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The High-Speed Cascade Wind-Tunnel of the German Armed Forces University Munich

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Abstract:

The present paper deals with the High-Speed Cascade Wind-Tunnel which was formerly in operation at the DFVLR in Braunschweig and has now been rebuilt at the German Armed Forces University Munich. First some fundamental aspects of cascade testing are mentioned and the principles of construction and operation of the cascade wind-tunnel are explained. Then the special features of the High-Speed Cascade Wind-Tunnel at the Jet Propulsion Institute are described. Finally an outlook on the future research work in the rebuilt wind-tunnel is given.

Contents:

Nomenclature:

a) Capitol symbols:

H	[mm]	test section height
Ma	[-]	Mach number
P	[kW]	power (general)
P_1	[kW]	power of first vacuum pump
P_2	[kW]	power of second vacuum pump
Re	[-]	Reynolds number
T	[K]	static temperature
T_t	[K]	total temperature
Tu	[%]	degree of turbulence
$\dot{V}$	[m^3/s]	air flow rate

b) Small symbols:

ax	[-]	axial direction
d	[m]	blade thickness
e_M	[m]	distance of wake measurement plane
f	[m]	blade camber height
l	[m]	chord length
n	[rpm]	number of revolutions
p	[bar]	static pressure
p_t	[bar]	total pressure
q	[bar]	dynamic pressure
r	[-]	radial direction
t	[m]	blade spacing
u	[m]	probe position within the wake
w	[m/s]	flow velocity
x	[-]	chord direction
y	[-]	direction normal to chord

c) Greek symbols:

β	[°]	flow angle
β_s	[°]	stagger angle
Π	[-]	compressor total pressure ratio

d) Indices:

1	upstream condition
2	downstream condition
2th	downstream condition for isentropic flow
2u	condition in wake measurement plane
K	within the pressure tank
V	within the settling chamber
l.e.	lower endwall
u.e.	upper endwall

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1. Introduction

The real flow in a turbomachine is highly three-dimensional, compressible, viscous, and unsteady. Therefore it has to be simplified in order to make it accessible to fundamental studies. Although nowadays first numerical solutions of the Navier-Stokes-Equations are being presented, these computer programs won't still be practicable for designing new turbomachinery bladings in the near future.

A very customary simplification for axial turbomachines is the plane cascade model. It can be obtained by geometrically developing a cylindrical blade-to-blade surface which intersects the interesting blade row (see Fig.1). This procedure results in a mathematically infinitely long radial projection of the considered problem (see Ref./4/,/5/)

The cascade model allows the two-dimensional theoretical treatment of basic flow phenomena. For experimental studies a section of it can be tested in the cascade wind-tunnel. A unique facility of this type is the High-Speed Cascade Wind-Tunnel which was formerly designed and operated at the DFVLR in Braunschweig and has now been rebuilt at the German Armed Forces University Munich.

2. The High-Speed Cascade Wind-Tunnel

2.1 General considerations (see also Ref./3/)

Fig.2 shows a sketch of a cascade section. Its main geometrical parameters are

- thickness ratio d/l and thickness distribution y_d (x),
- camber ratio f/l and camber distribution y_f (x),
- blade spacing ratio t/l,
- stagger angle β_s.

The blade thickness is severely influencing the critical Mach number, whereas the camber is responsible for the static pressure change within the cascade. The blade spacing is a measure for the aerodynamic loading of the blade row and the stagger angle determines the position of the blade chord against the circumferential direction.

The main aerodynamic parameters are

- flow angles β_1 and β_2,
- Mach numbers Ma_1 and Ma_2,
- Reynolds number Re_1 (or Re_2 for turbine cascades).

The Reynolds number describes the influence of viscosity and is defined as the ratio of inertial force to friction force. A decreasing Reynolds number, therefore, indicates an increasing danger of flow separation.

In the high subsonic and, of course, in the transonic region compressibility becomes more and more important. Its influence is measured by the Mach number which is defined as the ratio of flow velocity to sonic velocity.

During flight a turbojet engine is faced with a large variety of operating conditions. A change of the flight level, for instance, results in a change of the Reynolds number which is mainly caused by the different density; but it also leads to a change of the Mach number, as temperature is changing with the flight level, too. On the other hand the Mach number is also influenced by the engine speed.

The various combinations of Reynolds numbers and Mach numbers are severely influencing the flow through a blade row. Therefore, a cascade wind-tunnel should have the capability of independently changing these two parameters; this, in order to make the cascade measurements transferable to turbomachines.

2.2 Principles of construction and operation

The High-Speed Cascade Wind-Tunnel is a continuously operating open loop test facility with an open test section. It consists of two main parts (see Fig. 3), the driving unit and the wind-tunnel itself, of which the latter is installed within a cylindrical pressure tank. The necessary air flow is delivered by a six-stage axial compressor. By varying its number of revolutions, any desired Mach number between 0.2 and 1.05 can be obtained. Since a constant Reynolds number requires a constant total temperature within the tank, the whole energy which is equivalent to the compressor work must be cooled out of the air flow again. For independently setting the Reynolds number the pressure within the tank can be varied between 0.05 and 1.2 bar, thus achieving a Reynolds number range of $10^6 m^{-1} \leq Re/l \leq 1.5 \cdot 10^7 m^{-1}$. The complete performance map of the High-Speed Cascade Wind-Tunnel is shown in Fig. 4 including the limits of operation.

2.3 Special features (see also Ref. /1/,/2/,/3/)

Fig.5 shows a sectional drawing of the whole test facility. The driving unit on the right-hand side, which is outside the pressure tank, consists of an a.c. electric motor of about 1300 kW power, a hydraulic coupling, and a gear box with a transmission ratio of 4.4. By this means the number of revolutions of the axial compressor within the pressure tank can continuously be altered in the range of about 1500 to 6200 rpm. Its maximum air flow is about 30m ^{3}/s and a maximum total pressure ratio of 2.14 can be achieved. Since each cascade works like a throttle and, therefore, corresponds to a different working point in the performance map of the compressor, a variable bypass helps to prevent the compressor from stalling.

As mentioned in the chapter before, all the compressor work must be cooled out of the air flow again. This is achieved by a lamella cooler for the main flow and by two smaller ones for the bypass air. To increase the cooling efficiency of the main flow cooler, a diffusor is built in in front of the cooler. Although the main flow cooler already acts like a straightener, a settling chamber follows the cooler for mixing out pressure and temperature non-uniformities. After this the flow is reaccelerated within a nozzle until it reaches the desired upstream Mach number of the cascade to be measured.

