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13. ABSTRACT (Maximum 200 words)

The predominantly phenomenological study has been oriented towards basic physical understanding of the development and structure of transonic flow in closed curved channels, namely of the strong interaction of the terminal shock wave with various vortical structures. A new classification of vortical structures according to the forces generating them has been suggested.

Flow separation in this typically three-dimensional case has been analyzed and several simple separation criteria have been suggested. They can be used in the analysis of experimental results as well as in numerical studies. However, it has become obvious that the local separation criteria are not sufficient and that rather some global criteria have to be looked for.

Experiments carried out so far were based on the flow and surface streamline visualization. They provide material for the basic qualitative analysis of the flow phenomena but are only of a limited value for quantitative measurements. For this purpose a double pulse laser has been commissioned with the intention to apply the particle image velocimetry.

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Introduction

The impetus to solve this problem came from internal aerodynamics, namely of cascades and inlets, where the very meaning of separation, as well as the phenomenon itself, is found to be quite different from that in external aerodynamics.

Separation can be induced by channel geometry or by adverse pressure gradients, as, e.g. in shock waves terminating local supersonic regions. Interaction between these shock waves and all the viscosity dominated regions (boundary layers on the channel walls, incl. the corner boundary layers, separated flows, etc.) is a *strong interaction.* This means that all phenomena entering the interaction depend on each other, and affect each other. As a consequence, in an analytical or numerical solution they have to be treated simultaneously, and the classical local separation criteria become questionable.

There are several other phenomena typical of closed curved channels affecting separation. Approaching the critical cross section (or the $M \sim 1$ section), the velocity profile becomes more "full" and its displacement thickness drops down considerably. This acts against separation, as much as the aerodynamic choking. On the other hand, due to relatively large regions of subsonic flow, a considerable upstream effect is to be expected, which enhances separation, as well as instability of the flow configuration.

Obviously, the whole *problem is strictly three-dimensional.*. There are numerous *vortical structures* in the flow - due to secondary flows (channel vortices), corner boundary layers, flow separation, horse-shoe vortices in front of inserted bodies, etc. They substantially contribute to the three-dimensional nature of the flow, as well as to its unsteady behaviour.

The formulation of a mathematical model for theoretical and experimental solution of such a complex problem as transonic separation in closed curved channels is, has to start with a state of-the-art review and with the possibly most detailed phenomenological study. The latter has been the main research objective of this project in the first year.

Research Objectives

The objectives have already been formulated in the Proposal and are evident even from the title. They should ultimately explain the rôle, structure, and effects of *transonic flow separation in the context of the whole transonic flow development in closed curved channels*, as, eg. cascades, bends, ducts, etc. As stated in the proposal, the investigation should concentrate on the basic flow physics rather than on a great variety of possible flow patterns and applications.

Like in any phenomenological study, the success and profoundness of this research depends on the quality of experimental methods and techniques used. The investigators have recently commissioned a double pulse laser and have been acquiring the necessary measurement technique of Particle Image Velocimetry and the relevant evaluation methods. Though this may slow down the whole research for the moment being, it will be instrumental in obtaining more information about the investigated phenomena in the future.

Research objectives for the first year were detailed as follows

- to summarize previous experiments in the "ONERA" type channel and to analyze conditions leading to flow separation,
- to design and manufacture a test channel with greater wall curvature (so called "CAMEL" type channel),
- to undertake a phenomenological study of transonic flow with separation in the "CAMEL" type channel and to analyze a typical situation with the main emphasis on the effect of the complex flow structure on separation,
- to make the new double-pulse laser operational for the application in experimental research of transonic flow in closed channels,
- to master the PIV (particle image velocimetry) technique and the necessary methods of evaluation.

Experimental facilities

All experiments were carried out in a small high speed wind tunnel in the aerodynamic laboratory of the Institute of Thermomechanics at Novy Knin. The wind tunnel is of a blow-down type, breathing atmospheric air through a silicagel dryer and a pebble and cloth filters into a vacuum storage. It has a total volume of 6500 m^3 and can be evacuated by 3 vacuum pumps down to 0.1×10^5 Pa, so that with the mass flow of about 1 kg s^{-1} the running time is almost unlimited.

