computer. Due to the fact that this type of oscilloscope has two channels, only two out of three pressure transducers were read out simultaneously. The oscilloscope has two memory registers, which were used to store data from both channels using a different time-base during one run. Consequently, during one run both channels produce two sets of measurements. The data was subsequently transferred to a computer where the measurements were stored in 'raw data' files. Using the program Testpoint from Capital Equipment Corporation programs were written to process these data files.



Figure 3.5: Schematic Layout Test Section with FESTIP-model



Figure 3.6: Schematic Cross Section of the FESTIP-model







Figure 3.7: Location of Pressure Taps in FESTIP-Model

# **Chapter 4**

# **RESULTS OF THE FIVE-HOLE PROBE TRAVERSES**

#### 4.1 Procedure of the Investigation

Five-hole probe surveys (3 series) at the base of the model and behind the model across the plume were made in order to investigate the nature of the flow field. Each series consists of a number of traverses executed at different axial distances, i.e., x, behind the base of the model. The free stream Mach number was kept at  $M_{\infty} = 2.98$  and the ratio of jet stagnation pressure to free stream static pressure  $N = p_{tj}/p_{\infty}$  was maintained at a certain level, different for each series. Table 4.1 shows the test matrix for these radial five-hole probe traverses. For each series three traverses were performed in the base region (up to x=17.0mm) and five traverses were performed behind the model across the plume (from x=17.0mm to further downstream positions). Dimension of the model can be found in Fig. 3.6. It was attempted to capture the complete core flow and the most downstream traverse was performed right after the reflection point of the barrel shock at the axis of symmetry of the jet. Because of the fact that employment of a five-hole probe in the jet region involves high risks of damaging the probe a substitute five-hole probe was put to use. This probe was not re-calibrated, but calibration-coefficients of an identical five-hole probe were used. Experience with similar probes has shown that Pitot-pressures and flow directions may be measured with accuracy without actual calibration [4]. determined. Because of the distance between the probe head and the pressure transducers a time lag is introduced. This time lag is mainly dependent on the length and thickness of the tubing, which connects the probe to the pressure transducer. The time lag causes the pressure to reach its final measured value exponentially. Consequently a substantial amount of time is needed for a single traverse. As a result the traverse could only contain a certain number of measurement points and the final result may not be as refined as desirable.

$M_{\infty}$	$p_{ti}/p_{\infty}$	axial position of traverse, measured from base [mm]
2.98	no-jet	2.0,7.0,12.0,17.0,26.5,36.5,51.5,66.5
2.98	200	2.0,7.0,12.0,17.0,26.5,36.5,51.5,96.0
2.98	400	2.0,7.0,12.0,17.0,36.5,51.5,66.5,125.0

Table 4.1: Test Matrix for the Radial Five-Hole Probe Traverses

### 4.2 Pitot-pressure

The Pitot-pressures obtained by the radial five-hole probe traverses are graphically represented in Figures 4.1, 4.2, 4.3, 4.4, 4.6 and 4.7. A distinction has been drawn between the traverses in the base region and the traverses in the jet region. All axial distances are measured starting from the base; all the radial distances are measured starting from the axis of symmetry. The Schlieren photographs of Figures 4.5 and 4.8 show the flow fields in the jet cases. Lines indicate the axial distances of the traverses. The geometry of the flow field might be clarified by Figures 2.1 and 2.2.

#### 4.2.1 Base Region

In case of the traverses in the base region, the traverses up to an axial distance of 17.0 mm, a safe distance between the probe and the model had to be taken into account. The probe travelled from z=12.0 mm to z=28.5 mm for most traverses. However, for the traverse at the axial distance of 2 mm in the case of no-jet the probe travelled from z=10.0 mm to z=26.5 mm. The measurements were made intermittently with steps at an interval of 1.5 mm. This interval was dictated by the time period provided by the capacity of the external high-pressure supply, which was used to supply the gas for the exhaust jet. A smaller interval might have been useful to obtain more detailed pressure distributions, however, the present procedure provided a global picture. In order to obtain dimension-less values the Pitot-pressures,  $p_p$ , were divided by the static pressure,  $p_{\infty}$ . For clarity the Pitot profiles representing measurements at increasing distances downstream from the base, at one ratio of jet stagnation pressure to free stream static pressure  $N = p_{tj}/p_{\infty}$  are represented in one figure.