The rectangular test section is 300 mm broad for verifying high aspect ratios. The height is variable between 250 mm and 500 mm depending on the upstream flow angle β_1 of the cascade (see Fig. 6). The latter is mounted between two rotatable discs, which allow a continuous variation of β_1 between 25° and 155° with β_1 measured against the circumferential direction.

Especially if measuring compressor cascades the endwall boundary layers can't be neglected. Therefore, the wind-tunnel is equipped with a special suction system, which is based on a centrifugal compressor of 155 kW power (not shown in Fig.5). Suction of the upper and lower endwall boundary layers (see Fig.6) provides the necessary inlet flow periodicity. Suction of the left and right endwall boundary layers allows to control the axial velocity density ratio, which is measuring the flow acceleration due to the flow contraction within the cascade.

In experiments with blade boundary layer control by blowing or with simulating the cooling of turbine blades an additional air supply is necessary. For this a 1000 kW screw compressor will be built up, which is scheduled to be operational in 1987.

Another important parameter, which is severely influencing the flow through a blade row, is the upstream turbulence. By using different types of turbulence generators various degrees of turbulence Tu_1 between about 0.3% and 6% are simulated. As the generators are inserted within the nozzle (see Fig.5), which is some distance away from the cascade, a nearly uniform upstream velocity profile can be achieved.

2.4 Constructional changes compared to the DFVLR configuration

After disassembly of the wind-tunnel in Braunschweig some constructional changes have been made.

The most conspicuous one is the building of a new pressure tank. This was necessary because the rebuilt wind-tunnel is scheduled for operation up to a tank pressure of 1.2 bar, whereas in Braunschweig it was only operated up to atmospherical pressure. Another reason was the better accessibility of the wind-tunnel equipment within the tank, which is achieved by a larger tank diameter(the new diameter is 4m compared to 2.4m at the DFVLR).

Furthermore a totally new control system for the three parameters total temperature, dynamic pressure, and static pressure was designed. Any of the three control loops is based on a fully digital controller. By this means the following controlling accuracies can be achieved:

- total temperature	± 1K
- dynamic pressure	± 0.002 bar
- static pressure	± 0.002 bar

Since the measurements in Braunschweig always suffered from oil leakages in the compressor region, the wind-tunnel oil system was divided into two independent parts. The new second oil system, which now mainly provides the lubrication of the compressor bearings, is pressurized by the tank pressure p_K. By this means the loading of the seals is removed and no further leakages are exspected.

Finally all the pipe connections and most of the electrical equipment had to be renewed.

2.5 Types of measurements

For investigating the aerodynamic behaviour of cascades the following measurements have been made in Braunschweig:
- wake measurements,
- measurements of the profile surface pressure distribution,
- boundary layer measurements,
- Schlieren measurements
- special measurements like hot-wire measurements and flow visualization.

After rebuilding the High-Speed Cascade Wind-Tunnel in Munich only the first two types of measurements will be carried out for some time; this, in order to become familiar with the whole test facility.

Usually the wake measurements are carried out by traversing a wedge probe (see Fig.7) behind the cascade. The traversing plane is about half a blade spacing behind the trailing edge of the blade (see Fig.8). Both the total pressure p_{t2u} and the static pressure p_{2u} are recorded at each probe position u. Due to the design of the wedge probe the exit flow angle β_{2u} can only be measured in the outer wake regions. Therefore, a so-called Neptun probe (see Fig.7) is used, if the flow angle distribution within the wake is of special interest.

3. Future research work in the wind-tunnel

Shortly before disassembly of the High-Speed Cascade Wind-Tunnel in Braunschweig some calibration tests have been carried out (see Ref./9/), which shall be reproduced, when the rebuilding of the cascade wind-tunnel in Munich will have been completed. The turbine cascade T106 (see Fig.9) was selected for these tests, because it has been measured very intensively in the past few years.

After these calibration tests the research work in the High-Speed Cascade Wind-Tunnel will be started. It will be the main test facility for supporting the development of new design concepts for turbomachinery bladings. As part of this research work a highly-loaded controlled diffusion compressor profile (see Fig. 10) was designed, which is to be measured in the wind-tunnel now, in order to demonstrate the validity of the design method.

Further topics of the research work at the Jet Propulsion Institute will be:
- boundary layer control of profile and endwall boundary layers at compressor bladings,
- transition and separation of boundary layers and shock/ boundary layer interaction,
- secondary flow effects, i.e. effects of aspect ratio.

As part of this work a modern data acquisition system will be built up during the next few months.It shall replace the old system which has already been used in Braunschweig. Some sophisticated measurement techniques like laser anemometry and the use of hot film probes will also be established in the wind-tunnel test facility in the near future.