The "ONERA" type test section (see ***Fig.1***) was built for experiments studying the effect of channel width on transonic shock wave- boundary layer interaction. The width could be changed stepwise from 0.01 to 0.12 m. The attainable Mach number was about 1.8.

For experiments of the present project, the test section has been replaced by the one in ***Fig.2*** . (the so called "CAMEL" type test section). It has a constant width of 80 mm.

The laboratory is equipped with a Mach-Zehnder interferometer with a built-in schlieren system. By the end of 1993 a double pulse laser has been commissioned for the particle image velocimetry. This technique should increase the possibilities of 3D measurements, namely in rather narrow closed channels, where any material probe caused a collapse of the whole flow structure investigated. The PIV method is a very progressive technique, however, so far it has been used mainly in external aerodynamics. Therefore, the small team working on it in our Institute has to develop its own way of obtaining pictures of the plane normal to the mean velocity vector. Namely for this reason it has been decided not to loose too much time on the method of evaluation of the pictures and rather to buy a professional software from the AEA Harwell (UK).

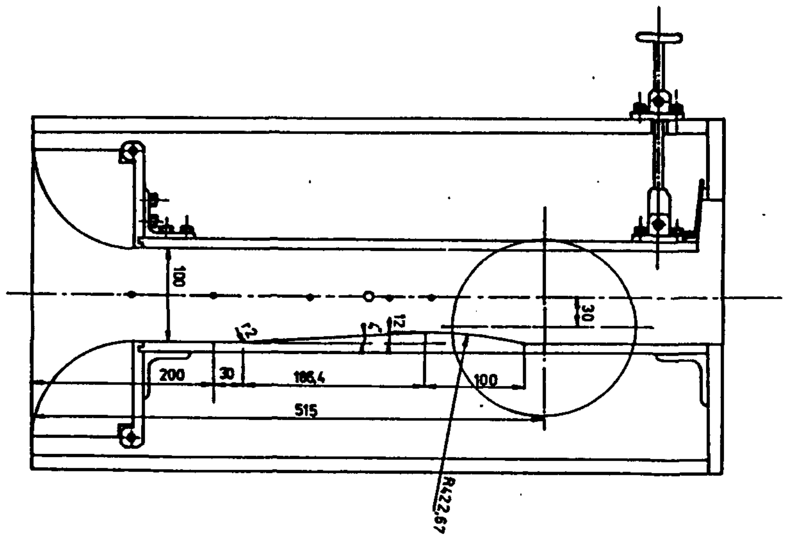

Fig.1 "ONERA" type test section

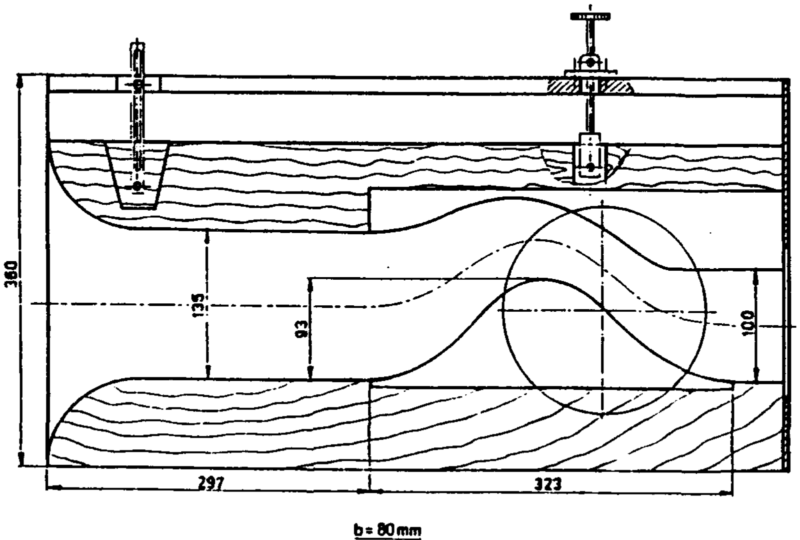

Fig.2 "CAMEL" type test section

Status of the Research Effort

Brief Summary of the Previous Experiments

The first set of experiments in the ONERA type channel was to study whether and to what extent our measurements are - at least in the time averaged parameters - comparable to those performed by ONERA[see e.g. 1]. From the previous experiments we have been aware of the great effect of channel width, and so it has been decided to repeat the measurements with the same channel shape and the same reference parameters, but with different channel widths [2]. ***Fig.3*** shows typical examples of the visualized surface streamlines on the shaped wall for four channel widths. Only in the widest channel can a clear separation line and a well defined separation bubble be seen. The narrower the channel, the less clear is the separation (though visible on the schlieren pictures) and any traces marking the reverse flow. The flow in the narrowest channel has a character of a shear flow with no sign of separation and reverse flow. ***Fig.4*** shows the pressure distribution in the mid plane for the above cases. These results have definitely proved that any measurements in closed and not too wide channels are biased by the effect of the side walls, and any conclusions drawn from these measurements have to be considered very carefully.

