Paper 7

TRANSONIC STEAM FLOWS: WAKE VISUALISATION AND MEASUREMENTS BEHIND MODEL BLADES

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1 Introduction

At the trailing edge of a turbine blade the flow separates in an unsteady way creating at the same time an alternate vortex row. The study of this unsteady flow behaviour is important for different reasons, to name but a few:

- modelling the trailing edge flow is very important as a boundary condition for numerical calculation: the geometry of the base pressure region determines the position and strength of eventually occurring aerodynamic shocks.

- the vortex shedding is a source vibration. Attention has to be paid to the intensity level of this vibration since chord and span of the blades are increasing while the blades stiffness decreases.

- in the wake mixing process, the trailing edge flow plays an important role. The mixing process is important with respect to the losses or performance estimation of the blade.

The study of the wake in the present effort concentrates upon two aspects:

1. the visualisation

2. the vortex frequency determination.

2 The experimental set-up.

2.1 Facilities

Two different tunnels are used:

1. a blow down wind tunnel, where air is the working fluid. This tunnel is used in order to set up the optical system.

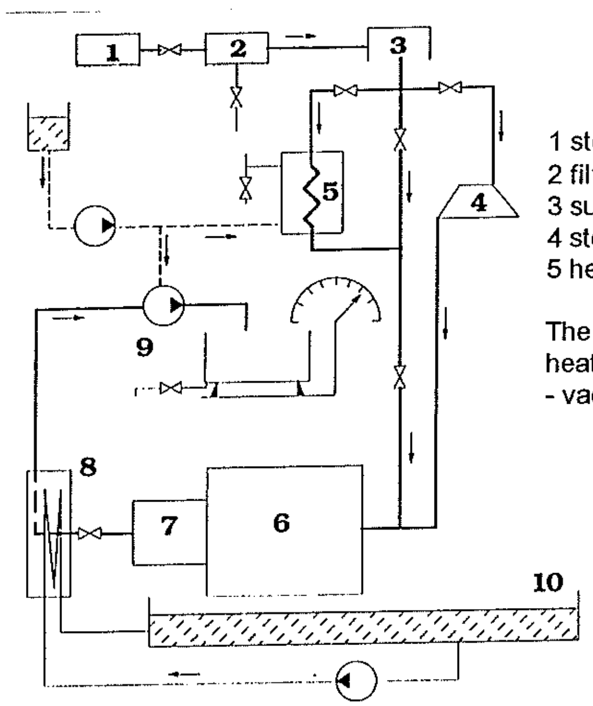
2. a continuous steam tunnel.

2.1.1 Air tunnel

In the blow down tunnel the air flows from a pressure reservoir through ejectors behind the test section. In this way air is sucked away in the area downstream of the test section, depending upon the design of the nozzle, either a sonic or a supersonic speed is realised in the test section.

2.1.2 Steam tunnel

In the steam tunnel the working fluid flows from the generators, via a filter, a superheater and a settling chamber through the test section. From there it enters the condenser, which is cooled by the swimming pool water



1 steam generator
2 filter
3 superheater
4 steam turbine
5 heat exchanger
6 settling chamber
7 test section
8 condensor
9 combined extraction-vacuum pump
10 swimming pool (cooling water)

The dashed lines represent the flow of water fed to the heat exchanger and to the combined extraction - - vacuum pump

Fig.1 The layout of the steam tunnel

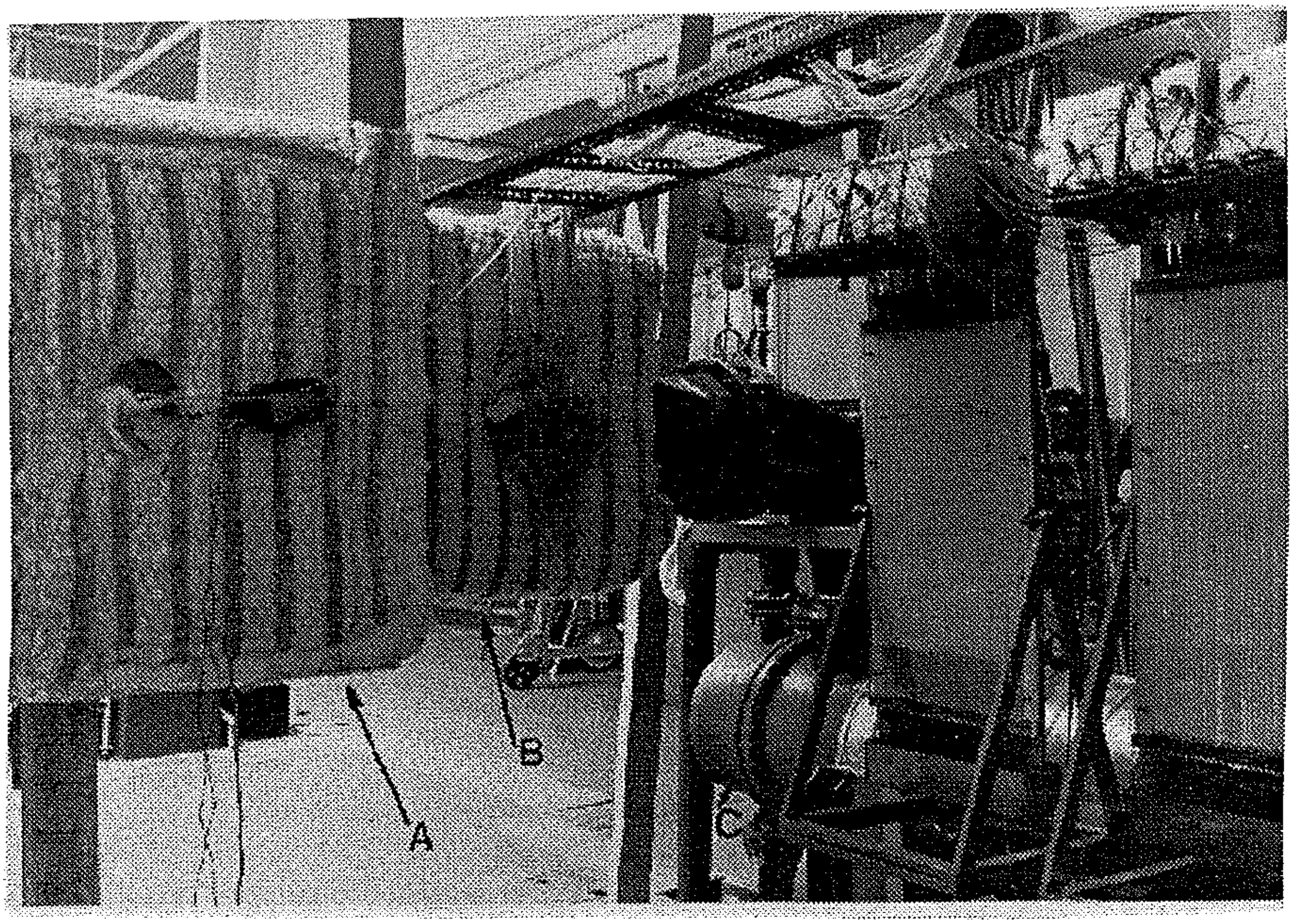


Photo 1 The settling chamber (a), test section (b) and condensor (c) of the steamtunnel

2.2 The optical system

The visualisation is based upon the conventionally arranged schlieren optical system. As a light source a nanolite is used: it generates a spark between two electrodes. The nanolite spark generator can be compared with the spark plug in a classical Otto-engine. The nanolite gives a light flash during 20 nanoseconds, with a 0.1 joule energy. The light source is in fact nearly punctiform and can therefore be placed (directly) at the focal distance of a lens. Since the flash is projected in a 90°, angle the lens should be placed close to the nanolite while for the same reason a mirror cannot be used. The nearly parallel light beam traverses the tunnel and on the opposite side strikes a concave mirror. In the focal plane of which is a knife edge, so that the light beam is in this place nearly punctiform. On the other side of the test section no lenses are used in order to diminish the optical aberrations. The knife edge must be adjusted very carefully to yield very high sensitivity. The screen is replaced by a photo sensitive plate upon which the image of the test section is generated. Films of 800 up to 4000 ASA are used. For this kind of visualisations a perfect dark room is created.
The illumination of the photographic plate diminishes as the knife cuts more light. This is as such not an inconvenience for continuous light sources but when using flash lights high light intensites are required.