#### 4.2.2 Jet Region

For the traverses in the jet region, the traverses from an axial distance of 17.0 mm (the end of the nozzle is located at x=16.4mm), a distinction was drawn between an inner and an outer region. In the outer region the jet was of little influence and a relatively large step was applied to obtain a picture as complete as possible within the limited time interval, dictated by the external pressure supply. The radial distances over which the probe travelled, as well as the transition point from the inner to the outer region and the interval steps belonging to the inner and outer regions, are given in Table 4.2. The minimum and maximum radial positions of the probe were z=-3.0mm and z=48.0mm, respectively. Table 4.2 shows the data for all the traverses in the jet region for the different ratios of jet stagnation pressure to free stream static pressure. Because of the high jet pressure, at  $p_{tj}/p_{\infty} = 400$ , the traverse at the axial distance of 17.0mm was limited to z $\geq$ 9.5 mm. The probe travelled from z=9.5mm to z=28.5mm and steps were taken at an interval of 1.5mm. In the graphical representation of the Pitot-pressures this traverse is shown together with the traverses in the base region. The Pitot profiles representing measurements at increasing distances downstream from the base, with the pressure ratio  $N = p_{tj}/p_{\infty}$  maintained at the same level, are represented in two separate figures.

4.2 Pitot-pressure

$p_{ti}/p_{\infty}$	x [mm]	zbegin [mm]	zend [mm]	z <sub>trans</sub> [mm]	$step_i[mm]$	step <sub>o</sub> [mm]
no-jet	17.0,26.5,	-1.5	40.5	27.0	1.5	4.5
	36.5,66.5					
no-jet	51.5	-3.0	37.5	24.0	3.0	4.5
200	17.0,26.5	-1.5	43.5	19.5	1.5	6.0
200	36.5	-1.5	43.5	21.0	1.5	7.5
200	51.5	-1.5	48.0	24.0	1.5	12.0
200	96.0	-3.0	39.0	-	-	3.0
400	36.5,51.5	-2.0	44.0	28.0	2.0	8.0
400	66.5	-2.0	40.0	24.0	2.0	8.0
400	125.0	-3.0	42.0	-	-	3.0

Table 4.2: Radial Five-Hole Probe Traverses in Jet Region

#### 4.2.3 Results, No-jet

The Pitot-pressure curves for the base region, measured by the five-hole probe, in case of no-jet are shown in Fig. 4.1. Moving from the expansion fan, emanating from the end of the cylindrical part of the model, into the base region the pressure falls quickly from the undisturbed value before entering the shear layer to a low, almost constant, value. The further downstream the traverse, the later the pressure drop ends. For the axial distance of 2mm the transition to the region of almost constant pressure occurs at z=22mm, whereas for the axial distance of 12mm the transition takes place at z=19.5mm. The shape of the shear layer causes this effect. In the actual base region all three traverses show nearly the same pressure distribution. The pressures are low and increase slightly travelling towards the nozzle. This indicates that the region between the base of the model and the nozzle is a region of low, nearly constant pressure, physically similar to a wake. The expansion fan from the edge of the base and the shear layer cause the pressure to drop tremendously. On average the Pitot-pressure has dropped to a value of 0.6 times the free stream static pressure.

The Pitot-pressure curves for the jet region, generated by the five-hole probe measurements, in case of no-jet are shown in Fig. 4.2. (Although in this case no jet is present the designation 'jet region' is maintained for practical reasons.) Moving from outside the expansion fan, emanating from the end of the afterbody, towards the axis of symmetry the pressure drops due to the passing of the expansion fan. Travelling through the shear layer causes the pressure to fall more quickly. The locations of the expansion fan and the shear layer are indicated in Fig. 4.2. At axial distances further downstream the shear layer is located closer to the axis of symmetry. Like in the case of traverses in the base region, the pressure is almost constant for each traverse after having passed the shear layer. The region of circulation, or inner region, has been entered. At larger axial distances the cross-section of this region decreases and the Pitot-pressure itself slightly increases. The co-flowing supersonic flow brings about an increase in pressure while travelling downstream along the axis of symmetry. Nevertheless, at an axial distance of 66.5 mm the Pitot-pressure is only approximately 1.2 times the free stream static pressure.

#### FIVE-HOLE PROBE TRAVERSES





#### 4.2.4 Discontinuities in the Flow Field Caused by the Jet

Discontinuities in Pitot-pressure are due to the five-hole probe passing through shock waves. The physics of the flow field containing a jet can be ascertained by looking at the changes in Pitot-pressure. Figures 4.4b and 4.7a clarify the following description. The influence of the plume shock, shear layer and barrel shock on the Pitot-pressure profile at an axial distance of 51.5mm is depicted for pressure ratios  $N = p_{tj}/p_{\infty} = 200$  and N = 400.

Moving from the free stream into the plume, the non-dimensional Pitot- pressure starts to fall slightly. This effect is most likely caused by the Mach number gradient between the expansion fan and the plume shock due to rotational flow generated by the model. Next there is a pressure rise caused by the plume shock (illustrated in Figures 4.4b and 4.7a). Because of the relatively large step interval the plume shock is not accurately captured. The pressure rise is followed by a dip in the profile, caused by the passage of the probe through the shear layer. The pressure rises again to indicate the region of high-density plume gas that has been compressed by the barrel shock. The fall in Pitot-pressure shows passage through the barrel shock (see Figures 4.4b and 4.7a). The core flow inside the plume causes the pressure to rise. The 'flat' region within the core represents the flow from the nozzle which is expanded conically while the points either side of this region where the pressure starts to fall (when moving inside out) represent the position at which the leading characteristics from the nozzle exit intersect the source flow.