The side wall effect on the transonic interaction and the whole flow structure varies according to the channel width. In wider channels the threedimensional interaction enhances generation of vortical structures, preserving at the same time in the mid plane an almost twodimensional model of interaction. In the very narrow channels the shear-flow-like character smears off both the separation and reattachment lines, and most probably even some of the vortical structures. On the other hand, it changes qualitatively the process of supersonic/subsonic transition[3]. Instead of in one shock wave, the transition occurs in a series of shock waves (the so called *pseudo-shock wave*), ***Fig.5***. Though very detailed measurements were carried out, no definite conclusions can be made. Most probably the transition takes place in the first shock that generates a strong dissipative region with a series of standing (acoustic) waves in which the remaining increase of static pressure is mainly due to viscous losses.

All measurements in relatively narrow channels, however, have provided new views on flow separation in the process of transonic interaction. Despite the generally accepted model of pseudoshock waves with separation between the shock waves, direct measurements of skin friction in the wave have never shown $c_f < 0$. They have also not found reverse flow to be a typical characteristics of separation. These measurements have also shown that the local separation criteria based on the boundary layer theory do not work in closed and relatively narrow channels. An attempt to derive global separation criteria on the basis of the thermodynamic stability theory has not proved successful so far. First of all a definition, or at least an explanation, of what separation really means in closed or relatively narrow channels has to be provided.

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1 Delery J.M.: Investigation of strong shock turbulent boundary layer interaction in 2D transonic flows with emphasis on turbulence phenomena ONERA T.P. 1981-65, 1981

2 Dvorak R.: Transonic shock wave-boundary layer interaction in channels *(In Czech)* Inst.of Thermomechanics, Research Report No Z-860/83, 1983

3 Dvorak R.: Supersonic-subsonic transition in pseudoshock waves trojnicky casopis SAV, Vol.39, No 6, 1988

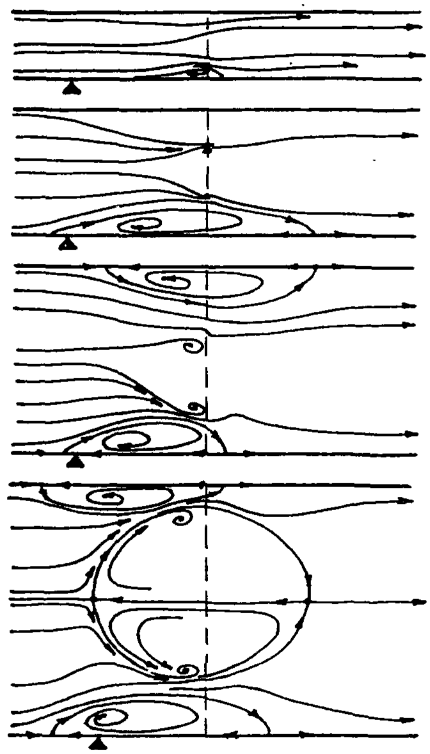

Fig. 3 Surface streamline patterns as visualized at 4 channel widths (ONERA type test section, the shock wave position marked by Δ)

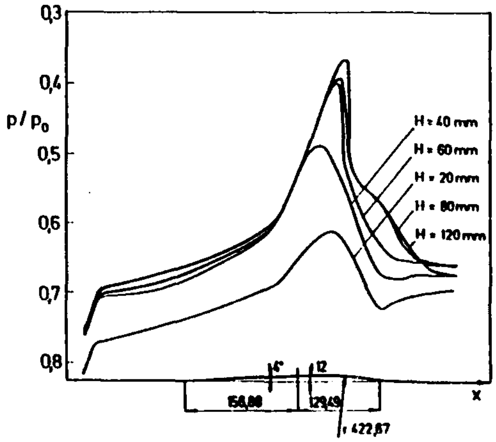

Fig. 4 Pressure distribution along the channel axis (ONERA type test section, constant back pressure)