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5. List of Figures

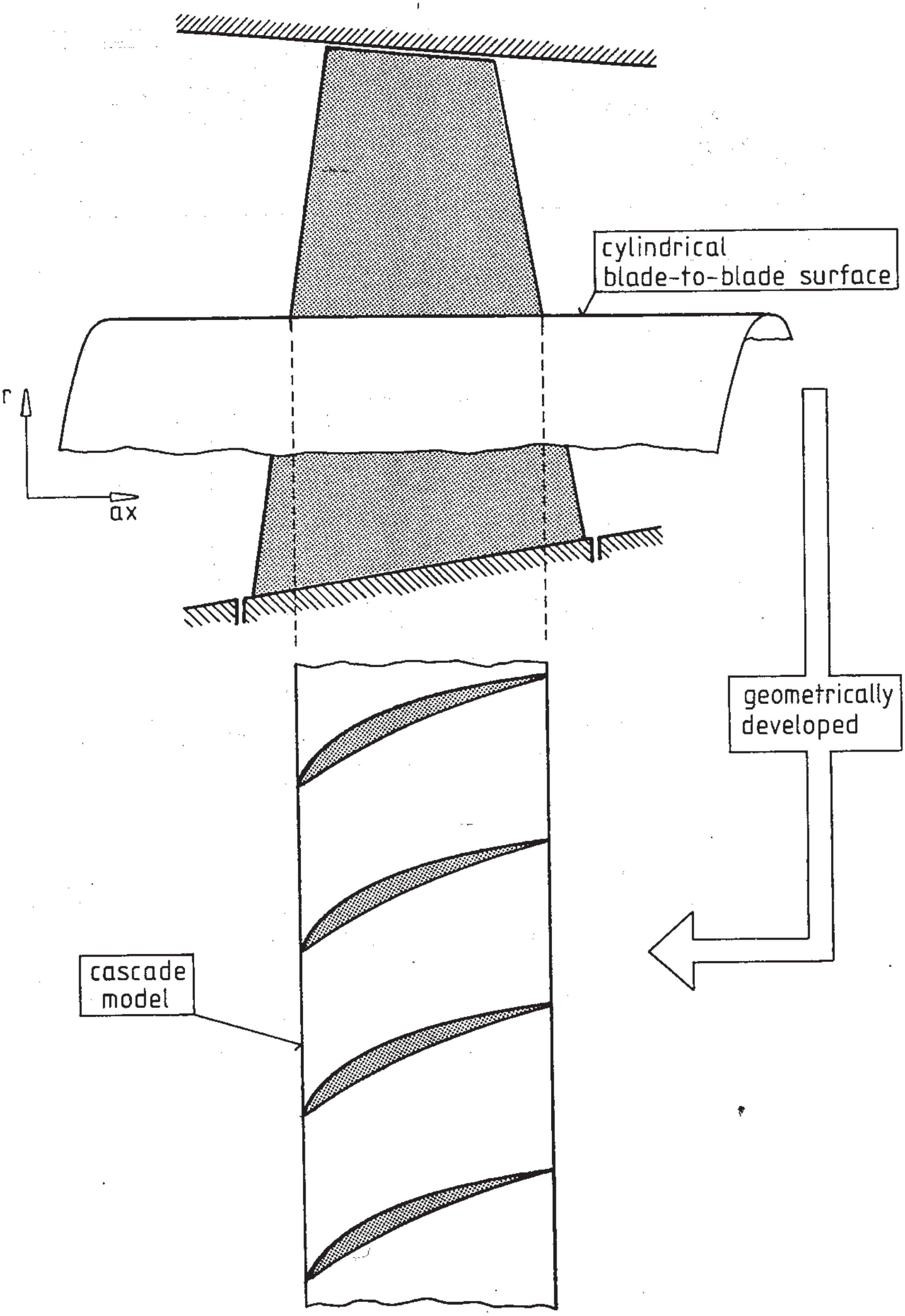

Fig. 1: The cascade model as geometrical development of a cylindrical blade-to-blade surface

