# Transition to turbulence in laminar hypersonic flow

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## 1. Introduction

This report gives a short discussion of the progress in a recently started project aimed at the prediction of transition to turbulence in hypersonic flow. The prediction of transition to turbulence is a very important issue in the design of space vessels. Two space vehicles currently under investigation, namely the aeroassisted transfer vehicle (AOTV) and the trans-atmospheric vehicle (TAV), suffer from strong aerodynamic heating. This heating is strongly influenced by the boundary layer structure. These aerospace vehicles fly in the upper atmospheric layer at a Mach number between 10 and 30 at very low atmospheric pressures. At very high altitudes the flow is laminar, but when the space vessel returns to a lower orbit, the flow becomes turbulent and the heating is dramatically increased.

The prediction of this transition process is commonly done by means of experiments. The experimental facilities available nowadays cannot model the hypersonic flow field accurately enough by limitations in Mach and Reynolds number. These facilities also have a large free stream disturbance level which makes it very difficult to investigate transition accurately. An alternative approach is to study transition by theoretical means. Up to now numerical studies of hypersonic flow only discussed steady laminar or turbulent flow. The project discussed in this report tries to extend this theoretical approach to the study of transition in hypersonic flow by means of direct numerical simulations and additional theoretical investigations to explain the mechanisms leading to transition. This report gives a brief outline of how we plan to carry out this research.

## 2. Important Physical Phenomena

There are several important new physical phenomena in hypersonic flow which are not important in supersonic flow. The flow exhibits extreme heating, especially in the stagnation point region. This causes non-equilibrium chemical reactions, dissociation, and ionization, which have to be taken into account. Also, the effect of radiation cannot be neglected. The gas is rather dilute, so the limits of the continuum approach are reached, but with slight modifications, the Navier-Stokes equations still can be used.

## 3. Transition to Turbulence

There are several techniques for studying the transition phenomena. The most widely used technique is linear stability theory, using the normal mode approach in both space and time coordinates. This technique is, however, not very reliable for the prediction of the position and behavior of the actual transition phenomena and, in many cases, additional empirical information is necessary for accurate prediction. This empirical information is very scarce in hypersonic flow so accurate numerical solutions are necessary.

The main reason for the failure of linear stability theory can be attributed to the fact that finite amplitude disturbances, requiring non-linear stability theory, cannot be neglected. This is demonstrated by experiments on a cone conducted by Stetson (1988). A more general valid theory describing the transition process is given by Ruelle and Takens (1971). It assumes that the change from a laminar to a turbulent state takes place by means of a finite number of bifurcations. Studying these bifurcations by theoretical means and direct numerical simulations can give more detailed information about the transition process. This method allows large disturbances and gives more freedom than a linear theory.

Direct numerical simulations of hypersonic flow accurate enough to predict transition will be very time consuming. An additional problem with direct numerical simulations is caused by the fact that there are so many independent parameters that it is hardly possible to investigate all relevant situations by this method. It is, therefore, necessary to study the transition problem by means of a coupled theoretical and numerical approach. The aim of this study is to obtain detailed information on the actual mechanisms leading to transition in hypersonic flows and to obtain information useful for engineers.

## 4. Achievements

The project started in September 1988, so there are only limited results. During this period, the literature and basic phenomena in hypersonic flow were studied. The results of this study are to be used to make a project proposal for the study of hypersonic transition.

## 5. Proposal for the Calculation of Transition to Turbulence in Laminar Hypersonic Flow

**General:** The main purpose of this research is to get insight in the phenomena which lead to transition from laminar to turbulent hypersonic wall bounded flows. In order to accomplish this goal, two main tools will have to be developed:

- An accurate code for the direct numerical simulation of time dependent hypersonic flows.

- A mathematical model for investigating the stability and bifurcation phenomena leading to transition in hypersonic flow.