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Figure 4.3: Five-Hole Probe Measurement, Pitot-pressure Base Region,  $p_{tj}/p_{\infty} = 200, M_{\infty} = 2.98$ 

#### **4.2.5** Results, Jet, $N = p_{tj}/p_{\infty} = 200$

The Pitot-pressure curves for the base region, measured by the five-hole probe at a jet pressure ratio of  $N = p_{tj}/p_{\infty} = 200$  are shown in Fig. 4.3. The same physical effects as in the case of no-jet can be found in this case. The jet causes the shear layer to curve towards the axis of symmetry. In addition to the decrease of Pitot-pressure caused by the co-flowing supersonic stream, the jet also causes the pressure in the base region to decrease. On average the Pitot-pressure has dropped to a value of 0.4 times the free stream static pressure.

Fig. 4.4 shows the experimental Pitot-pressure distribution in the jet region. The physics of the flow field can be determined by looking at the Pitot-pressure curves generated by the five-hole probe traverses. Section 4.2.4 describes the nature of these pressure curves. The influence of the plume shock, shear layer and barrel shock on the Pitot- pressure profile at an axial distance of 51.5 mm is depicted in Fig. 4.4b. At x=17.0 mm (the jet exits at x=16.4 mm) the shock system caused by the jet is not significantly developed yet. As from x=36.5 mm the complete shock system is clearly present. At larger axial distances the shock waves have gained strength and their effects are more evident. To illustrate the positions of plume shock and barrel shock with increasing axial distance Fig. 4.5 depicts a Schlieren photograph of the flow field. The Pitot-pressure in the plume core decreases for increasing axial distance. The traverse at an axial distance of 96.0 mm passes behind the barrel shock reflection at the axis of symmetry. The effect of the plume shock and the shear layer on the Pitot-pressure is visible, also, the pressure at the axis of symmetry has substantially increased.



Figure 4.4: Five-Hole Probe Measurement,  $\stackrel{(b)}{\text{Pitot-pressure Jet Region}}$ ,  $p_{tj}/p_{\infty} = 200, M_{\infty} = 2.98$ 



Figure 4.5: Schlieren Photograph,  $N = p_{tj}/p_{\infty} = 200, M_{\infty} = 2.98$ 

#### **4.2.6** Results, Jet, $N = p_{tj}/p_{\infty} = 400$

The measured Pitot-pressure curves for the base region for  $p_{tj}/p_{\infty} = 400$  are shown in Fig. 4.6. The physical effects are not fundamentally different from the previous cases. The effect of inward bending of the shear layer is not as prominent as in the previous case, because the plume is larger at higher jet pressures. The average Pitot-pressure has dropped to a value of 0.4 times the free stream static pressure, the same as for  $p_{tj}/p_{\infty} = 200$ . The pressure curve at the x-location just behind the nozzle exit has a similar physical nature as the pressure curves discussed above. The start of the Pitot-pressure rise caused by high-density plume gas that has been compressed by the barrel shock is clearly visible.

The results for the jet region are given in Fig. 4.7. A Schlieren photograph of the flow field in which the axial distances of the traverses are indicated is shown in Fig. 4.8. When comparing to the case of  $N = p_{tj}/p_{\infty} = 200$  no additional remarks are necessary, the overall qualitative picture is similar.

#### 4.3 Flow Directions

Fig. 4.9 shows the flow directions in the case of no-jet, obtained by means of five-hole probe measurements. In this case there is only an external supersonic flow causing an expansion fan emanating from the end of the edge of the base, a shear layer and a large low-pressure region with vortices. The supersonic flow expands towards the axis of symmetry. The shear layer



Figure 4.6: Five-Hole Probe Measurement, Pitot-pressure Base Region,  $p_{tj}/p_{\infty} = 400, M_{\infty} = 2.98$ 

shows up at the sudden change of direction in each traverse.

Figures 4.10 and 4.11 show the measured flow directions at a pressure ratio  $N = p_{tj}/p_{\infty} = 200$ and 400, respectively. Here, in addition to the co-flowing supersonic flow and the phenomena present in the no-jet case, a plume shock, a shear layer and a barrel shock are measured. In comparison with the previous case there is a relatively small expansion of the co-flowing supersonic flow. The location of the plume shock, shear layer and barrel shock may be deduced from the changes in direction.