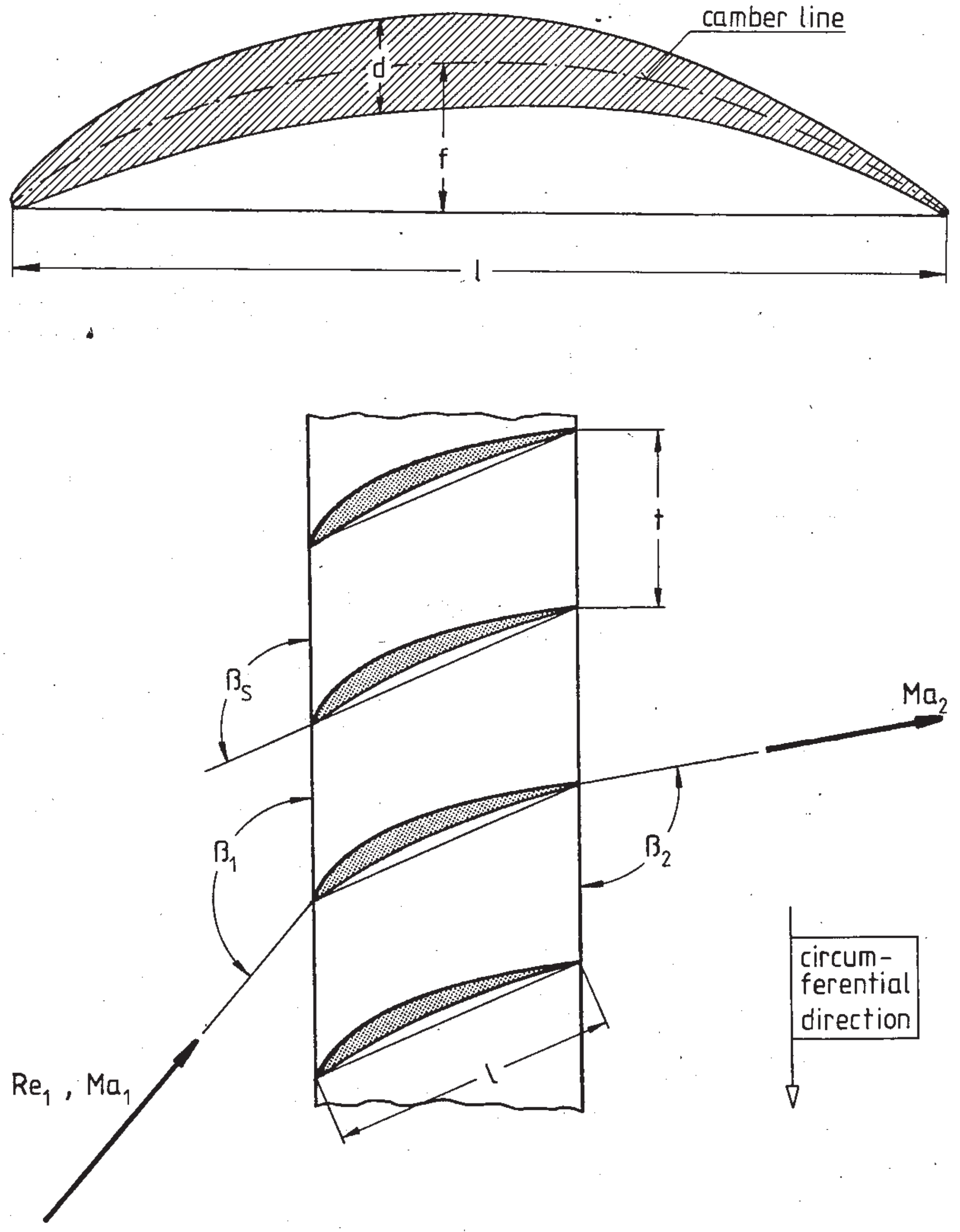

Fig.2: Geometrical and aerodynamic parameters of a cascade

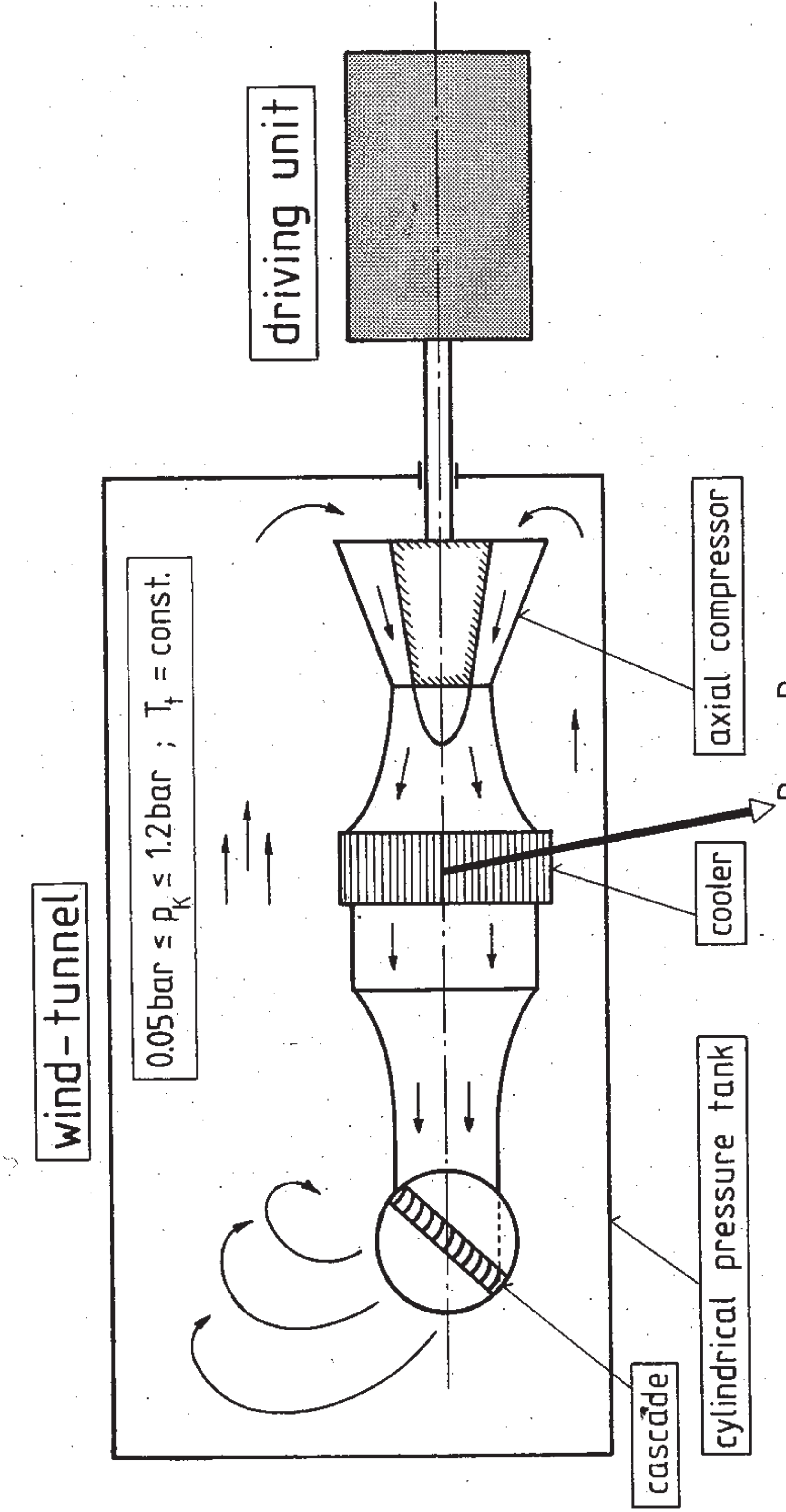

Fig.3: Principles of construction and operation of the High-Speed Cascade Wind-Tunnel

