Experiments versus theory on streaky structures in compressible flow

L. de Luca¹, G. Cardone¹ & D. Aymer de la Chevalerie²

¹Università di Napoli “Federico II” - DETEC, I-80125 Naples, Italy. Email: deluca@unina.it
²CNRS, URA 191, F-86036, Poitiers, France

Abstract

Streaky structures and Goertler vortices are detected experimentally in attached flows over 2D concave wall models as well as over 2D (flat plate/ramp) and 3D (delta wing/ramp) wedge models tested in viscous interaction regime. The strong influence of the leading edge geometry upon such structures, confirmed by some ad hoc numerical computations, is stressed.

1 Introduction

Centrifugal instability of boundary layer flows may occur over concave curved walls. This instability manifests itself in the form of counter-rotating streamwise vortices that are commonly referred to as Goertler vortices. The study of the Goertler instability is of practical interest since the combined effects of the Tollmien-Schlichting waves and the centrifugal force may drive the transition process in the boundary layer. Past experimental works showed that a laminar boundary layer flow over a concave wall becomes turbulent at Reynolds numbers smaller than those for flows over flat plate. The presence of the vortices generally contributes to rise (both in compressible and incompressible regimes) the average wall heat transfer coefficient, even though very few quantitative measurements are available in the literature. The formation of Goertler vortices over the space shuttle’s surfaces during reentry can produce a significant increase of the local heating, that in turn imposes severe constraints on the thermal protection system.

The investigations concerned with the Goertler instability in compressible flow generally deal with the instability of attached supersonic and/or hypersonic
flows over concave walls (e.g., Fu & Hall\textsuperscript{11}). On the other hand, experimental evidence shows that the boundary layer becomes unstable, leading to spanwise oscillations of velocity and/or temperature which are reminiscent of the effect of Goertler-type vortices, also in the reattaching flow after the boundary layer-shock wave interaction due to a ramp (e.g., de Luca, Cardone, Aymer de la Chevalerie \& Fonteneau\textsuperscript{8}, Aymer de la Chevalerie, Fonteneau, de Luca \& Fonteneau\textsuperscript{2}). In this latter case the spanwise oscillations should be ascribed to the development of Goertler-type vortices due to the flow curvature above the separation streamline (Inger\textsuperscript{13}).

Within a linear analysis (valid for attached flows over concave walls) theory suggests that the disturbance characterized by the particular wavelength maximizing the total amplification has the optimal conditions to grow. This is usually referred to as wavelength selection mechanism. (El-Hady \& Verma\textsuperscript{10}, Jallade\textsuperscript{14}, Aymer de la Chevalerie, Creff \& Fonteneau\textsuperscript{1}). However, it is very important to remark that, in a real experiment the selection process may be strongly affected by the characteristics of the experimental apparatus determining the entry location to the locus of the maximum growth rate. Thus the measured wavelength generally does not agree with theory (the selection mechanism is weak) and the problem of the receptivity of Goertler vortices to disturbances seems to be still open (Bottaro \& Zebib\textsuperscript{4}).

On the other hand, experiments show that the presence of spanwise variations in nominally two-dimensional flows (both over concave models and flat plate/ramp configurations) is evident upstream of the curved surface or of the ramp. Such a pre-existence of spanwise streaks can be explained in the light of the so called pseudomodes theory and the related lift-up effect. It is known (Trefethen, Trefethen, Reddy \& Driscoll\textsuperscript{17}, Reddy \& Henningson\textsuperscript{15}) that in subcritical flows, that is to say flows for which all the eigenmodes decay exponentially, the linear problem may still have growing solutions although they will eventually decay (this behaviour is generally referred to as transient growth). As a general result, it is found that the largest transient growth is achieved for disturbances with zero streamwise wavenumbers, namely the amplification process is such that a perturbation to the velocity field in the form of a streamwise vortex evolves into a higher amplitude streamwise streak. As outlined by Butler \& Farrell\textsuperscript{5} "we expect to see streaks generated by the streamwise vortex recur frequently and persistently. It is not surprising that experimentalists encounter difficulties in eliminating these streaks from their experiments".

2. Theory and experiments

This paper analyzes and discusses the experimental work done on the Goertler instability of hypersonic boundary layer flow and its influence on the wall heat transfer coefficient. It is hypothesized that the presence of the streaks upstream of the concave wall or the ramp does influence the value of the maximum total
amplification and so the value of the observed wavelength of Goertler-type vortices.

Measurements, made in a wind tunnel basically by means of a computerized infrared (IR) imaging system, refer to the attached flow over 2D concave wall models as well as to 2D (flat plate/ramp) and 3D (delta wing/ramp) wedge models tested in viscous interaction regime. Experimental tests have been carried out in the hypersonic blowdown tunnel section of CEAT in Poitiers (France) at free stream Mach numbers $M$ equal to 7.14 and 8.15 and different unit free stream Reynolds number $Re_u$. Details about the experimental set-up and testing procedure are described by de Luca, Cardone, Aymer de la Chevalerie & Fonteneau and Aymer de la Chevalerie, Fonteneau, de Luca & Cardone. IR data, reduced by the thin-film technique are compared to thermocouples data reduced by the thin-skin one. The spanwise periodic variation of the convective heat transfer coefficient produces a variation of the model surface temperature which allows the streaks or vortices detection. The wavelength is assumed to be the (spanwise) distance between two subsequent peaks (or crests) of the convective heat transfer. Thermograms (i.e., surface temperature maps recorded by the IR camera) may also be used to visualize the surface flow.