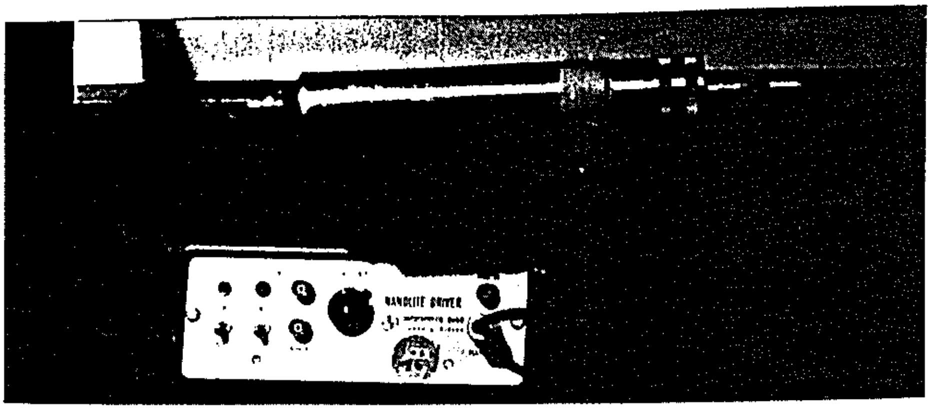


Photo 2 The nanolite

2.3 The windows

The choice of the material used to construct the windows is based on the following criteria:

- good optical quality
- heat resistant
- withstand thermal shocks
- mechanical resistance
- correct thermal dilatation coefficients

All of those criteria do have equal importance. With correct thermal dilatation coefficients is meant that a perfect sealing has to be realised at room temperature (i.e. when starting up the steam tunnel) as well as at operating temperature (this can be as high as 150° C). Thermal shocks occur when starting up and shutting down the tunnel.

The basic material for glass is SiO_2 what has to be heated up to extreme high temperatures in order to melt into natural quartz followed by a cooling process to its glass form. Since this process is not possible at a reasonable cost metal-oxides are added.

A first kind of glass is Borosilicat glass containing boor nand small quantities of aluminium. This glass is known as Pyrex. The inconvenience of this glass is that it is rarely hohogeneous and it contains a lot of strings and gas enclosures.

Almost 96% of the silica glasses is derived starting from Pyrex glass in which the alkali metals are removed by a chemical process. This material has extremely good characteristics but is very expensive.

Synthetic quartz is obtained by a chemical process during which the sicilian reacts with oxygen. Due to this procedure synthetic quartz is far better than natural quartz (no lines, no gas enclosures) but it is three to four times more expensive than Pyrex.

The transmittance curves of 20 mm thick glass plates show 85% transmittance for Pyrex while this is 93% for synthetic quartz. This means that in identical conditions there is a 20% difference in light intensity upon the photographic plate. Since the

2.4 Test models

2.4.1 In air

The model use in the wind tunnel has a span of 20 mm and a chord length of 38 mm. The trailing edge is straight. The blade is depicted in Fig.2.

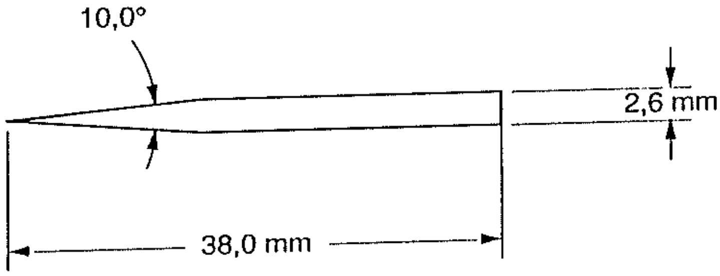


Fig. 2 The test model in the air tunnel

2.4.2 In steam

The blade used in the steam tunnel is a combination of simple geometries as can be seen on the schematic drawing below (Fig.3).

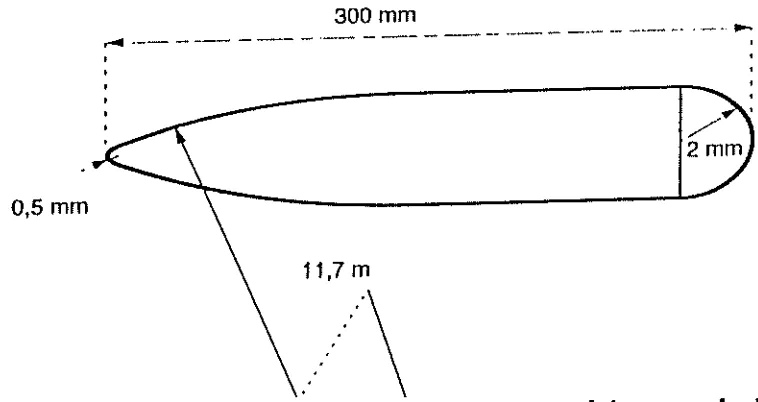


Fig. 3 The test model in the steam tunnel (no scale intended)

The trailing edge is either squared or rounded off.
The blade is placed within a convergent-divergent nozzle with a variable tailboard inclination. On the pressure side the geometrical minimum section is situated at the trailing edge while on the suction side the minimum section is situated in the neighbourhood of the corner. This corner will initiate a Prandtl-Meyer expansion and will permit different supersonic Mach numbers at both sides of the blade.

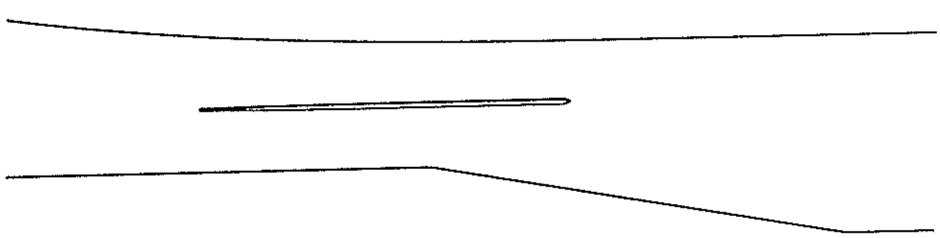


Fig. 4 The model blade in the test section of the steam tunnel

The variation of the tailboard inclination permits to obtain either subsonic or transonic conditions at the trailing edge. In the calculation result shown below a limit loading condition is simulated.

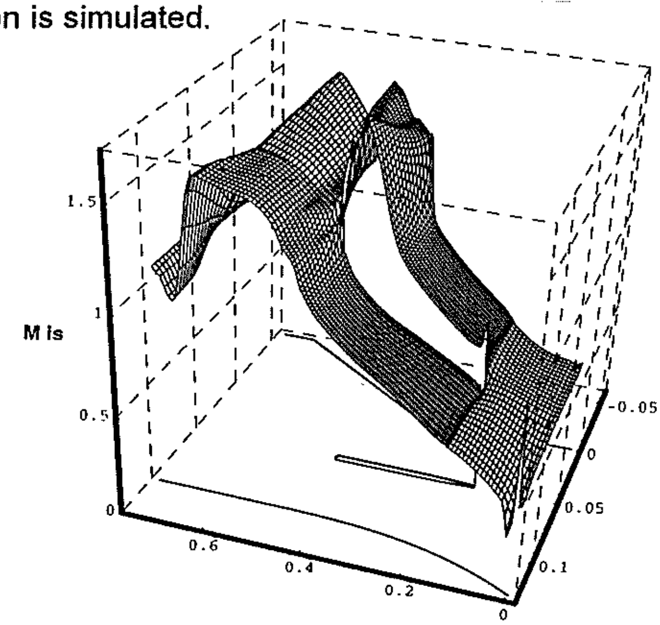


Fig. 5 The isentropic Mach number evolution in limit loading conditions

It is worthwhile noting that the vortices of the two vortex rows of the street are not of an equal intensity, due to the different flow cinditions at the pressure and the suction side of the blade. Especially the boundary layers are different.
A blade has been sandblasted by Corundum sand grains having a diameter of 0.12 to 0.25 mm. This makes the skin of the blade much rougher as can be seen on the photograph 3. In this way the nature of the boundary layer will be changed and the shedding of the flow at the trailing edge is different. As a result of this the Strouhal number will not only be affected by the diameter of the trailing edge, but also by the prior history of the boundary layer reaching the trailing edge.