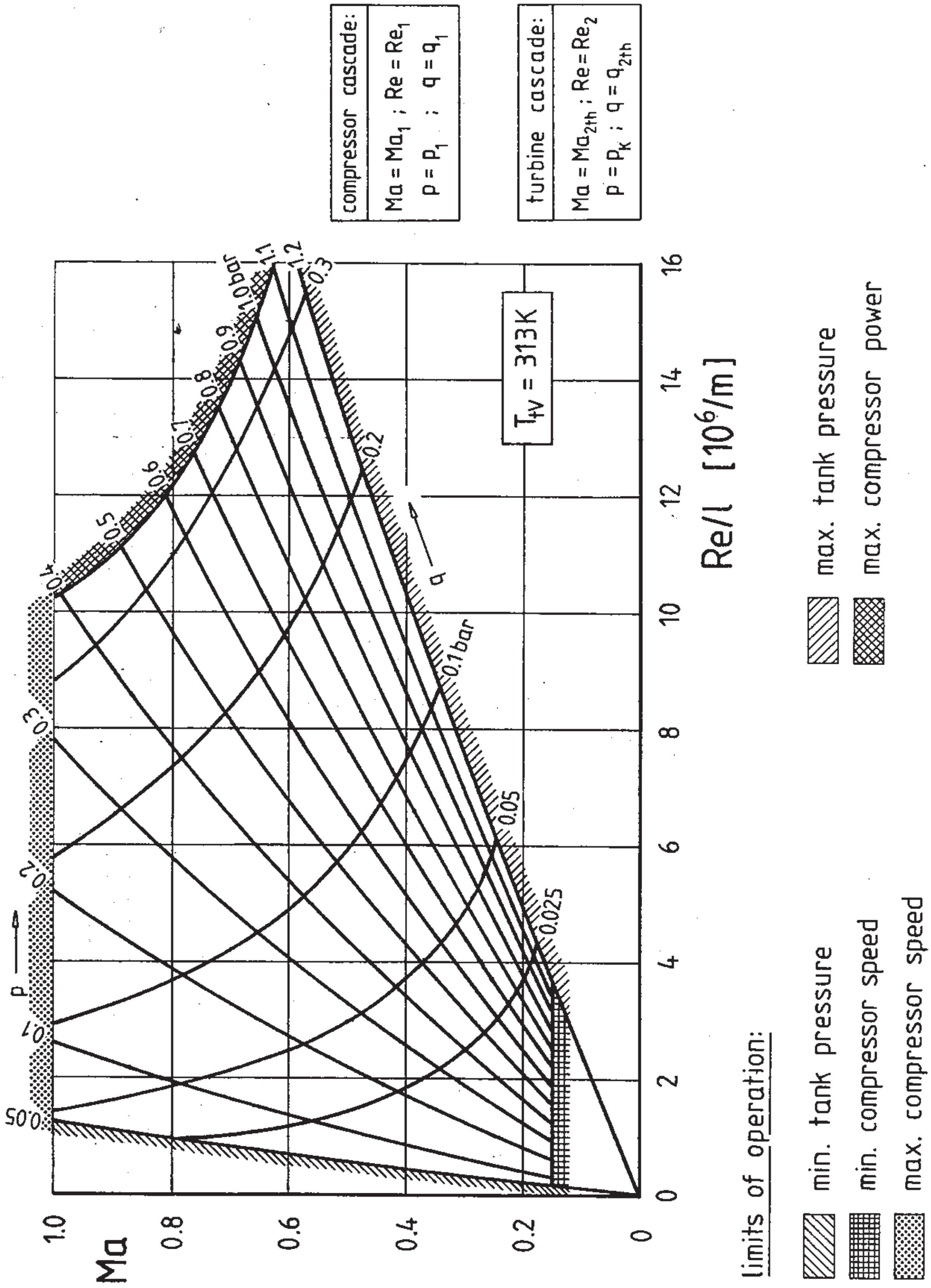

Fig.4: Performance map of the High-Speed Cascade Wind-Tunnel (see Ref./7/)

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test section data:

- Mach number : $0.2 \leq Ma \leq 1.05$
- Reynolds number : $10^6 m^{-1} \leq Re/l \leq 1.5 \cdot 10^7 m^{-1}$
- degree of turbulence : $0.3\% \leq Tu_1 \leq 6\%$
- upstream flow angle : $25° \leq \beta_1 \leq 155°$
- blade height : 300 mm

supply units:

- evacuating unit : $P_1 = 30$ kW, $P_2 = 20$ kW
- boundary layer suction (centrifugal compressor) : $P = 155$ kW
- additional air supply (screw compressor) : $P = 1000$ kW

wind-tunnel data:

- a.c. electric motor : $P = 1300$ kW
- axial compressor (six stages):
  - air flow rate : $\dot{V} = 30 m^3/s$ (max.)
  - total pressure ratio : $\Pi = 2.14$ (max.)
  - number of revolutions : $n = 6200$ rpm (max.)
- tank pressure : $0.05 bar \leq p_K \leq 1.2 bar$

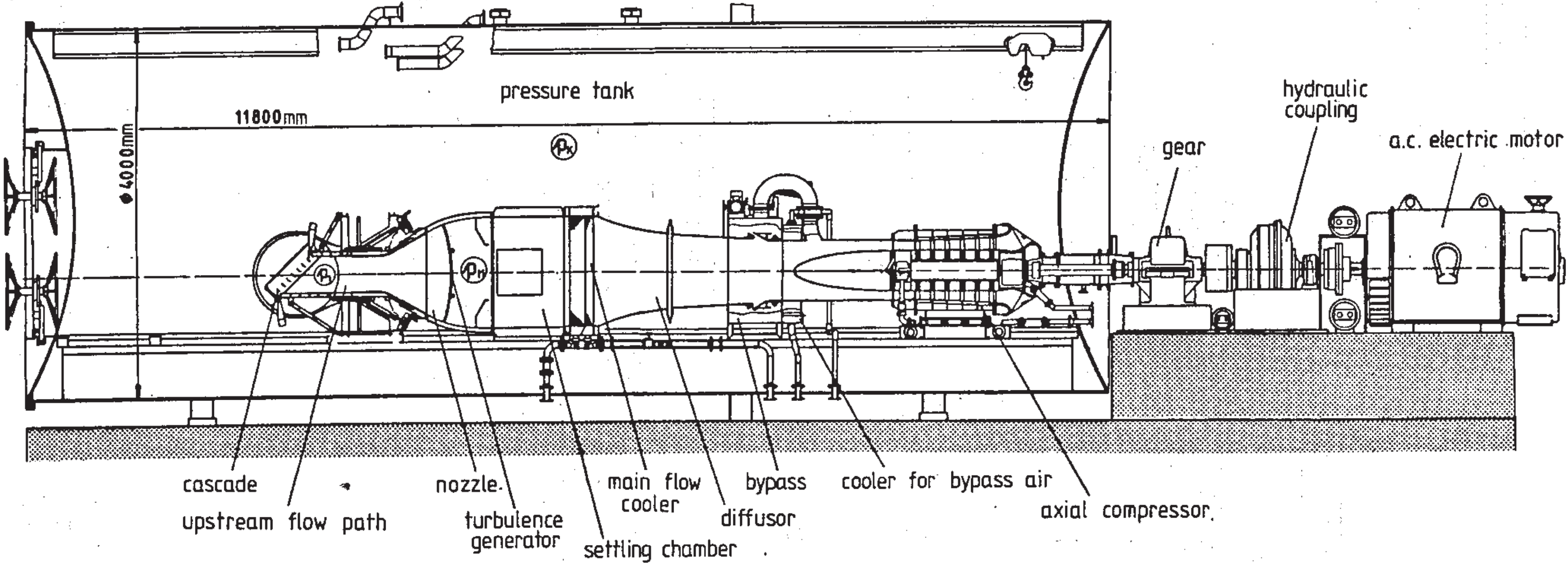

Fig.5: The High-Speed Cascade Wind-Tunnel (sectional drawing)