Figure 4.7: Five-Hole Probe Measurement,  $\stackrel{(b)}{\text{Pitot-pressure Jet Region}}$ ,  $p_{tj}/p_{\infty} = 400, M_{\infty} = 2.98$


Figure 4.8: Schlieren Photograph,  $N = p_{tj}/p_{\infty} = 400, M_{\infty} = 2.98$ 



Figure 4.9: Five-Hole Probe, Direction of Flow, No-jet,  $M_\infty=2.98$ 



Figure 4.10: Five-Hole Probe, Direction of Flow, $p_{tj}/p_{\infty} = 200, M_{\infty} = 2.98$ 



Figure 4.11: Five-Hole Probe, Direction of Flow,  $p_{tj}/p_{\infty} = 400, M_{\infty} = 2.98$ 

# Chapter 5

# **RESULTS OF THE BASE PRESSURE MEASUREMENTS**

## 5.1 Introduction

The three high sensitivity piezoresistive pressure transducers (see section 3.4) are, combined with their high resonance, very suitable for measuring dynamic pressures. The object of this investigation was to study the dynamic behaviour of the base pressures. In the present investigation the pressure taps 15, 23, and 26 are used (Fig. 3.7). The exact location of the taps is given in Table 3.1. The three pressure transducers were cyclically interchanged, which made comparison of all three signals possible.

Two series of measurements were conducted. For the first series the free stream Mach number was kept at  $M_{\infty} = 1.96$  and the free stream total pressure at  $p_{t\infty} = 2.05 bar$ . The ratio of jet stagnation pressure to free stream static pressure  $N = p_{tj}/p_{\infty}$  was maintained at a fixed level, which was different for each run. The free stream Mach number for the second series was kept at  $M_{\infty} = 2.98$  and the total pressure at  $p_{t\infty} = 5.71 bar$ . Again, the ratio of jet stagnation pressure to free stream static pressure  $N = p_{tj}/p_{\infty}$  was maintained at a constant level, different for each run. Table 5.1 shows the test matrix for these dynamic base pressure measurements. The data was subsequently transferred to a computer where the measurements were stored in 'raw data' files. Using the program Testpoint from Capital Equipment Corporation programs were written to process these data files.

$M_{\infty}$	$p_{tj}/p_{\infty}$	time-base [ms]	pressure tap
1.96	no-jet	1 & 2	15 & 23
1.96	50	1 & 2	15 & 23
1.96	90	1 & 2	15 & 23
1.96	170	1 & 2	15 & 23
1.96	350	1 & 2	15 & 23
2.98	no-jet	1 & 2	15, 23 & 26
2.98	115	1 & 2	15, 23 & 26
2.98	200	1 & 2	15, 23 & 26
2.98	400	1	15, 23 & 26
2.98	600	1 & 2	15, 23 & 26

Table 5.1: Test Matrix for the Base Pressure Measurements

## 5.2 Test Runs

Test runs were conducted with two of the pressure transducers connected to the before mentioned Philips and Fluke PM3335 oscilloscope and the remaining pressure transducer connected to a similar oscilloscope, which, however, could not be connected to a computer. Test runs with jet and co-flowing supersonic flow showed that a specific frequency was prominently present in all three signals. At first sight this frequency was estimated to be roughly 70 kHz. To examine whether or not this frequency was a phenomenon caused by the flow field, test runs were conducted with a supersonic external flow and no jet and with no external flow and only a jet. Again, these test runs showed that the same specific frequency was prominently present in all three signals. It could be concluded that this frequency was not a phenomenon of the flow field, but that this frequency was introduced by the pressure transducers. To obtain the dynamic pressure signals caused by the flow field itself, the anomalous frequency had to be analyzed and filtered out. This process is described in section 'Filtering the Data'.

## 5.3 Processing of Raw Data

The 'raw data' files transferred from the oscilloscope to the computer include both the channels A and B in screen units or counts. The screen of the oscilloscope consists of 256 counts vertically and 4096 counts horizontally. Using the oscilloscope settings for the time-base, voltage, and the offset of both channels separately the signals can be converted to the voltage-time plane. Using the specific pressure-voltage calibration for the accompanying pressure transducer the desired pressure signal is reproduced. Because of the fact that each pressure transducer is accompanied by a different calibration the reproduced pressure signals were stored into separate files for each channel.

#### 5.4 Spectrum Analysis

The pressure signals were transformed from the time domain to the frequency domain and vice versa by means of Fourier transformation. Because, the signal is complex in the frequency domain it can be represented by two separate, but coherent figures in which, respectively, the magnitude and the phase shift of the complex signal is plotted as a function of the frequency. The amplitude plot of the signal can now be used to determine at which frequencies interesting phenomena occur. With this spectrum analysis phenomena limited to a certain frequency range can now be isolated. For instance, spectrum analysis can be used to isolate the resonance frequency of a pressure transducer. The isolated frequency can be filtered out.

## 5.5 Filtering the Data

To analyze the frequency measured during the test runs a spectrum analysis was performed for all measurements. The phase shift and amplitude of the pressure signals were determined for a range of frequencies using a Fast Fourier Transform (FFT) technique. All measurements for a single pressure transducer gave similar results.