Once the channel width dropped under a certain value, it was no more the shape of the wall on which the interaction was studied that determined the configuration of the flow in the channel . The shock wave position, as well as the basic flow pattern, was then determined by the channel cross section area changes with the streamwise coordinate (similarly to 1D flows). This fact can also explain the strange results obtained on a skewed bump in ONERA (see eg. Fig. 7 in [1]). The whole flow structure was shifted to one side in the direction of the bump sweep, keeping at the same time the same character as in a 2D flow.

The comparison of our results with those of Doerffer and Dallmann [see eg 2] has also revealed a strong and qualitative dependence on the boundary layer character and thickness in the oncoming stream. The vortices observed in the interaction region had an opposite sense of rotation. This is most probably due to the artificial boundary layer thickening by blowing into the boundary layer through an upstream placed slot (see [3]).

Fig.5 "Pseudoshock wave"
a - constant area rectangular channel, $M_1 = 1.3$
b - "ONERA" test section, channel width 20mm

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[1] Delery J.: Recent Basic Studies on Transonic Shock Wave/Turbulent Boundary Layer Interactions
In: J.Zierep, H.Oertel (Eds.), Symposium Transsonicum III , Springer V., Berlin, 1989

[2] Dallmann U., Doerffer P.: Three-Dimensional Flow Separation caused by Normal Shock Wave/ Turbulent Boundary Layer Interaction
In: J.Zierep, H.Oertel (Eds.), Symposium Transsonicum III, Springer V., Berlin, 1989

[3] Dvorak R.: Three-Dimensional Effects in Transonic Channel Flows
In: Proceedings 2 ISAIF, Vol.1, Prague, 1993

Flow separation

Prior to analyzing transonic separation in channels let us recall the situation in an ordinary 2D separation. The flow will be considered separated at a point S if it detaches from the surface. This implies that the zero streamline ψ_0 leaves the surface. All streamlines beyond ψ_0 come from another direction, i.e. from the region well behind the separation point. Streamlines approaching the separation point come from two separate regions on either sides of the zero streamline. This implies that *there must be a region of reverse flow beyond S.*

It is assumed that the flow leaves the surface if the tangential viscous force is zero, or if the *skin friction coefficient is zero* ($c_f = 0$, $\tau_w = 0$). Unless caused by an abrupt change in the surface shape (step, edge), *separation exists only in decelerated flows.*

There are cases in 2D flows where separation occurs even if all the above conditions are not fulfilled, as e.g. unsteady flows, pseudoshock waves.

The 3D separation is much more complex, and it cannot be expected that the existing 2D criteria can be extrapolated into the 3D flows without any additional assumptions. Therefore, we shall look for a more general physical model which will comprise the 2D case as a special one.

Considering the fluid motion near the wall, it seems that the main reason for the flow to separate is the fact that the particles close to the wall cannot sustain the increased pressure in the decelerating flow, while the particles far away from the wall still can. If this happens in a 2D flow, the fluid has to separate from the surface, in the 3D case it can move along the wall in another direction than that of the pressure gradient vector. This can be expressed in the following two conditions

$\boldsymbol{U} \cdot grad\, p > 0$ — i.e., the flow is decelerating ($grad\, \boldsymbol{U} < 0$, i.e. $grad\, p > 0$),

$\tau_w \cdot grad\, p = 0$ — i.e., particles move streamwise if $\tau_w > 0$ and $grad\, p > 0$, if they move in the reverse direction $\tau_w < 0$, while $grad\, p > 0$. This condition thus relates the outer flow direction and the "near to the wall" flow direction.

The flow will be separated if in the meridional plane at the wall $w_x = 0$, $w_z = 0$, $w_y \neq 0$. Off the meridional plane, $w_x = 0$, $w_y \neq 0$, $w_z \neq 0$. As a direct consequence, there must be a layer of stagnant fluid at the wall (it may be just a point - the separation point S) or reverse flow beyond the separation point.