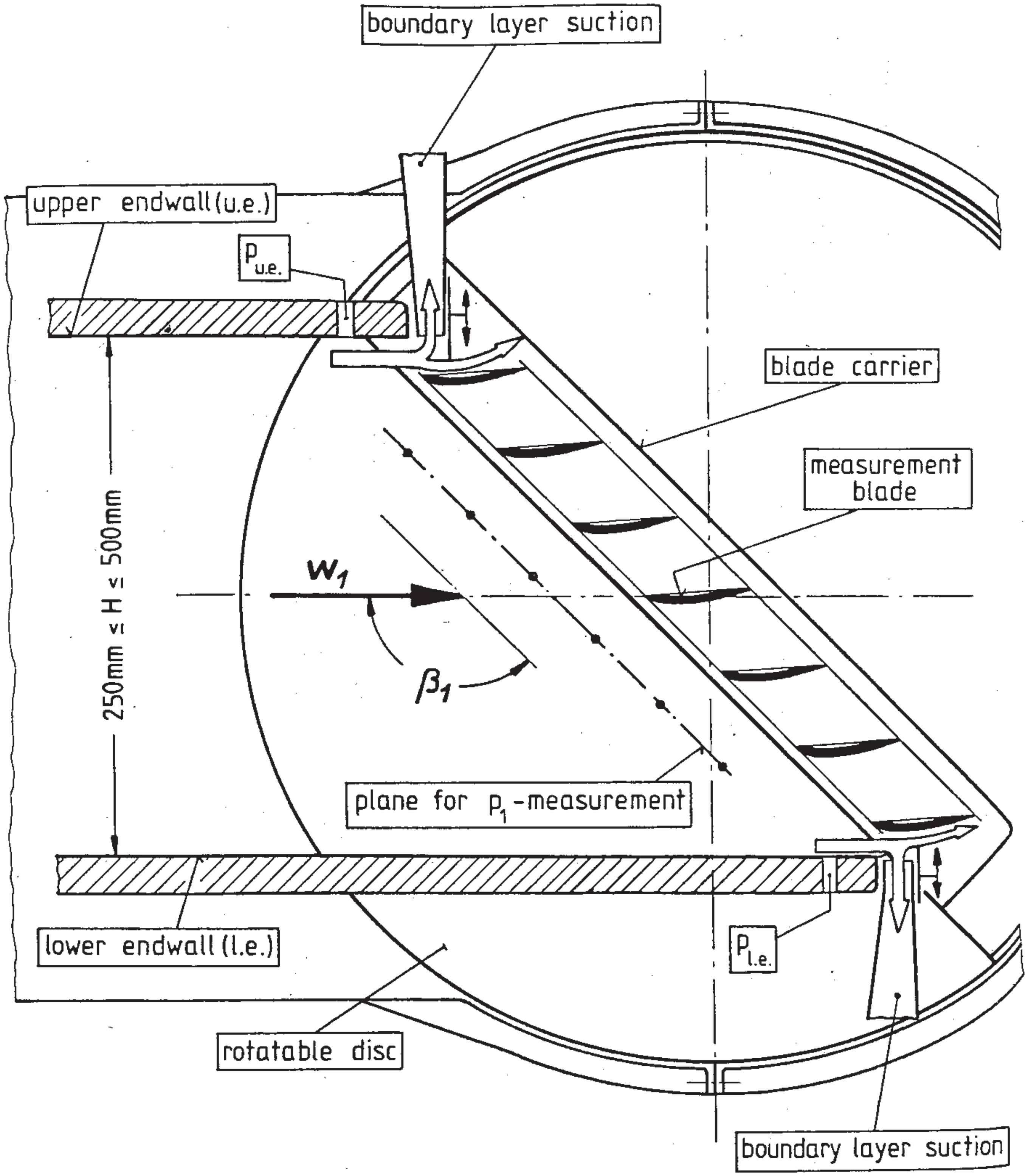

Fig.6: Test section with boundary layer suction at the upper and lower endwalls of the test section

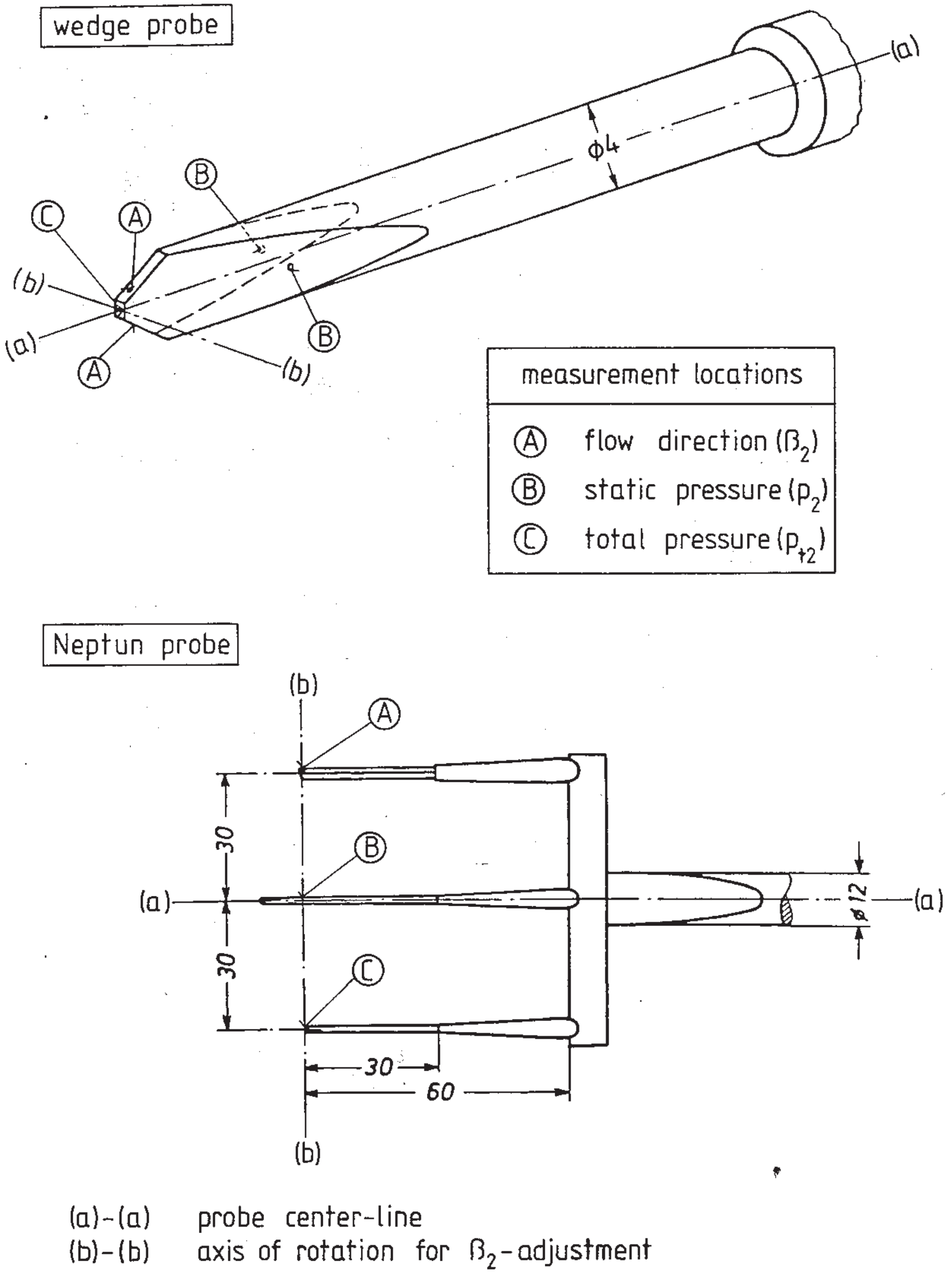

Fig.7: Probes used for wake measurements (see also Ref./8/)