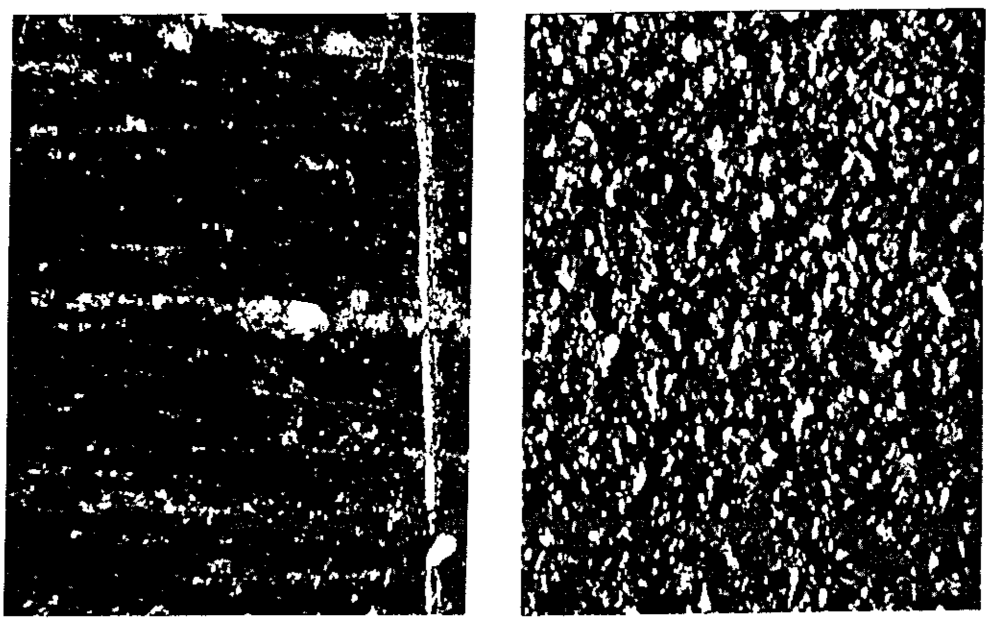


Photo 3 Surface before and after sandblasting by Corundum sand grains

With the set up described above the flow along both sides of the blade is shock free up to the trailing edge end this is unlike a transonic turbine blade. With a slightly different configuration of the tailboard one could obtain a shock impinging the suction side of the model blade. Therefore a little step has to be foreseen at the tailboard as demonstrated on the figure below (Fig. 6). The tailboard acts as a neighbouring pressure side trailing edge shock generator and the tailboard can be seen as the wake centre line of a second blade.

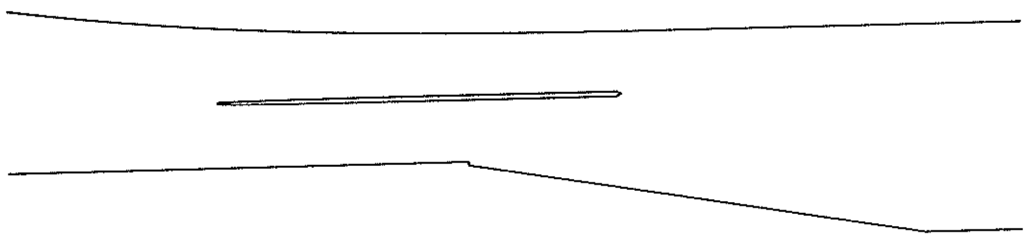


Fig. 6 The configuration with the tailboard acting as a shock generator

3 The visualisation results

3.1 In air

In the air tunnel we use synthetic quartz windows with an optical quality. Photograph 4 shows a schlieren image in "no flow" conditions; while the photographs 5 and 6 show nearly sonic conditions ($M_\infty = 0.92$ and $M_\infty = 0.98$). The alternate vortex street is clear. More light can be cut off when using very sensitive (4000 ASA) photographic plates. The scale factor for the images obtained on the original plates is about 72%.

3.2 In steam

In the steam tunnel both Pyrex and synthetic quartz windows were used. The windows are 20 mm thick. Photographs 8 - 9 are obtained with respectively Pyrex (poor optical quality, although optical Pyrex was ordered) and synthetic quartz in "no flow"conditions. The windows did not resist to succesive tests and broke (Photograph 10). As long as the quartz plates stay in their metallic supports the broken parts remain in their position such that they did not disturb the flow, but due to the light refractions the image is completly disturbed and of course those windows cannot be used any longer. As shown on the photograph 11 one can see how windows degenerate during successive tests.
On the photographs 12 and 13 the flow is visualised using alternate positions of the knife edge (either the North or South part of the light beam is cut off). Doing so the trailing edge shocks appear as light either as dark lines while on both photos the vortex cores remain as dark spots.
The difference in the quality of the photographs between steam and air tunnels is due to:

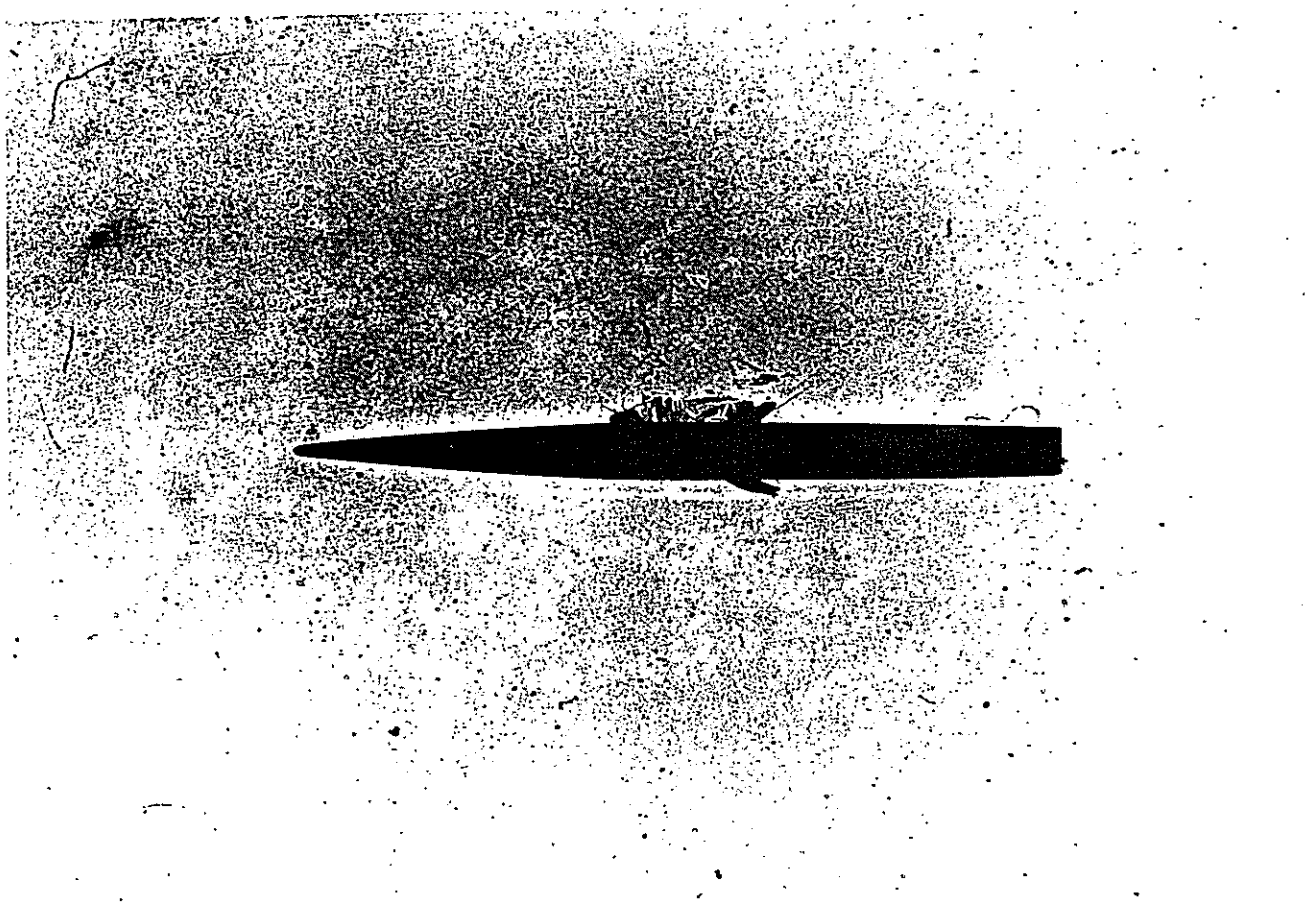


Photo 4 Air tunnel - No flow

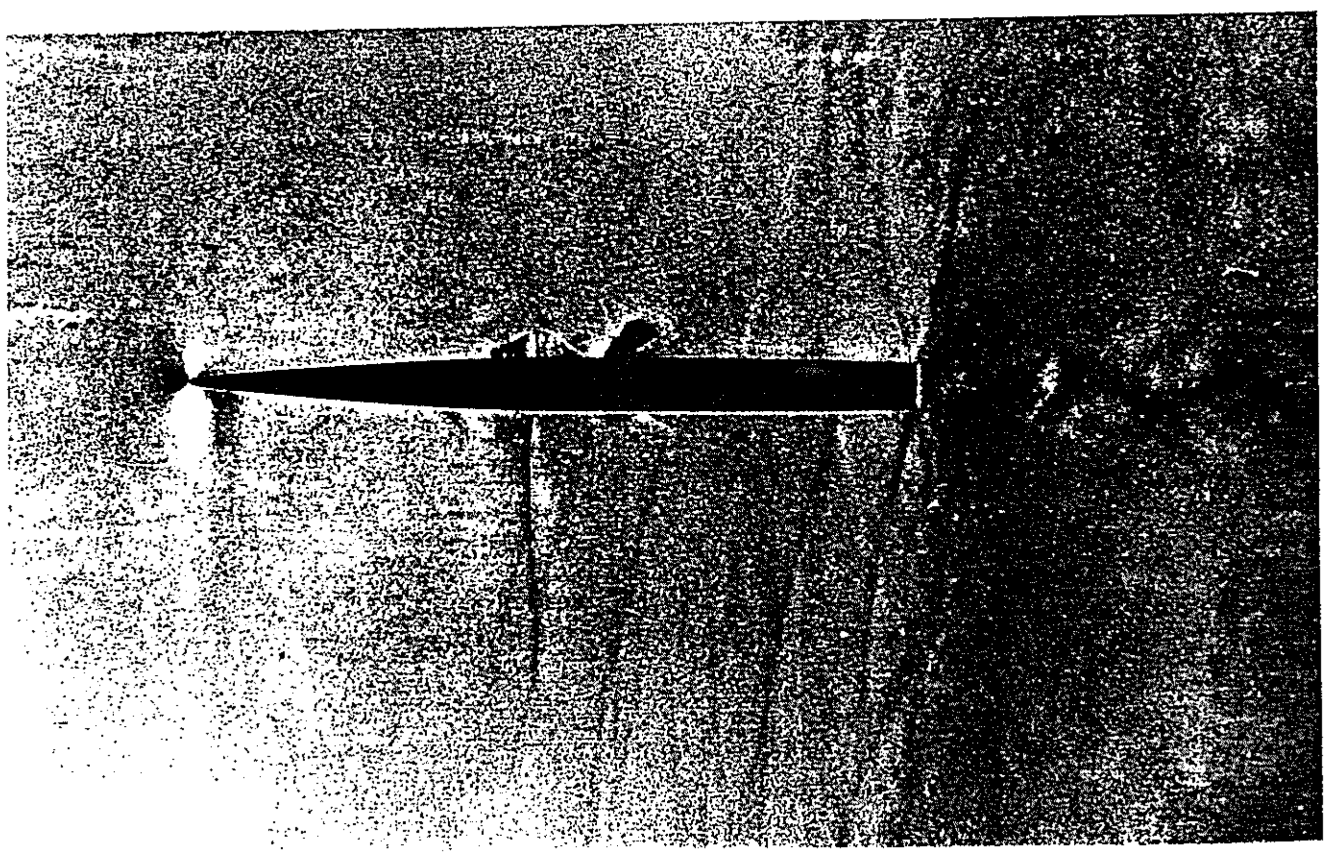


Photo 5 Air tunnel - 800 ASA film - $M_\infty = 0.92$

1. the thickness of the glass plates diminishing the transmittance of the light.

2. the deposit of dirt coming from in the steam pipes on the windows. During the start up a lot of water flows through the tunnel transporting rust particles. Some of those particles remain on the windows diminishing even further the light transmittance.

3. the vortex frequency is somewhat higher in the steam tunnel as compared to the air tunnel.

With the Pyrex glass plates no result at all was obtained as can be seen at photograph 14.
As the Mach number increases the vortex street completely disappears (Photograph 15).