In most cases, e.g. on slender delta wings, this criteria hold true even for the side separatrices, as the highest gradient is in the cross flow plane. The criterion of separation used in this case is due to Maskell[1]. *Separation occurs when two surface streamlines converge towards the separatrix where they combine and depart from the wall as a dividing surface which ultimately rolls up to form a "vortex".*
Despite this quite general approach and quite general validity of the above criteria, they do not cover all features of flow separation and, moreover, *they do not say anything about the*

[1] Maskell E.C. : Flow Separation in Three Dimensions, RAE Rep. No Aero 2565, 1955

behaviour of the separated flow off the surface and about the "feedback of this behaviour on the flow pattern at the surface.

Due to the presence of the side walls, any region of separated flow becomes closed and three-dimensional - *"local"* in the terminology of Tobak and Peake[1]. A *separation bubble* is formed, the extent of which depends mainly on the off-the-wall conditions and the channel geometry. While the frontal boundary of the separation bubble (the separatrix) is approx. normal to the free stream velocity vector, the sidelines of the bubble are formed by a bifurcation surface - the separatrix being thus colinear with the free stream velocity vector. The wall streamlines converge into it from either sides and turn off the wall along this surface .

Whether the separation bubble is closed (local) or open (global), i.e., whether the flow reattaches again to the surface from which it separated or whether it extends separated out of the channel, depends on the off-wall conditions.

If the bubble is closed, the separated flow along its sides will generate closed vortices inside the bubble. If the separation is open, the bifurcation surface will roll up into a streamwise oriented vortex surface.

All the above discussed criteria are local in the sense that they take into account only parameters in the close vicinity of the separation point. The effects of the channel configuration, or the history of the flow, or back pressure, etc., do not directly enter these criteria. As in closed channels, the strong interaction couples all parts of the flow field, and the application of the purely local criteria is uncertain.

Note 1.

In external flows there exist also other criteria for flow separation. They are based on the near-to-separation properties of the boundary layers, like e.g. rapid increase of boundary layer thickness, or of the displacement thickness, sudden rise of the form parameter, etc. These criteria , however, have only a limited value in internal flows, where a nicely developed boundary later is a rare exception.

Note 2

The lesson which could be learned from the above mentioned experiments by Delery et al. indicates that the "global"conditions given e.g. by the channel geometry together with the back pressure effect may seriously affect any local separation criteria. An attempt to use the thermodynamic stability theory to calculate the physically stable separated flow structure has not been successful so far, mainly due to our inability to express mathematically the entropy production in the vortical structures and separated flows. Nevertheless, this is one of the problems on which our attention in the next period will be focused.

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[1] Tobak M., Peake D.J.: Topology of Three-Dimensional Separated Flows, Ann.Rev.Fluid Mech., Vol.14, 1982, pp.61-85

Phenomenology of Transonic Separated Flows in Highly Curved Channels

The main emphasis in all the experiments carried out so far under this Project in the "CAMEL" type test section was on the phenomenology of transonic flows with local separation *(separation bubble)*.

Typical experimental results are presented in ***Fig.6***, where all the characteristic features of the local separation bubble can be seen on the surface streamlines pattern. The composite ***Fig.7*** offers a schlieren picture and an interferogramme of the same situation. In addition, a full cross flow plane total pressure traversing was made to assess the extent of the bubble in the normal direction.

The transonic flow separation in closed curved channels has usually its origin in the steep pressure gradient in the terminal shock wave, though the wall curvature (or namely the curvature gradient along the flow) also plays an important role. We cannot see this shock wave in the surface streamline patterns directly. It only very roughly coincides with the separation line S_1 the streamwise position of which depends considerably on the boundary layer thickness. Typical of these flows, however, are the side separatrices S_2, marking the side extent of the separation bubble. The bubble is closed by the reattachment line R..

While the terminal shock wave is typically *Mach number dependent* - its position depends on the back pressure, and the side separatrices are almost entirely *geometry dependent*, i.e. they depend mainly on the channel shape (either directly, or through flow structures generated by the channel shape - like the secondary flow vortices). Their existence does not even depend on the existence of the bubble. They are there as a consequence of the complex vortical structure in the channel, representing rather a trace of a bifurcation surface which off the surface rolls up into a streamwise oriented vortex surface.