Nonmodal analysis offers a linear explanation of why these streaky structures are so common, for although streamwise streaks are not eigenmodes of the linearized problem, they are pseudomodes. The procedures to analyze transient growths are described in different papers (for a review, e.g. see Henningson & Alfredsson), where they are applied to a number of both internal (pipes or channels) and external (boundary layer) flows. Despite the importance of 3D disturbances there exists only a few isolated experimental results in this field. By contrast to investigations on the excitation of TS waves, little is known on boundary layer receptivity to a strongly disturbed external flow field.

In compressible boundary flow the transient growth may play a slightly different role than in incompressible flows. For supersonic flows the most amplified linear wave is oblique with an angle of about 45°. The interaction of oblique may create streamwise vortices which force a strong transient growth of streamwise streaks.

3 Flow over concave wall models

The concave wall models tested by the present joint italian-french research group in compressible flow consist of two parts: a 2D flat plate placed at zero angle of attack, which is followed by a concave wall with a constant curvature radius.

The relief surface temperature distribution presented in Fig. 1 refers to a measurement frame recorded on the concave wall centered 125mm from the leading edge. Data have been taken 1.12s from the injection instant and are
relative to $M=7.14$, $Re_u=0.89\times10^7/m$, zero angle of attack (the arrow indicates the flow direction). The presence of the vortices produces the periodic temperature variation whose amplitude increases along the streamwise direction (the average wavelength is about 8mm). Note that it has been checked that the flow upstream of the vortices is laminar and that the heat transfer fluctuations are not due to turbulence induced by the model roughness. The experimental observations generally show that the measured vortices are unchanged along the flow direction.

Data are reduced so as to obtain the pairs of experimental values $(G_\delta - \bar{\beta})$ plotted in Fig. 2, where they are superimposed to the stability diagram of Aymer de la Chevalerie, Creff & Fonteneau, which applies to the same flow conditions as present tests, i.e. $M=7.14$ and $T_w/T_{aw}=0.5$. $T_w$ and $T_{aw}$ are the model wall temperature and the adiabatic wall temperature of the stream, respectively; $G_\delta$ is the local Goertler number (based on the boundary layer thickness $\delta$) and the wavenumber $\bar{\beta}$ is evaluated as $\bar{\beta} = 2\pi\delta / \lambda$, $\lambda$ being the measured wavelength. The local boundary layer thickness $\delta$ is evaluated at the streamwise location from which the vortices seem to be well developed.

As is evident, all the experimental points are located in the region where the disturbances have to be amplified according to the linear theory. The straight line for $\Lambda=1800$ (dotted line) is also reported in Fig. 2, where $\Lambda$ is based on the vortices wavelength $\lambda$. As predicted by Aymer de la Chevalerie, Creff & Fonteneau, this value corresponds to the wavelength that maximizes the total amplification of disturbances and is practically independent of the streamwise location $x$. Such a particular wavelength should be correlated to the one actually observed in the experiments. However, the wavelength selection mechanism is weak and any external factor imposed on the flow may affect the activation of the instability. In the present case one may hypothesize that Goertler instability is influenced directly by the pre-existence of spanwise streaks (not shown here) developing on the flat plate part of the models. Hence, only the disturbances characterized by a certain wavelength imposed by the streaks are amplified. For this reason, the average value of $\Lambda=3500$ (corresponding to the dashed-dotted line fitting the experimental data) obtained for the present measurements does not agree with the theoretical value. Note that the experimental findings of other authors (referring to subsonic conditions), e.g., Bippes, show the measured $\Lambda$ to be greater than the one predicted numerically. However, the slope of the correlation straight agrees with the slope (equal to $3/2$) predicted theoretically.

### 4 Two-dimensional reattaching wedge flow

Measurements refer to some cases of shock wave-boundary layer interaction in two-dimensional hypersonic flow over models consisting of a flat plate followed by a compression ramp (wedge) with its hinge line parallel to the model’s leading edge. Although the tested geometrical configurations are nominally two-
dimensional, some significant three-dimensional effects are to be expected in the reattaching separated (laminar or turbulent) flows. de Luca, Cardone, Aymer de la Chevalerie & Fonteneau reported a rather wide review of experimental papers dealing with the present matter.

The tested models differ from each other in the leading-edge shape, the ramp angle value $a$, and the flat plate length $L$. Furthermore, in order to investigate the dependence of the wavelength of heat transfer oscillations on the LE shape, and/or its nonuniformities, a model with a sinusoidal perturbation at its LE has been also tested. The wavelength of such a sinusoidal perturbation is 2mm and the amplitude is 0.5mm. End plates have been used with all of the models.