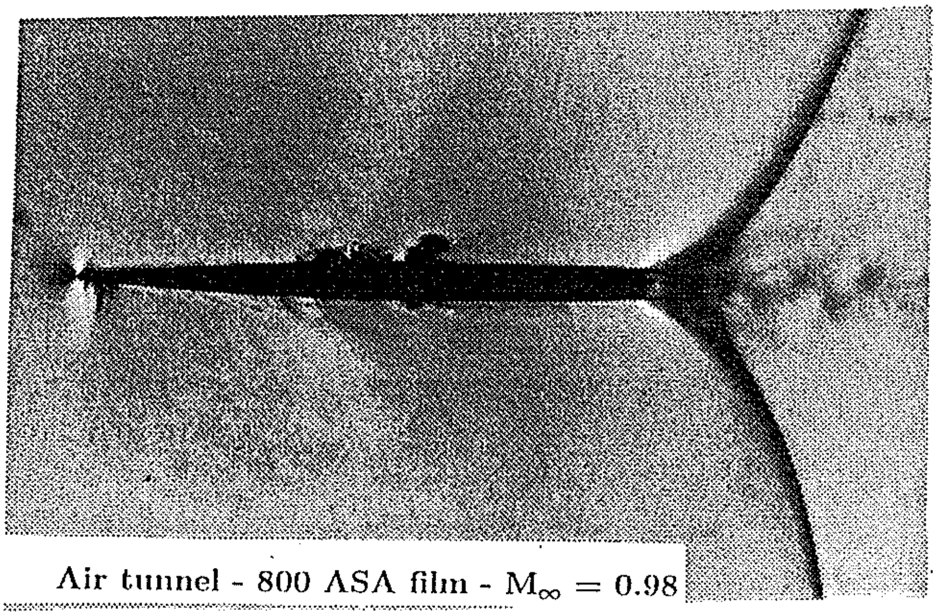


Photo 6 Air tunnel - 800 ASA film - $M_\infty = 0.98$

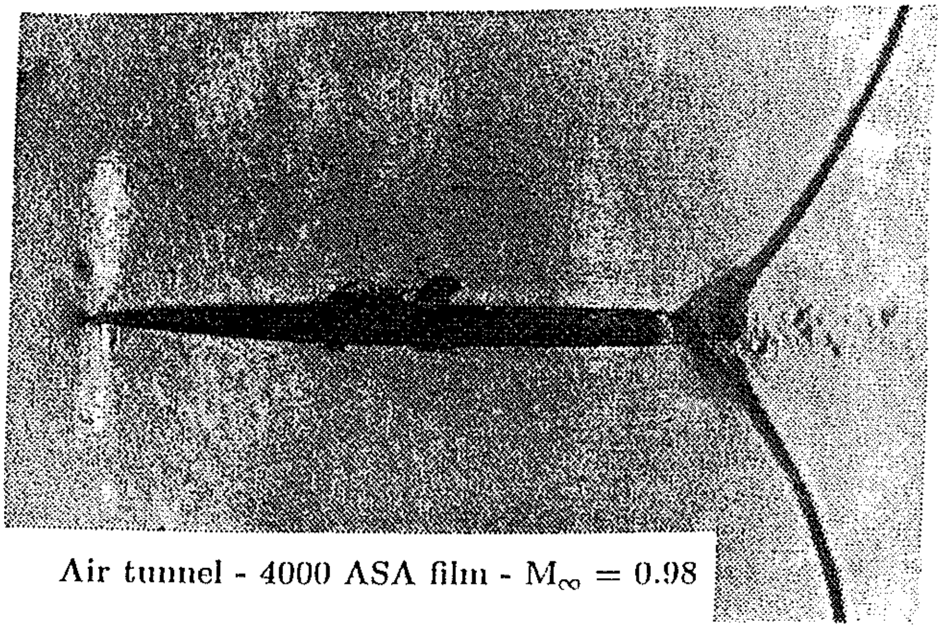


Photo 7 Air tunnel - 4000 ASA film - $M_\infty = 0.98$

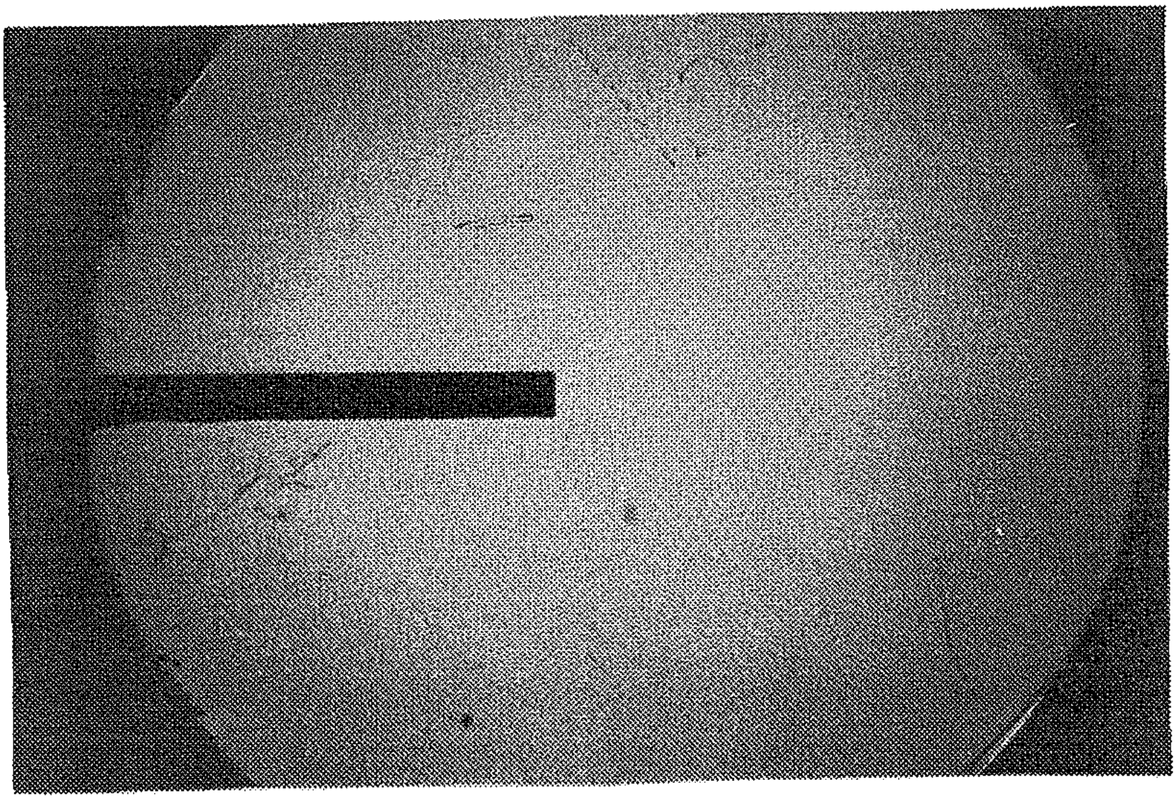


Photo 8 Steam tunnel - Pyrex window - No flow

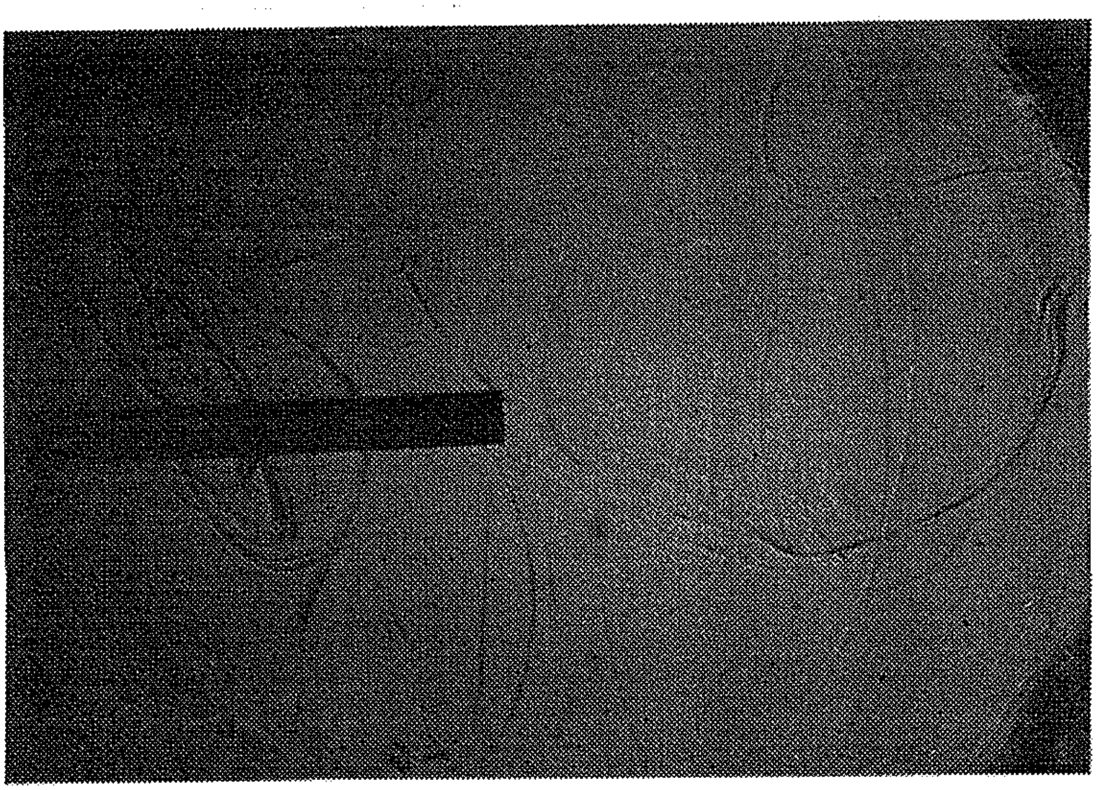


Photo 9 Steam tunnel - Quartz window - No flow

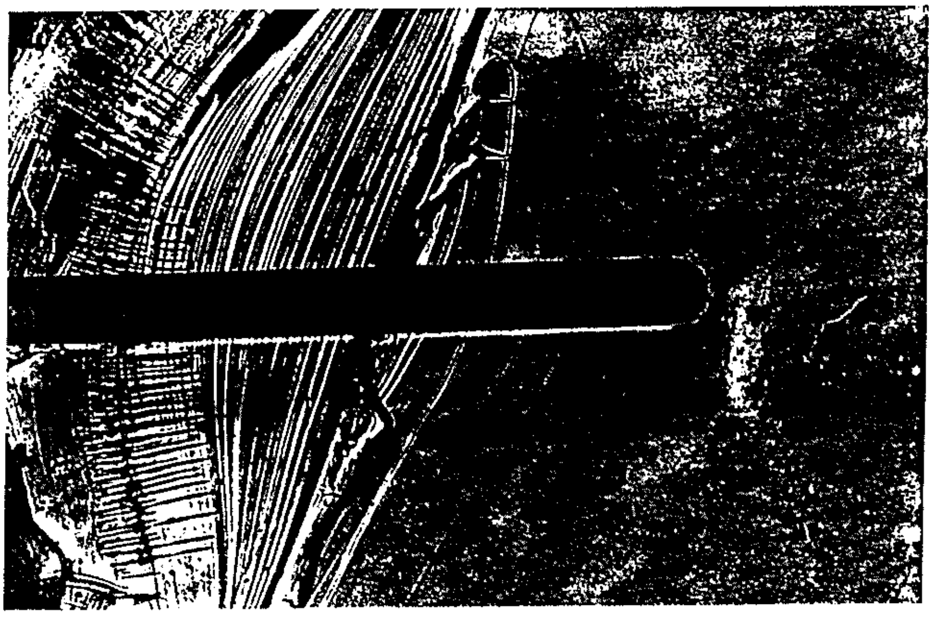


Photo 10 Steam tunnel - Quartz window - No flow - Broken window

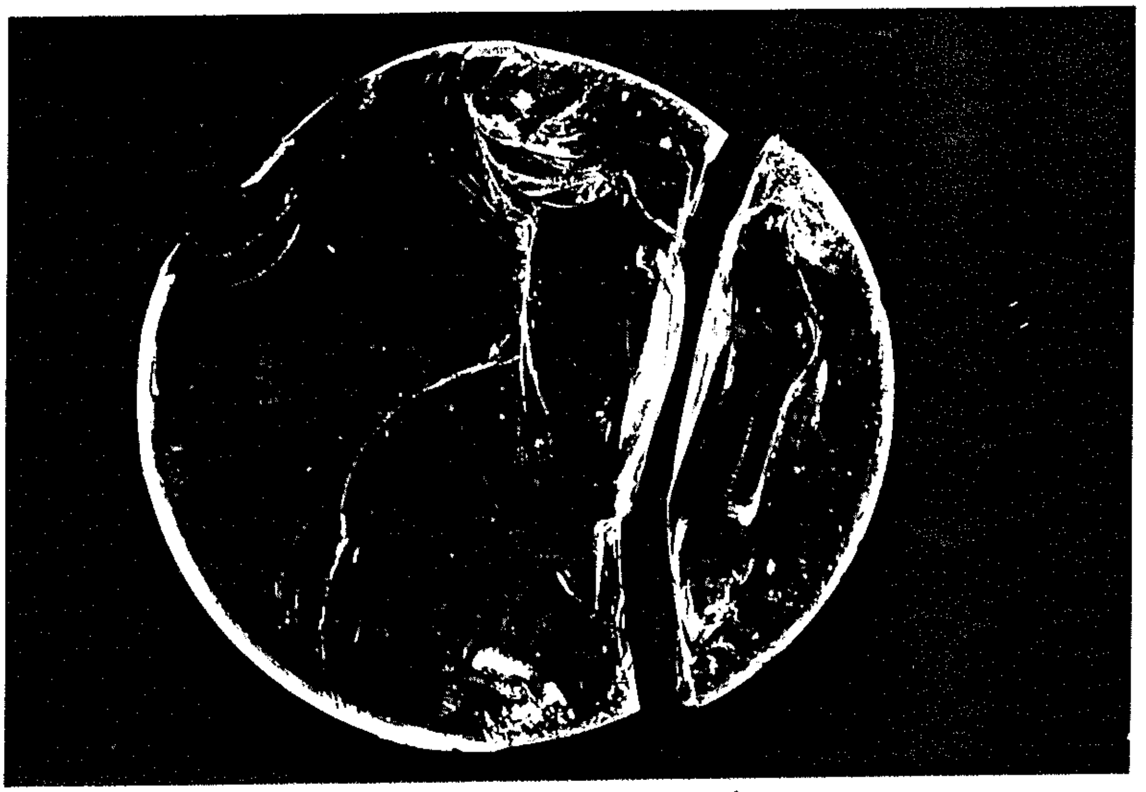


Photo 11 Broken window due to thermal shocks and mechanical compressions

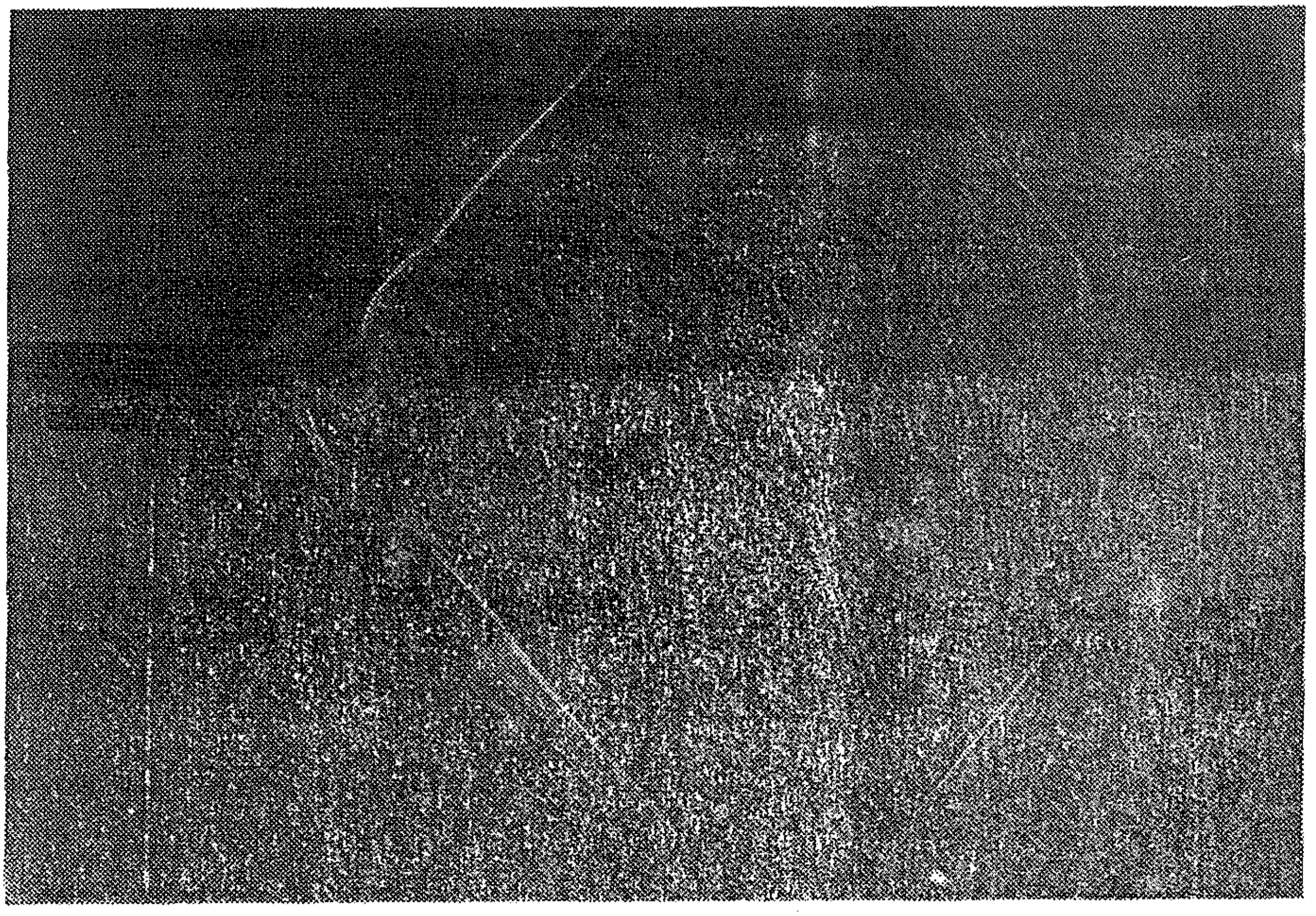


Photo 12 Nort part of the light beam is cut off