Total pressure measurements in the cross flow plane, as well as numerous flow visualization studies, indicate that details of the flow structure also depend on parameters determined by the oncoming stream, as e.g. the boundary layer thicknesses, or the ratio of boundary layer thicknesses on the adjacent walls, or by the channel geometry upstream of the test section, as e.g. the channel curvature determining the extent of the secondary flow vortices, or the channel width b. Therefore, any empirical correlation has to include the parameters (H/b) and $(\delta_{xy\,plane}/\delta_{xz\,plane})$.

In some of our measurements, as well as in measurements by Doerffer and Dallmann [1], there are vortices at the leading edge of the side separatrix.. They always appear only when the terminal shock wave is nearby. At higher Mach numbers with the terminal shock wave at the end of the separatrix S_2 they have not been observed. At lower Mach numbers (only slightly above the critical Mach number) or in cases with an artificially thickened boundary layer, they coincide with the typical vortices in front of the separation line S_1, rotating so that the velocity they induce in the channel axis is in the main stream direction.

The above phenomena are visualized in ***Fig.8*** and ***Fig.9***. The former case is only slightly supersonic, i.e. the shock waves are very weak and cannot be seen in the figures. In the latter

[1] see cit.2 on p.6

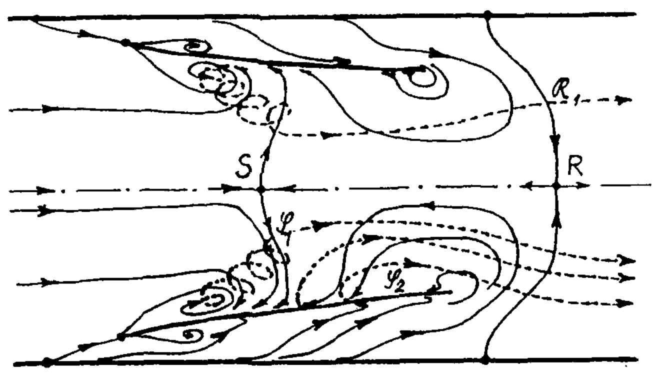

Fig. 6 Surface streamline pattern on a highly curved wall (CAMEL type test section), transonic case with a separation bubble. Dotted lines represent streamlines after they have taken off the surface

Fig. 7 Typical interferogramme and schlieren picture of the transonic flow in the "CAMEL" type test section (roughly corresponding to *Fig. 6*)

Fig.8 Surface streamline pattern on a highly curved wall (CAMEL type test section). The flow is slightly supersonic with a small separation bubble. Upon comparing the two pictures, the development of the "vortices" in front of the shock wave can be inferred

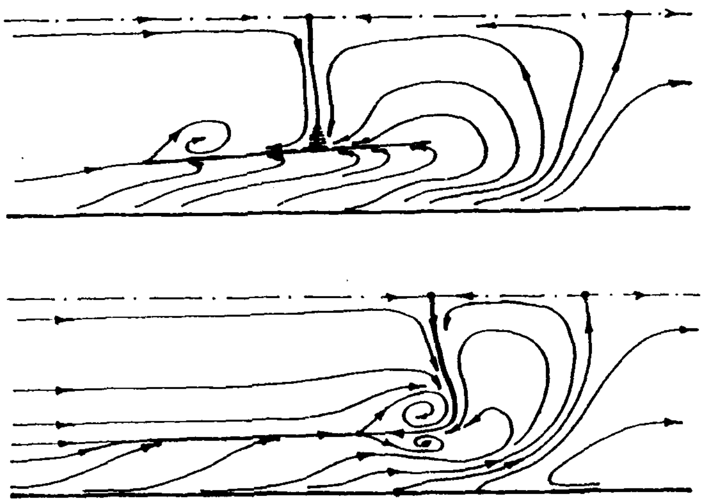

Fig.9 The same case as in *Fig.8* at higher velocities. The downstream movement of the terminal shock wave is due to decreased back pressure

case the Mach numbers are higher, and it can be seen how the shock wave moves streamwise with decreasing back pressure . All the pictures show the very "stable" position of the side separatrices and the surface streamline patterns between the separation and the reattachment lines.

The coiling up of the surface streamlines indicates that the fluid must leave the surface in the focus. It would be difficult to trace the whole body of the vortical column when it departs off the surface, however, the focus can be considered a starting point of a vortex line and one can look for its behaviour in the outer stream as well as for its interaction with other vortex lines. This is how the vortical structures in the stream can be investigated. To avoid any confusion when describing a vortex , we will rather speak about *regions of concentrated vorticity*, or about *vortical structures*.