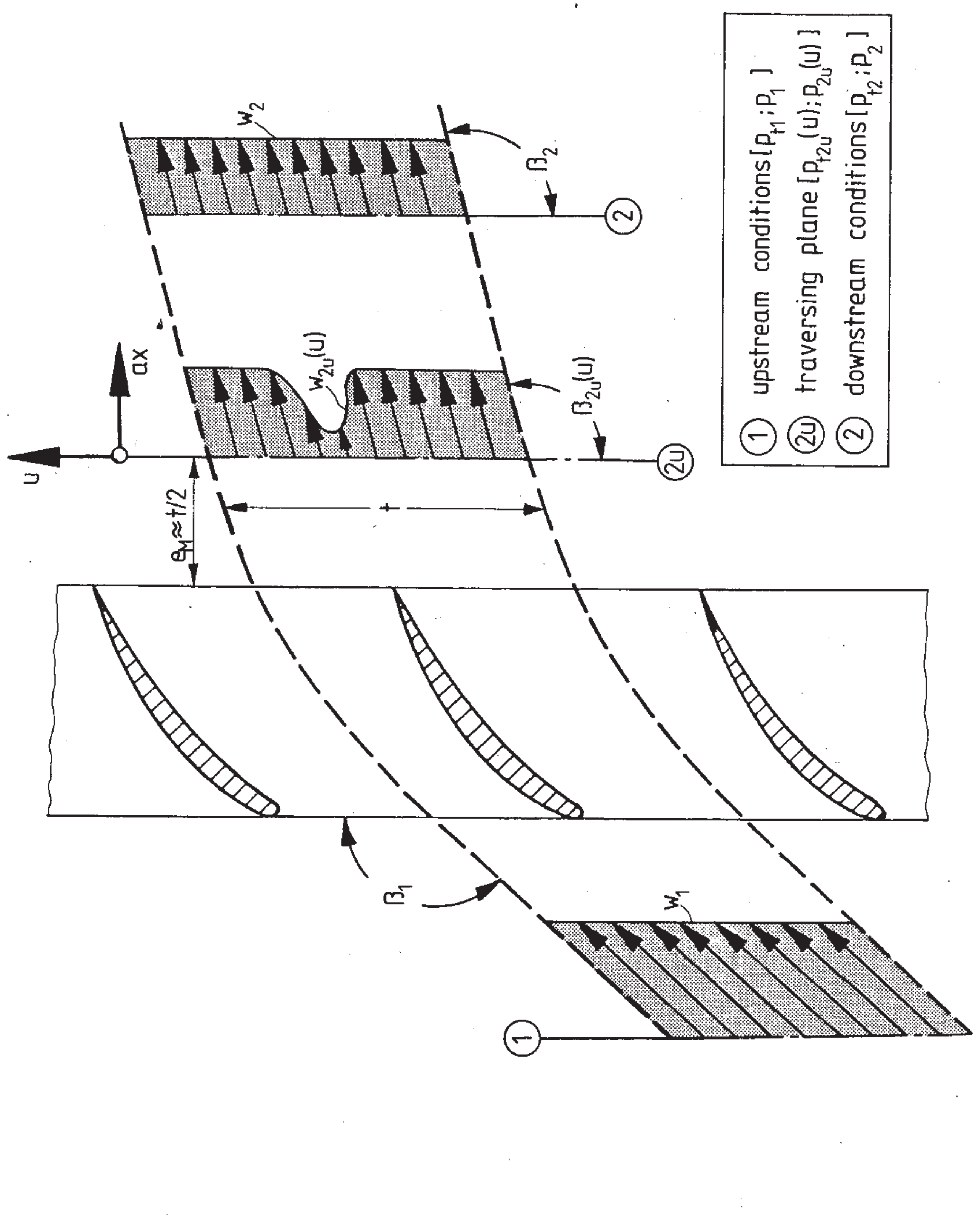

Fig.8: Principles of wake measurements

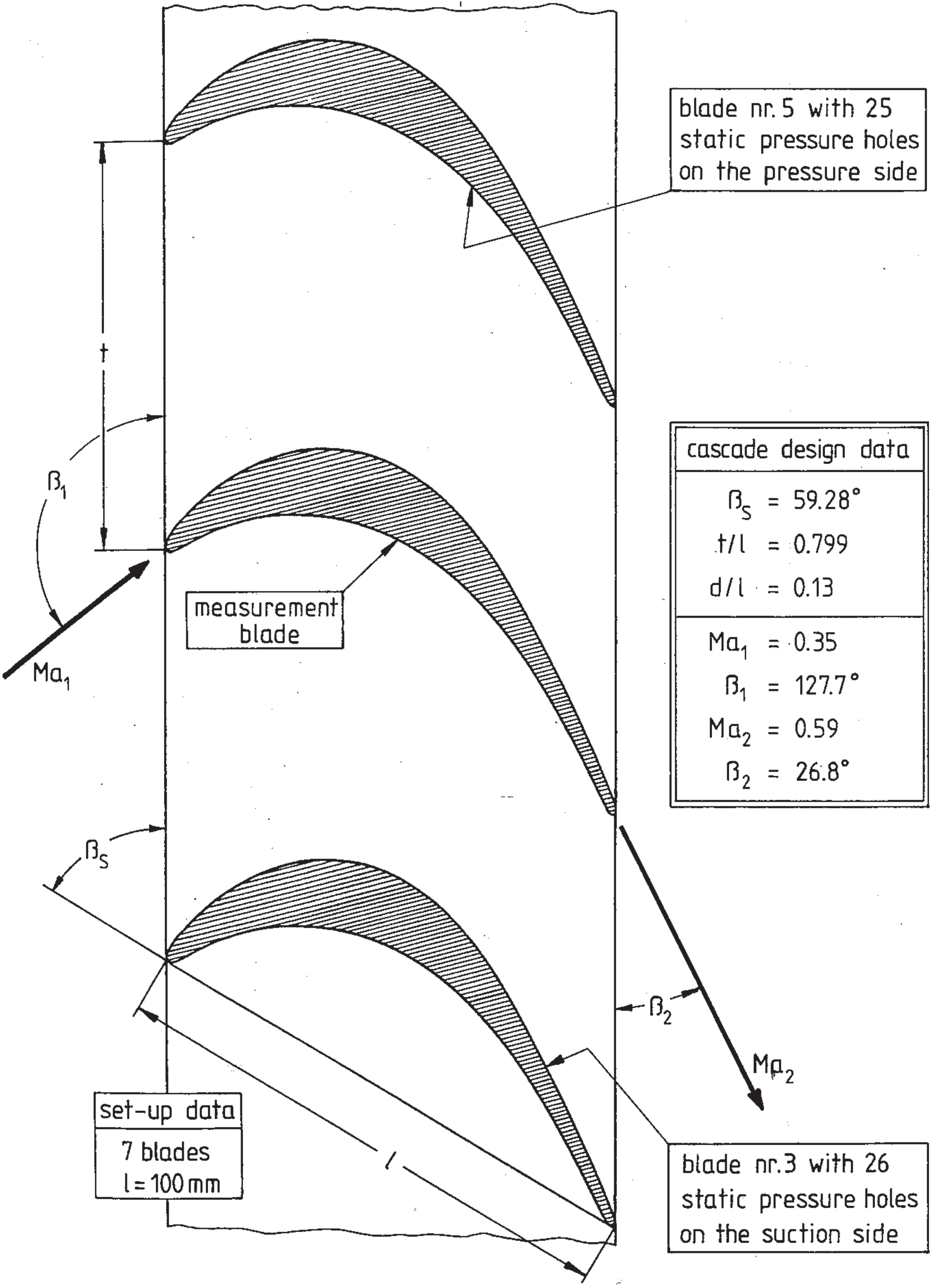

Fig.9: The turbine cascade