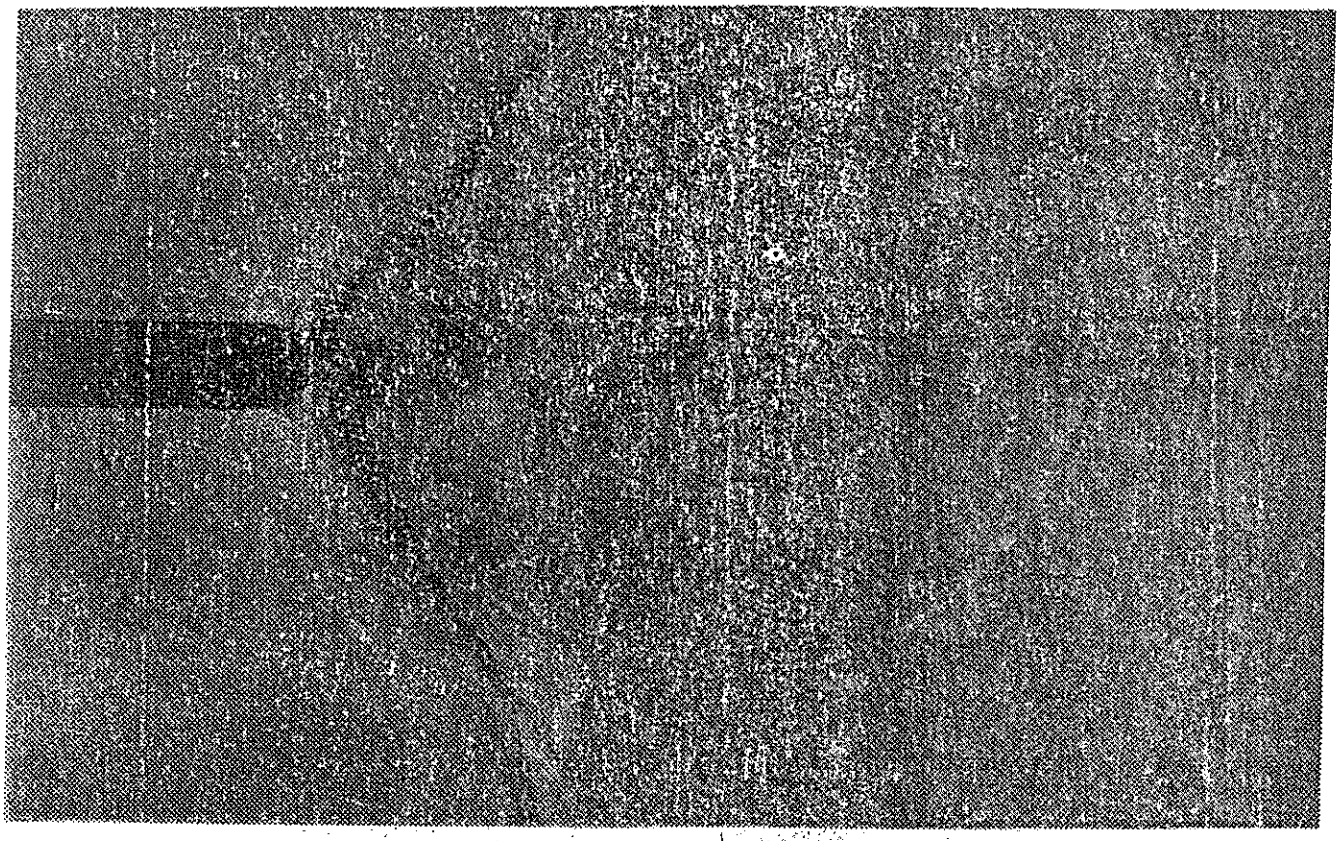


Photo 13 South part of the light beam is cut off

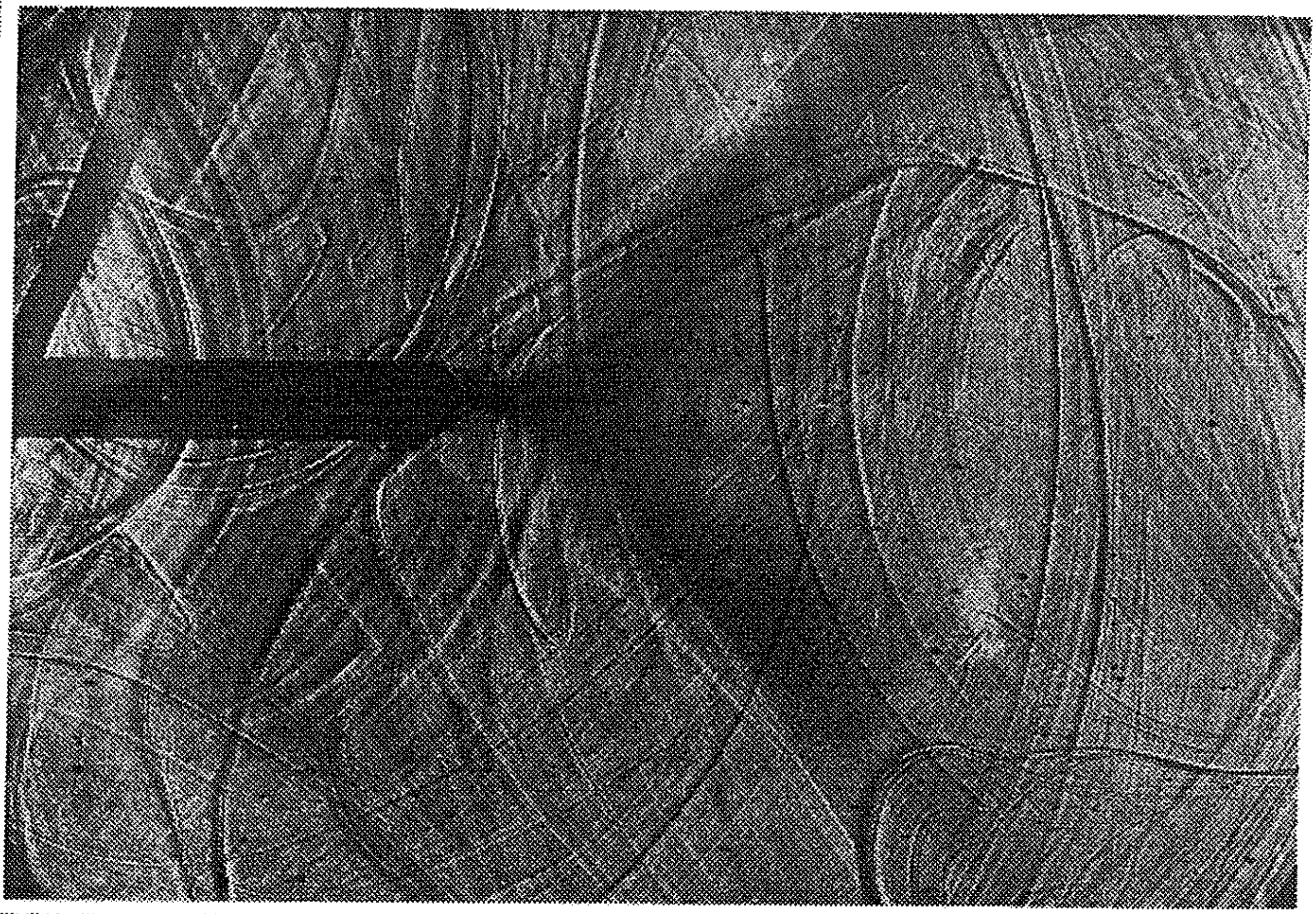


Photo 14 Bad result with a set of Pyrex windows

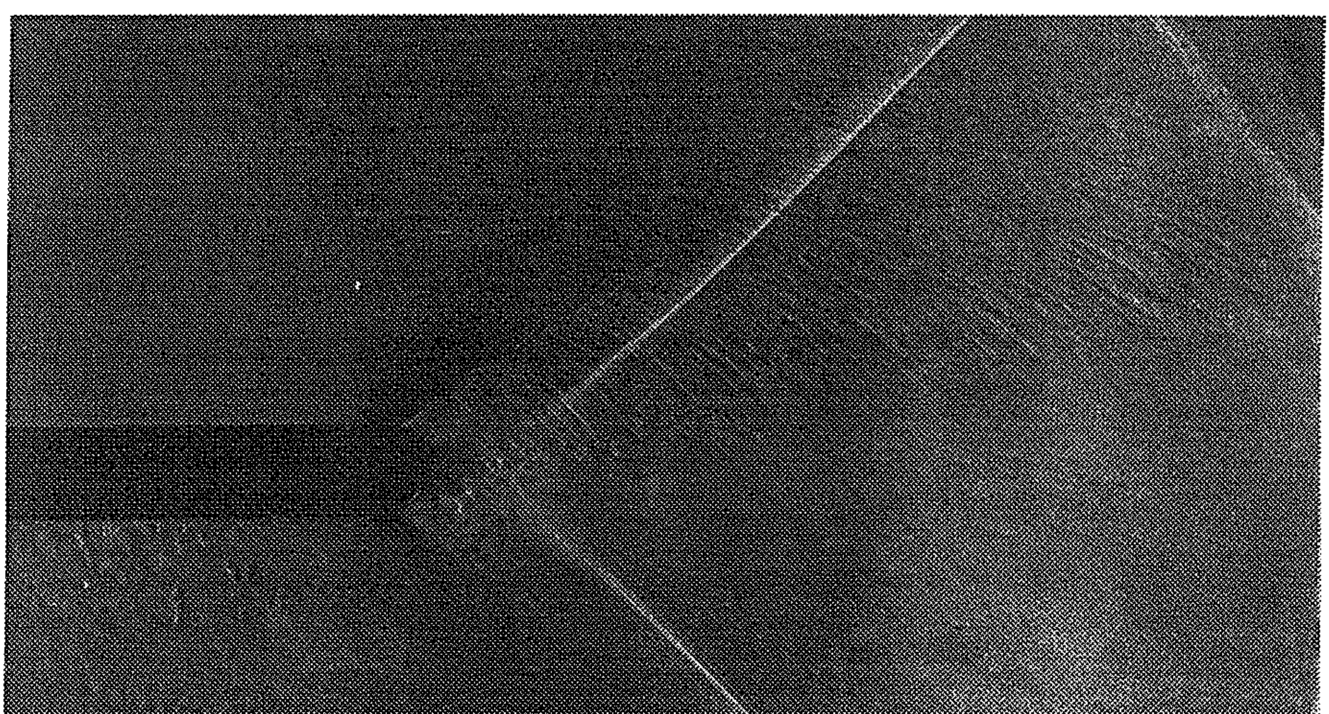


Photo 15 Wake in high supersonic flow conditions

4 The Strouhal number

The Strouhal number is defined as:

$$St = \frac{f.d}{u}$$

f = frequency of the vortex street

d = thickness of the blade at the trailing edge plus the boundary layer momentum thickness

u = the Mach number based on homogeneous flow conditions downstream of the blade or cascade.