There are quite a few vortical structures in closed curved channels. Depending on the channel curvature, there always appears a couple of counter-rotating regions of concentrated vorticity known as the *secondary flow*. It would be hardly possible to find their origin elsewhere on the wall. On the other hand, many other vortical structures originate directly on the wall or in the viscosity dominated regions like boundary layers (the so called corner vortices, the horse-shoe vortices, etc.). All these vortical structures affect the flow structure, i.e. the transonic flow development in the channel, including the separation bubble. Unless their origin, development, and structure are understood and described, we cannot think of any reliable analytical or numerical treatment of these flows.

The vortical structures in transonic flows in closed curved channels can be divided into two categories

- those due to the strong channel curvature (secondary flows), or due to the channel geometry (incl.the horse-shoe vortices),

- those due to the interaction of the shock wave with boundary layers, or due to the flow separation,

Vortical structures of the first category can again be divided into two groups, depending on what kind of forces have created them. Those in the first group are due to *volume forces*, i.e. even due to centrifugal forces which, together with the closeness of the channel, lead to e.g. secondary flows. Those of the second group are due to *surface forces* (both viscous or pressure forces) and include vortical structures arising from flow separation. Though viscosity plays an important role when these structures originate, once they depart off the surface into the free stream their behaviour is practically inviscid.

The above classification does not have only a formal value. All vorticity structures originating due to volume forces cannot be removed or destroyed, and any attempt to do so must fail. Of course, they can be optimized or affected indirectly by other structures. The vorticity structures due to surface forces can be controlled by the same means as e.g. flow separation.

Both types of vortical structures affect the development of the separation bubble. Its lateral, longitudinal (i.e. the S_l and R lines), and even its vertical extent thus depends not only on the character, thickness, and development of boundary layers on all channel walls (namely on their displacement effect), on the backpressure (influencing mainly the terminal shock wave position), but also on the circulation of all the vortical structures.The separation criteria of the

preceding paragraph consider only the streamwise changes of pressure or the main stream velocity, but do not take into account the effect of vortical structures.
In our experiments we made only a limited number of total pressure traversings in several cross flow planes of the test section to assess both the extent of the separation bubble, and the energy carried along by particular vorticity structures. All these measurements, however, can be considered as preliminary only, and it is expected that the PIV will provide more reliable data.

An attempt has been made to make a topological analysis of the vortical structures in the cross flow plane (see ***Fig.10***) . However, applying the same findings as in the case of surface streamlines is not justified here. To whatever phenomenon the surface streamlines belong, they are controlled by the same topological rules. On the other hand, what can be seen in the cross flow plane depends on the way the pictures have been recorded - they can represent only an instantaneous projection of streamlines belonging to different vortical structures (in case of a PIV picture), or a time mean picture (in case of visualizing the whole flow field by smoke, or a similar technique). These pictures are different, and different views have to be considered when analyzing them.

The topological analysis as described in the literature is based on the assumption that the flow is steady. Then, equations describing the particle paths reduce to an autonomous system with integral curves coinciding with the streamlines of the velocity field. However, the real situation is unsteady, and it is more than plausible that the instantaneous situations cannot be visualized by any routinely used means. The patterns of particle paths, as well as of streamlines, depend on the frame of reference and are not invariant - a fact not reflected in the topological analysis. Anyway, in the analysis of the cross flow plane patterns the interaction of all the colinear vortex lines (*vortical structures)* has to be taken into account.

At the surface, two neighbouring vortices must be counterrotating. This is not the case here - as if two neighbouring vortices have the same direction of rotation, they wind up into one vortical structure by rotating as one entity around the center of the whole system. It is namely this resulting situation that can be observed in a time averaged visualization.