The main experimental findings relative to the convective heat transfer measurements over the ramp may be summarized as follows. Regarding unit Reynolds number, the wavelength of the spanwise variations of the heat transfer coefficient (Stanton number, $St$) decreases with increasing unit Reynolds number. For ramp angle, the Stanton number average level on the ramp increases with increasing the ramp angle, while the spanwise oscillation wavelength decreases. Regarding flat plate length, it is found that shorter wavelengths of oscillations correspond to lower Reynolds numbers based on flat plate length.

Furthermore, two spanwise $St$ variations recorded along the same spanwise line have been compared. Measurements have been taken during two tests repeated after a significantly long time, so as to include also the effects due to the imprecise setting of stagnation temperature and pressure, model attitude, etc. The almost perfect superimposition of the two recordings is surprising (not shown herein). On the contrary, it has been found that two models macroscopically identical, having also the same LE radius of curvature, but with microscopically different leading edges (i.e., with white noise), lead to a quite different structure of the heat transfer periodic variations.

The model with a sinusoidal LE has also two types of interchangeable ramps to compare IR and thermocouples measurements. In Fig. 3 the spanwise $St$ variations recorded over both the ramps ($L=30\text{mm}$) at the streamwise location $x=44\text{mm}$ (as measured from LE) show a nearly periodic trend with an average wavelength practically equal to that of the leading edge (2mm). Note that the Invar thin skin ramp has been equipped with a traversing mechanism to allow the ramp itself to be moved in the spanwise direction. In fact, it has been impossible to put on the ramp as many thermocouples as the problem needed to obtain an adequate spanwise spatial resolution. So, an alternative approach consists of moving the thermocouples by moving the ramp from run to run. The position of temperature crests and troughs has been observed to remain practically unchanged for several subsequent tests (on the very same leading edge) when the ramp was moved laterally. IR and thermocouples recordings agree very well. In conclusion, the leading-edge geometry plays a key role in the mechanism of selection of the wavelength of the heat flux oscillations observed over the ramp. In fact, a practically deterministic influence of the leading-edge
geometry over the wavelength has been found experimentally, which may be summarized in two basic results: repeatability of the oscillations under the same test conditions and periodic variations wavelength equal to that of the sinusoidal LE.

Aymer de la Chevalerie, Fonteneau, de Luca & Cardone obtained also numerical results by using the full 2D laminar Navier-Stokes solver developed and tested by Tenaud & Alziary de Roquefort. The computed distribution of Stanton number, for $M=7.15$ and $Re_u = 8.5 \times 10^6/m$, $L=30mm$ and fixed $T_v$, is shown in Fig. 4. Three different LE geometries are tested, the first one being of (infinitely) sharp type, the other two of blunt type, having a square section. The effect of LE thickening is an increase in the distance of separation and a decrease of the peak heat flux. The simulated results corresponding to the 50mm thick LE are compared to experimental values for the same flow conditions. Note that the distances from the hinge line of the experimental peaks are larger than the predicted ones, while the peak $St$ is higher. This feature suggests that the flow behind the reattachment is at least transitional or that the non-linear effects are very important. Indeed, previous computations and experiments of literature with a Goertler vortices analysis in incompressible flow show that the effect of nonlinearity is to increase the mean heat flux.

5 Three-dimensional viscous interaction

Some tests have been carried out also over a delta wing/ramp configuration to study the effect of three-dimensional viscous interaction (de Luca, Cardone, Carlomagno, Alziary de Roquefort & Aymer de la Chevalerie, Carlomagno, de Luca & Cardone). Fig. 5 shows the thermogram relative to a delta wing with a swept angle 60° and a ramp angle of 15°; the delta wing is 76mm in length. In the case shown in Fig. 5 the unit Reynolds number is $15.4 \times 10^6/m$. Although one has to kept in mind the influence of the LE geometry as discussed above for the 2D case, it is found that, as a general trend, the vortices wavelength is smaller for the 3D interaction as compared to the 2D interaction; in all the cases it decreases as unit Reynolds number increases. Mach number seems to have a minor influence, at least within the limited range of values of the reported tests.

6 Future work

In the future it is planned to perform some numerical work to study: transient growth on flat plate in compressible flow; enforcement of vortices on the wall (receptivity problem). On the other hand, from the experimental point of view, systematic tests will be carried out in order to visualize the oscillations of the convective heat transfer coefficient over simple flat plate models as well as to compare the spectrum of such oscillations detected on the flat plate part of concave models and on the curved one.
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References


Figure 1: Relief surface temperature map taken over a concave wall model.
Figure 2: Comparison of experimental and numerical results on stability diagram.

Figure 3: IR thermography and thermocouples data for sinusoidal LE.
Figure 4: Influence of the leading edge thickness.

Figure 5: Surface temperature map relative to a delta wing with ramp.