Fig. 5.1 shows the pressure plots for pressure tap 15 in the time domain and the frequency domain (amplitude and phase shift plot), measured at  $M_{\infty} = 2.98$  and  $N = p_{tj}/p_{\infty} = 200$ . The filtered pressure signal in the time domain is also given. In the amplitude plot, the high peak at zero frequency represents the mean pressure without the fluctuations. As can be seen there is a distinct peak at about 90 kHz. Examination of the pressure signal shows that this represents the frequency found during the test runs. The resonance frequency of the model 8507C-5 pressure transducer is, according to the specifications, 85,000 Hertz. Apparently the frequency disordering the dynamic pressure measurements is the resonance frequency of the pressure transducer itself. This resonance frequency is found for both free stream Mach numbers and without regard of the ratio of jet stagnation pressure to free stream static pressure.

Pressure plots in the time domain and the frequency domain for pressure tap 23, measured at  $M_{\infty} = 2.98$  and  $N = p_{tj}/p_{\infty} = 400$ , are shown in Fig. 5.2. The same representation as used in the previous case is used here. In this case a resonance frequency of 89.0 kHz is found. Again this resonance frequency was independent of the ratio of jet stagnation pressure to free stream static pressure and for both free stream Mach numbers.

Fig. 5.3 shows the pressure plots for pressure tap 26 in the time domain and the frequency domain, measured at  $M_{\infty} = 2.98$  and  $N = p_{tj}/p_{\infty} = 400$ . In this case a resonance frequency of 86.0 kHz is found.

For the purpose of finding the dynamic pressure signals of the flow field a program that applies notch filtering to the pressure signal was written using the program Testpoint from Capital Equipment Corporation. A Fast Fourier Transform (FFT) technique was utilized.

#### 5.6 Dynamic Pressure Signals

#### 5.6.1 Introduction

The procedure of notch filtering the dynamic base pressure signals has been applied to all measurements, in order to eliminate the influence of the resonance frequency. Because of the fact that only for the measurements with the free stream Mach number of  $M_{\infty} = 2.98$  all three pressure transducers were used, the following description is based on these measurements. The figures in the present section only show the notch filtered base pressure signal (in the time domain). Results from the following description are tabulated in Table 5.2.



(b) Notch Filtered Signal, Time Domain









(b) Notch Filtered Signal, Time Domain

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(d) Original Signal, Phase Shift Plot





(b) Notch Filtered Signal, Time Domain

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$M_{\infty}$	$p_{tj}/p_{\infty}$	average p <sub>b</sub> [mbar]	FESTIP96 p <sub>b</sub> [mbar]	freq.range dynamics [kHz]	concentration dynamics [kHz]
2.98	no-jet	50	53	0-10	3,5
2.98	115	36	36	0-15	4,9
2.98	200	39	37	0-15	3,<10
2.98	400	42	45	0-10	<6
2.98	600	48	50		<8

Table 5.2: Dynamic Behaviour Base Pressure Signals

#### **5.6.2** No-jet, $M_{\infty} = 2.98$

The notch filtered base pressure signals for the case of no-jet and a free stream Mach number of  $M_{\infty} = 2.98$  are shown in Fig. 5.4, for all three pressure taps. For pressure tap 23 the resonance frequency is more prominently present than for pressure taps 15 and 26. All three pressure transducers show a similar pressure signal after the influence of the resonance frequency has been eliminated and show an average pressure just below 50 mbar. This corresponds to the steady base pressure measurements conducted for the FESTIP Aerothermodynamics [3] investigation, where an average value just below 53 mbar was found.

From the spectrum analysis it can be deduced that there is no specific frequency at which the amplitude of the pressure signal is substantially large. The dynamic behaviour mainly occurs within the frequency range of 0 to 10 kHz. A concentration of dynamic behaviour can be found around 3 and 5 kHz. However, no specific frequency dictates the dynamic behaviour, and therefore no regular disturbances are present. This indicates that in these base pressure measurements there seems to be no physical phenomenon like alternating vortex shedding present. The amplitudes of the disturbances are within a few percent of the average base pressure value. The dynamic behaviour is a relatively minor effect.

## **5.6.3** Jet, $N = p_{tj}/p_{\infty} = 115$ , $M_{\infty} = 2.98$

The average value of the filtered pressure signal is just below 36 mbar (see Fig. 5.5). The steady base pressure measurement in the FESTIP Aerothermodynamics [3] investigation showed a value slightly above 36 mbar. No significant difference considering the average value of the base pressure is shown by the three pressure taps used.

As in the previous case the spectrum analysis does not show a specific frequency with a pronounced amplitude of the pressure signal. The frequency ranges between 0 and 15 kHz, with a concentration of dynamic behaviour close to 4 and 9 kHz, with amplitudes within a few percent of the average base pressure value.

#### **5.6.4** Jet, $N = p_{tj}/p_{\infty} = 200, M_{\infty} = 2.98$

The average value just below 39 mbar (Fig. 5.6) was found as compared to an average value slightly above 37 mbar for the FESTIP Aerothermodynamics [3] investigation. The pressures,



(b) Pressure Tap 23



(c) Pressure Tap 26

Figure 5.4: Filtered Base Pressure Signals, No-jet,  $M_{\infty} = 2.98$ 

measured at the three different taps, show no significant difference in the average value of the base pressure.