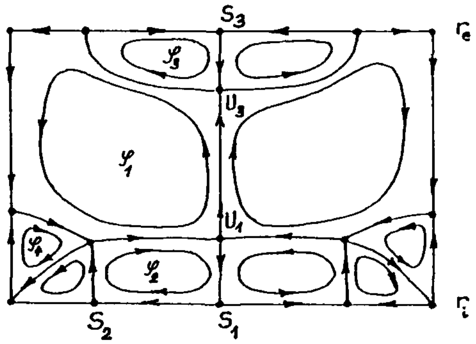

Fig.10 The assumed system of the vortical structures in a cross-flow plane, corresponding roughly to the flow in *Fig.7*

Stability and Unsteadiness of the Transonic Separated Flows in Closed Curved Channel

It has been observed, though not directly measured and analysed in details so far, that the transonic separated flow in closed curved channels is unsteady and that it may also be unstable.

The unsteadiness is inherent in these flows, being caused by the spatial interaction of the various vortical structures (as mentioned e.g. in the preceding paragraph).

Not all the patterns observed are stable. It has been observed experimentally that, even in a completely symmetrical set up, there appears a reproducible sudden change into an asymmetrical flow pattern, disappearing when the flow parameters are changed in any direction. Should this arise in a cascade (or any other turbomachinery element), serious aeroelastic problems may follow. ***Fig.11*** shows the incipient asymmetry, as well as the fully developed asymmetry , as apparent from the surface streamline patterns.

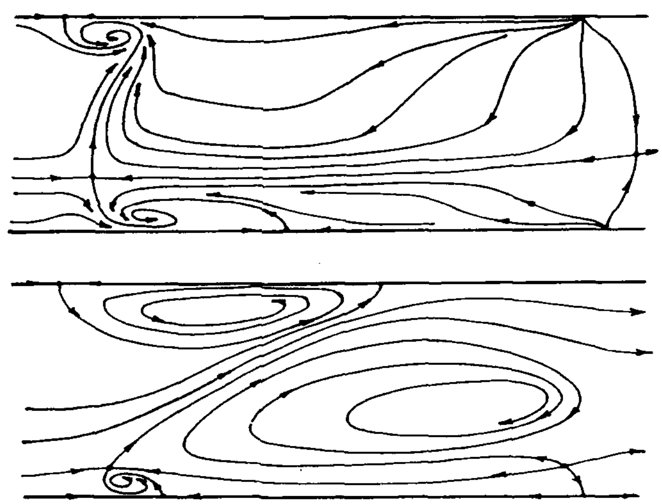

Fig.11 The incipient and developed asymmetry in the surface streamline pattern

Publications and other activities stemming from the Project

Publications

Dvořák R.: *Flow Separation in Closed Curved Channels*
IT News, Vol.3, No 1, March 1994

Dvořák R.: *Three-dimensional Effects in Transonic Channel Flows*
In: Proceedings 2 ISAIF, Eds.R.Dvořák, J Kvapilová, Vol.1, Praha, 1993

Papers presented at conferences, seminars, etc.

Dvořák R.: *Three-dimensional Effects in Transonic Channel Flows*
2nd International Symposium on Experimental and Computational Aerothermodynamics of Internal Flows, Praha, July 12 - 15, 1993

Dvořák R.: *On Transonic Separation in Closed Channels* (In Czech)
Colloquium FLUID DYNAMICS '93, Praha, 1993

Dvořák R.: *Vortical Structures in Closed Channels* (In Czech)
Seminar TOPICAL PROBLEMS IN FLUID MECHANICS, Praha, 1994

Dvořák R.: *Transonic Flow in Narrow Channels*
Lecture, University of Manchester, 22.Sept., 1993

Dvořák R.: *Vortical Structures in Closed Curved Channels*
Paper submitted to the 2 EUROMECH Conference to be held 20.-24.Sept., 1994, Warszawa

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13. ABSTRACT *(Maximum 200 words)*

The predominantly phenomenological study has been oriented towards basic physical understanding of the development and structure of transonic flow in closed curved channels, namely of the strong interaction of the terminal shock wave with various vortical structures. A new classification of vortical structures according to the forces generating them has been suggested.

Flow separation in this typically three-dimensional case has been analyzed and several simple separation criteria have been suggested. They can be used in the analysis of experimental results as well as in numerical studies. However, it has become obvious that the local separation criteria are not sufficient and that rather some global criteria have to be looked for.

Experiments carried out so far were based on the flow and surface streamline visualization. They provide material for the basic qualitative analysis of the flow phenomena but are only of a limited value for quantitative measurements. For this purpose a double pulse laser has been commissioned with the intention to apply the particle image velocimetry.

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