T106 (see Ref./9/)

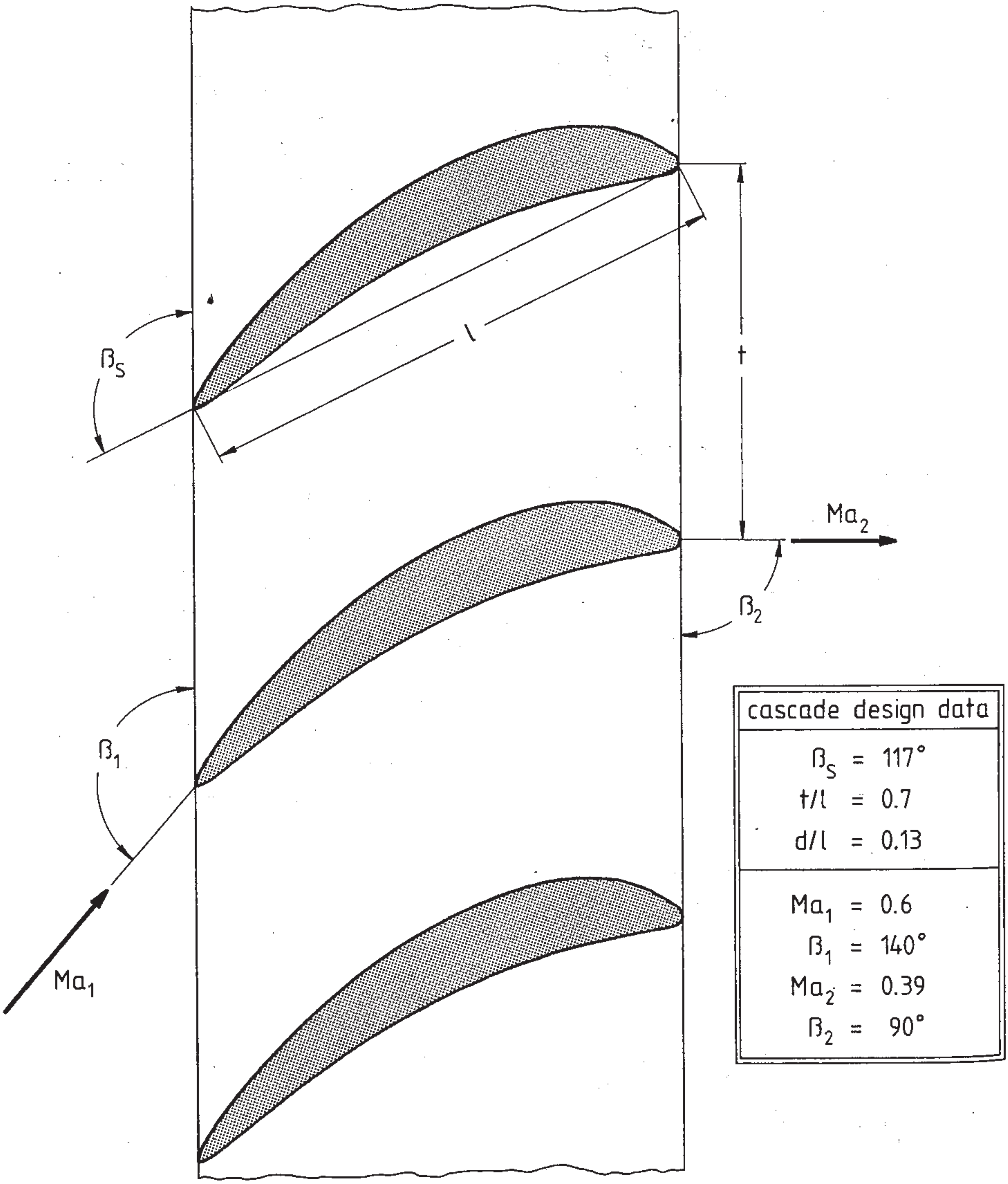

Fig. 10: Highly-loaded controlled diffusion compressor cascade V102 (see Ref./10/)