The dynamic behaviour is primarily limited to the frequency range of 0 to 15 kHz and is generally found below 10 kHz. A concentration of dynamic behaviour can be found around 3 kHz.

**5.6.5** Jet,  $N = p_{ti}/p_{\infty} = 400$ ,  $M_{\infty} = 2.98$ 

The average value of the pressure just above 42 mbar (Fig. 5.7) is measured by the signals of the pressure taps 15 and 23. The signal of pressure tap 26 shows a slightly higher average value. For the steady base pressure measurements conducted in Ref. [3] the average pressure was 45 mbar. The dominant frequencies are found in the range of 0 to 10 kHz, generally below 6 kHz.

#### **5.6.6** Jet, $N = p_{tj}/p_{\infty} = 600$ , $M_{\infty} = 2.98$

The average value of of the dynamic measurements (Fig. 5.8) and the result of the steady measurements [3] are respectively 48 mbar and 50 mbar. The frequencies are primarily found below 8 kHz.



(b) Pressure Tap 23



(c) Pressure Tap 26

Figure 5.5: Filtered Base Pressure Signals,  $N = p_{tj}/p_{\infty} = 115$ ,  $M_{\infty} = 2.98$ 

$M_{\infty}$	$p_{tj}/p_{\infty}$	average $p_b[mbar]$	FESTIP96 p <sub>b</sub> [mbar]
1.96	no-jet	130	146
1.96	50	88	80
1.96	90	93	89
1.96	170	100	100
1.96	350	110	115

Table 5.3: Dynamic Behaviour Base Pressure Signals, Pressure Tap 15

#### **5.6.7** Pressure Tap 15, $M_{\infty} = 1.96$

Since no significant difference in pressure signal was found for the three separate pressure holes for the series of measurements with  $M_{\infty} = 2.98$ , the discussion of results of the series of measurements with  $M_{\infty} = 1.96$  is restricted to those of pressure tap 15. Tabulated quantities may be found in Table 5.3.

The pressure signals for the various cases considered are shown in Fig. 5.9. The average pressure of 130 mbar of the no-jet case does not correspond to that of the steady base pressure measurements conducted for the FESTIP Aerothermodynamics [3] investigation, where an average value of approximately 146 mbar was found. The discrepancy of 12.5 percent might be explained by the fact that a slight difference in jet pressure causes a relatively large difference in base pressure for minor jet pressures, due to the entrainment effect. The difference will be explained in more detail in the next section. The external high-pressure supply adjustment was not that accurate. The just described discrepancy decreases with increasing jet stagnation pressure,







(c) Pressure Tap 26

Figure 5.6: Filtered Base Pressure Signals,  $N = p_{tj}/p_{\infty} = 200, M_{\infty} = 2.98$ 

see Table 5.3.

Similar to the results for the series of measurements at  $M_{\infty} = 2.98$ , there is no specific frequency at which the amplitude of the pressure signal is substantially large. The dynamic behaviour is primarily limited to the frequency range of 0 to 10 kHz and is generally found below 5 kHz. However, in the case of  $N = p_{tj}/p_{\infty} = 170$  a small peak is found at 0.6 kHz and in the case of  $N = p_{tj}/p_{\infty} = 350$  small peaks at 0.2 and 0.5 kHz are found. Nevertheless, no evidence is found that these results are not incidental. The amplitudes of the disturbances are within a few percent of the average value of the base pressure signal. The disturbances are more distinctly present for the series of measurements with  $M_{\infty} = 1.96$  than for the series of measurements with  $M_{\infty} = 2.98$ . In conclusion, the dynamic behaviour may be considered as a secondary effect.

#### 5.7 Static Pressure

Fig. 5.10a shows the static pressures of both series of pressure measurements (divided by the free stream static pressure). A curve has been fitted through the static pressure points from the runs with jet in order to study the development of the graph. For each ratio of jet stagnation pressure to free stream static pressure, at constant free stream Mach number  $M_{\infty}$ , the deviation of the static pressure to the average value never exceeds 5%. The static pressures for  $M_{\infty} = 1.96$ 



(b) Pressure Tap 23



(c) Pressure Tap 26

Figure 5.7: Filtered Base Pressure Signals,  $N = p_{tj}/p_{\infty} = 400, M_{\infty} = 2.98$ 

are higher than those for  $M_{\infty} = 2.98$ , thus for a lower free stream Mach number the co-flowing supersonic stream causes a higher base pressure.