Since for the present effort a blade is placed in a convergent-divergent nozzle, a downstream blade Mach number is not easy to define. We propose to use the base pressure Mach number: the calculated Mach number is based upon the ratio of the static pressure in the dead water region (the base of the blade) and the total pressure in the settling chamber.

4.1 Frequency determination

The determination of the frequency of the vortex shedding is done with the help of a hot wire anemometer system from TSI. Results do not show a clear peak indicating the presence of vortices. But with a base pressure Mach number of 1.1 the power spectrum indicates a small peak at 20.795 Hz as can be seen in Fig. 7.

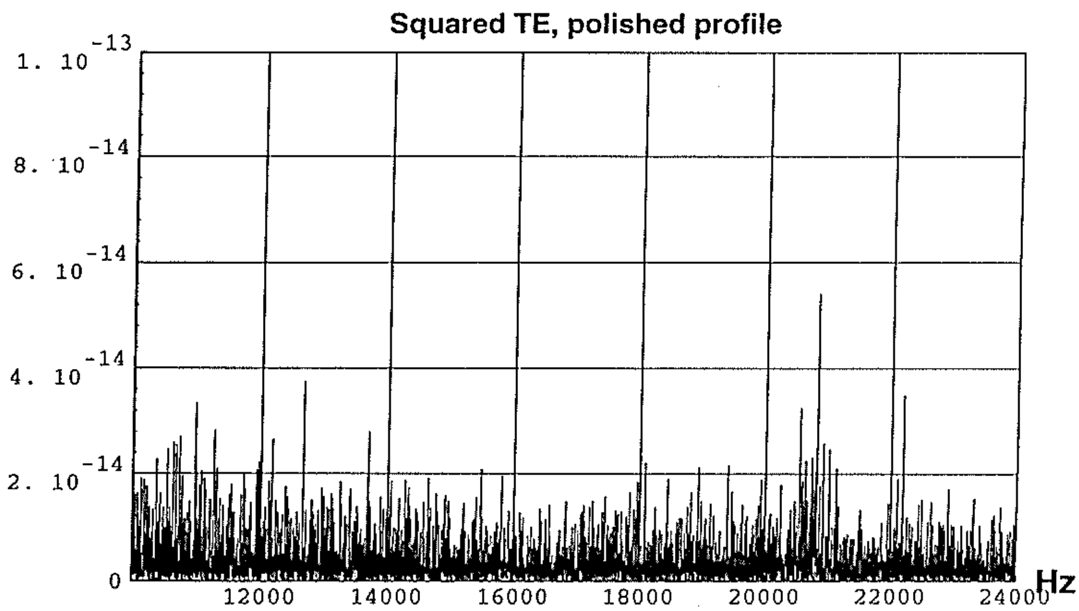


Fig. 7 The power spectrum of the Hot Wire signal

The Strouhal number calculated with those measurements equals 0.28. This value is rather high. However this can be considered as normal since the base Mach number is higher than the Mach number at the separation point.

5 Conclusions

It is clear that the flow visualisation in steam is far more difficult than in air. This is due to:

- the thickness of the windows
- the deposit of dirt on the windows
- higher frequencies
- the presence of large temperature gradients in the neighbourhood of the tunnel

The measurement of the vortex frequency can be done in different ways, the Hot Wire anemometer being one of the possibiilities.