Due to the facts that we have to start from scratch and that there are large uncertainties about the method, it is very important to follow a stepwise procedure. This approach is summarized below:

## -A Solution of Two-Dimensional Navier-Stokes Equations for a Flat Plate

The first step will be to make a computer model for the viscous supersonic two-dimensional flow on a flat plate at low Mach number ($M \leq 3$) using a finite difference method.

It is assumed that there are no shocks in the flow field. The numerical model, however, must solve the Navier-Stokes equations in conservation form together with the ideal gas equation of state. The use of a conservative formulation provides the opportunity of shock capturing in a later stage of the project. The numerical method has to be at least partially implicit in time in order to be able to add a chemistry model for the reacting gas flow while avoiding serious restrictions on the time step due to stiffness. Possible numerical methods are the implicit Mc Cormack and Beam and Warming schemes which are second order accurate in time and space (Anderson, Tannehill and Pletcher 1984).

Due to the geometric simplicity a new program will be written instead of using an existing general purpose computer program which would need modifications to be efficient for a flat plate.

- The purpose of this part is:

1. Obtain experience with these type of calculations. Although existing numerical methods will be used, it is important to test these methods on a relatively simple problem and especially to investigate the effect of numerical parameters like time step, number of grid points, stability, and numerical diffusion.

2. Test the accuracy of the numerical algorithm by comparing the growth rate of an Orr-Sommerfeld wave with the prediction obtained with linear stability theory by Mack (1984).

3. The direct numerical simulations will be used to compute the evolution of finite amplitude disturbances and study the effect of wall temperature.

## -B Three-Dimensional Direct Numerical Simulations of the Flow on a Flat Plate

There is a severe restriction on using a two-dimensional model for direct numerical simulations because, at high Mach numbers, oblique waves become more unstable than two-dimensional waves. In order to investigate this phenomenon, the numerical model will be extended to three-dimensional flow on a flat plate.

• This part of the research should give a more accurate representation of the flow field and offer the opportunity to investigate three-dimensional effects. It can also be used for a thorough investigation of the accuracy of the $e^N$ method widely used in engineering applications.

### -C The Effects of Chemistry

The effects of chemistry on transition are not very clear. In order to investigate these phenomena, both with respect to their effects on the numerical algorithm and on the flow field, they will be added to the two-dimensional numerical model. Initially the chemical model for non-equilibrium chemistry of Candler (1988) will be used. This model is a seven species chemical model for $N_2$, $O_2$, NO, N, O, $NO^+$ and $e^-$. The effects of ionization will be neglected in this stage, so the rate equations for $NO^+$ and $e^-$ will not be used.

• This part of the research should give information about the effects of the chemical reactions on transition phenomena and velocity profiles.

### -D Further Study of Transition

In the investigation of the phenomena leading to transition, linear stability theory is not always accurate enough. The most important reason is the fact that linear stability theory gives no information about finite amplitude disturbances. A non-linear stability study will be conducted to investigate these effects.

• This part of the study would give more detailed information about the actual phenomena leading to transition and they can be further investigated with the numerical model.

### -E The Effects of Internal Energy and Ionization

At higher temperatures, energy associated with internal degrees of freedom and ionization effects become important. These effects are incorporated by adding an additional energy equation for the vibrational energy and an equation for the electron translational energy. At this stage, it is supposed that there are three relevant temperatures, viz. a translational temperature, a vibrational temperature and electron temperature.

• This part of the research should give information about the internal energy and ionization effects on transition.

## -F Direct Numerical Simulation of the Flow Field around a Cone

The procedure discussed for the flat plate can also be used to investigate the flow field around a cone. The calculation of the flow field around a cone is more difficult, so it is advantageous to start this research when more experience is obtained with the flat plate. An interesting phenomenon in this flow is the interaction between the boundary layer and a shock. The shock has a strong effect on the flow field. However, it requires a high resolution which is probably difficult to obtain in three-dimensional flows. The study will, therefore, start with an axisymmetric model.

• This part of the research can provide more information about the effects of interaction between shock and boundary layer on transition.

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