The graphs shown in Fig. 5.10a show two distinct stages. The first stage concerns the no-jet case and in the second stage (cases with jet) the base pressure increases for increasing jet pressure. For steady base pressure measurements Schoones [17] found similar graphs, which are shown in Fig. 5.10b. For a thorough understanding of the physical nature Reid and Hastings [16] explored the effect of jet pressure ratio on the base pressure for the complete range of jet pressures, starting at the no-jet condition. A distinction was drawn between three different physical phases (see Fig. 5.11a). Schematic diagrams of the base flow are shown in Fig. 5.11b through d. The starting point of phase 1 corresponds to the no-jet-flow case. Under these conditions all the air entrained by the external stream is returned to the base region by the pressure rise across the trailing shock, and a closed region of circulating flow results as shown in Fig. 5.11b. The internal jet supplies part of the entrained air when  $p_{ti}$  is increased, and the mass and momentum of the trapped circulating air decrease. Consequently the pressure rise necessary to return this trapped air to the base region decreases also and the base pressure rises. This trend continues until all the air entrained by the external flow is supplied by the internal jet so that the original eddy and trailing shock disappear. As the velocity of the internal stream increases a small pair of eddies will be created in the region bounded by the external and internal streams and the base. The flow pattern at this point will therefore be as shown in Fig. 5.11c. The flow is still subsonic throughout the nozzle.

In the second phase the flow in the nozzle has has developed such that a supersonic flow region exists in the nozzle throat involving a forked shock system which causes separation from the



(b) Pressure Tap 23



(c) Pressure Tap 26

Figure 5.8: Filtered Base Pressure Signals,  $N = p_{tj}/p_{\infty} = 600, M_{\infty} = 2.98$ 

nozzle wall. This shock system moves downstream with increasing jet pressure. At the same time the base pressure decreases. Finally the initial shock reaches the nozzle exit plane. At this point the Mach number at the nozzle exit  $M_e$  reaches its design value. Thereafter the nozzle runs full, so that  $M_e$  and  $p_j/p_{tj}$  are constant. Consequently, as  $p_{tj}$  is increased,  $p_j$  increases also and the shock weakens until  $p_j = p_b$  and the internal flow is discharged parallel to the axis. The third phase has now been entered. Beyond this point  $p_j$  rises above  $p_b$  and an expansion fan forms at the nozzle lip (under-expanded jet, Fig. 5.11d). The compression waves on both sides of the dividing line a-b-c-d coalesce on the upper side into the plume shock and on the lower side start to develop the barrel shock for high  $p_{tj}/p_{\infty}$  values. In this third phase a trend of increasing base pressure with increasing jet pressure is visible.

The measurements for the current investigation were made under conditions of a full running nozzle, as indicated in Fig. 5.11d. The graph of  $p_b/p_{\infty}$  versus  $p_{tj}/p_{\infty}$  obtained from these data consists therefore of third phase data, and a single first phase point (the no-jet case).



(b)  $N=p_{tj}/p_{\infty}=50$ 



(d)  $N = p_{tj}/p_{\infty} = 170$ 

<u>50</u>



Figure 5.9: Filtered Base Pressure Signals, Pressure Tap 15,  $M_\infty = 1.96$ 



(b) FESTIP96 Investigation Figure 5.10: Static Base Pressure







# **Chapter 6**

# **CONCLUSIONS AND RECOMMENDATIONS**

The structure of under-expanded jets in a co-flowing supersonic free stream has been described using analytical and physical models.

Results of a single nozzle plume with a high supersonic exit Mach number of 4 exhausting in co-flowing supersonic free streams of Mach 1.96 and 2.98 have been presented for a number of conditions, ranging from  $p_{tj}/p_{\infty} = 350$  to no-jet flow at Mach 1.96 and from  $p_{tj}/p_{\infty} = 600$  to no-jet flow at Mach 2.98. The Reynolds numbers based on the model length were greater than  $5x10^6$  and in addition the boundary layer on the model was tripped.

The data consists of dynamic surface pressure measurements at the base of the model and of detailed radial five-hole probe pressure surveys behind the model across the plume.

After filtering out the resonance frequency no distinct frequency is present in the dynamic base pressure signals. In general the dynamic behaviour occurs within the range of 0 to 10 kHz or 0 to 15 kHz with a concentration of dynamic behaviour generally below 5 kHz.

The dynamic effect appears to be a secondary effect. It can be concluded that the base pressure signals show a steady behaviour. No difference in behaviour was found for the different pressure holes.

The data of the static surface pressures at the base of the model are confined to the third phase: under-expanded supersonic jet exit flow.

The radial five-hole probe pressure surveys show the physical nature of the flow, e.g., the location of the various shock waves, expansion fans, and shear layers. As a result Pitot-pressures and the flow direction were determined.

The Pitot-pressure in the base region is 0.6 times the free stream static pressure for the no- jet case. In the cases with jet a Pitot-pressure in the base region of 0.4 times the free stream static pressure is found. A relationship between the Pitot-pressure in the base region and the jet pressure is not evident, because only two different jet pressures were used.

In addition to the Pitot-pressure curves, the measured direction of the flow field also gives an indication of the location of the shock systems.

The time lag, found at the five-hole probe traverses, causes the pressure to reach its final measured value exponentially. In order to reduce the interval time between two measurements it is recommended to evaluate the (exponential) relationship. Once this relationship is known the measurement can be stopped before the final value is reached.

Finally, it is recommended to acquire more data concerning the circulation, because no comparison of computational results with experiments can be made due to lack of experimental data concerning the circulation.

# REFERENCES

- Adamson, T.C. Jr., and Nicholls, J.A. 'On the Structure of Jets from Highly Under- expanded Nozzles into Still Air', Journal of the Aero/Space Sc., 1959, Vol. 26, No.1, pp 16-24.
- [2] Albini, F.A. 'Approximate Computation of Under-expanded Jet Structure'. AIAA Journal, 1965, Vol. 3, No. 8, pp1538.
- [3] Bannink, W.J., Bakker, P.G., and Houtman, E.M. 'FESTIP AEROTHERMODYNAMICS 1996: Experimental Investigation of Base Flow and Exhaust Plume Interaction', Memorandum M-775. Faculty of Aerospace Engineering, Delft University of Technology, March 1997.
- [4] Bannink, W.J., and Houtman, E.M. 'The Calibration and Measuring Procedure of a Five-Hole Hemispherical Head Probe in Compressible Flow' Report LR-585. Faculty of Aerospace Engineering, Delft University of Technology, April 1989.
- [5] Boynton, F.P. 'Highly Under-expanded Jet Structure: Exact and Approximate Calculations', AIAA Journal, 1967, Vol. 5, No. 9, pp1703-1704.
- [6] Cain, T.M., and Jones, T.V. 'Pitot Surveys of Two Moderately Under-expanded Jets', Paper 31 AGARD-CP-479, Madrid, 1990.
- [7] Cain, T.M., and Jones, T.V. 'Pitot Measurements in the Exhaust of a Cluster of Four Small Scale Supersonic Nozzles', Report No. OUEL 1862/90, Dept. of Eng. Sc., Univ. of Oxford, 1990.
- [8] Cain, T.M. 'An Experimental Study of Under-expanded Jets', Report No. OUEL 1959/92, Dept. of Eng. Sc., Univ. of Oxford, 1992.
- [9] Chernyi, G.G. 'Introduction to Hypersonic Flow', Academic Press, 1961, p.125.
- [10] Hubbard, E.W. 'Approximate Calculation of Highly Under-expanded Jets', AIAA Journal, 1966, Vol. 4, No. 15, pp1877-1879.
- [11] Korst, H.H., White, R.A., Nyberg, S.E., and Agrell, J. 'Simulation and Modelling of Jet Plumes in Wind Tunnel Facilities', Journal of Spacecraft, 1981, Vol. 18, No. 5, pp 427-434.
- [12] Moran, J.P. 'Similarity in High Altitude Jets', AIAA Journal, 1967, Vol. 5, No. 7, pp1343-1345.
- [13] Moran, J.P. 'Mixing Layers for Highly Under-expanded Supersonic Jets in Hypersonic Streams', Journal of Fluid Mechanics, 1974, Vol. 65, part 1, pp 153-175.
- [14] Morris, N., Buttsworth, J.T., and Brescianini, C. 'An Experimental and Computational Study of Moderately Under-expanded Rocket Exhaust Plumes in Co-Flowing Hypersonic Free-Stream', AIAA Paper 95-6127, 1995.

- [15] Peters, C.E., and Phares, W.J. 'The Structure of Plumes from Moderately Under-expanded Supersonic Nozzles', AIAA Paper 70-229, 1970.
- [16] Reid, J., and Hastings, R.C. 'The Effect of a Central Jet on the Base Pressure of a Cylindrical After-body in a Supersonic Stream', Analytical Research Council, Ministry of Aviation, R&M 3224, London, 1961.
- [17] Schoones, M.M.J. 'A Study on Base Flow and Exhaust Plume Interaction', Pre-thesis High Speed Aerodynamics. Faculty of Aerospace Engineering, Delft University of Technology, February 1997.
- [18] Simons, G.A. 'Effect of Nozzle Boundary Layers on Rocket Exhaust Plumes', AIAA Journal, 1972, Vol. 10, No. 11, pp1534-1535.

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An experimental study of the flow field along an axi-symmetric body with a single operating exhaust nozzle has been performed in the scope of an investigation on base flow-jet plume interactions. The structure of under-expanded jets in a co-flowing supersonic free stream was described using analytical and physical models. Results of a single nozzle plume with a high supersonic exit Mach number of 4 exhausting in co-flowing supersonic free streams of Mach 1.96 and 2.98 are presented for a number of jet stagnation pressure to free stream static pressure ratios, ranging from  $P_{tj}/P_{\infty} = 350$  to nojet flow at Mach 1.96 and from  $P_{tj}/P_{\infty} = 600$  to no-jet flow at Mach 2.98.

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The dynamic base pressure signals showed a resonance frequency of the pressure transducers. After filtering out the resonance frequency no distinct frequency was present in the dynamic base pressure signals. Apart from signal noise the base pressures showed a steady behaviour.

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