Experimental Study on Drag Reduction of Hypersonic Transport Configuration

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Abstract

A study for reduction of the drag of the future hypersonic transport is made with the Mach number for its cruising assumed as 7. Characteristics tests with several variations of its configuration reveal that total slenderizing and blending of wing-body assembly are effective to lower the drag. The maximum lift/drag ratio available up to this time is 5.5. Significance of fundamental research to improvement of characteristics is appreciated. Thermal control of the flow is also a matter calling for attention.

1. Introduction

Recent interest in hypersonic aerodynamics stems from the circumstances that the development of hypersonic transport is considered in many countries. Here are to be taken up the problems of the flow field surrounding the hypersonic transport (HST). In the first place the background of the problem is briefly described.

The HST is being developed as an intercontinental transport and the inauguration of its commercial service is bound to have great impact on the airplane industry. It will involve advances in various technologies related to aviation at high speed, evolution of medium and short range transports efficiently linking the local airports to the major ones served by the HST, improvement of airport facilities, and increased efficiency of ground transport. Meanwhile, the impact on the society as a whole will be equally great.

As it has been the case with development of the conventional means of transportation, the HST will further promote the human intercourse. At the same time, the global extension of human mobility in a day that the HST will bring about is likely to make it possible for the local features of the world to be grasped on a global scale.

Furthermore, supply of methane or hydrogen to the HST as the fuel will stimulate the exploitation of alternative energy source for the future generation.

Selection of the cruise Mach number M is important in designing the HST performance; it will involve various factors, M will be selected considering various things such as economy, environment, aerodynamic heating and heat-resistant materials, propulsion system, integration of design including the fuselage and the propulsion system. The operational economics of the HST as a basic design will be studied by modelling the M-related items such as L/D (L; lift, D; drag) and Isp (specific impulse) which are specific problems of the HST. Validity of the modelling can be judged by comparing the estimation derived with the projections about the HST. Investigations about variations of $(W_p \cdot R)/(W \cdot R_g)$ - where W_p; payload, R; range, W; take-off weight, R_g; half the global circumference - with M indicate that its maximum value will be obtained at M=7. Next, the increase of the so-called productivity, i.e., $(W_p \cdot M)/(OEW \cdot M_g)$ - where OEW; operational empty weight, M_g; standard Mach number 6.8 - with M will tend to become dull beyond M =7. From these predictions it can be said that M=7 provides one target for the HST.

Now assuming W=300t, $W/S=700\text{kg/m}^2$ (S; wing area) and $R=R_g$ for M=7, it can be said that if L/D=4 can be attained at hypersonic speed, the HST will be able to transport 300 passengers in a flight of less than 2 hours and 30 minutes. Further from a sensitivity analysis of the HST to the landing weight it can be said that the aerodynamic problem to be solved for an increased payload will be how to raise L/D at hypersonic speed(1). To be more specific, the problem is how to decrease D holding a required L.

Numerous attempts have so far been made to increase L/D for various configurations of HST and it is realized how difficult it is to attain the desirable L/D(2). It is also known that an effort to increase the volume coefficient τ (fuselage volume/(main wing area)$^{3/2}$) for the purpose of securing an ample fuel capacity will result in a decreased L/D.

2. Study on Aerodynamic Characteristics of HST Configuration and the Ambient Air Flow

In the investigation into the aerodynamic characteristics of HST, it is important to study the relation between the characteristics and the basic configuration. The aimed characteristics based on the modelling are such that the drag in the cruising should be small; L/D be over 4; and the longitudinal staic stability.

As for the main wing, the effects of the supersonic and subsonic leading and trailing edges on a thin delta-wing were investigated, and a supersonic leading edge delta-wing with the maximum thikness position shifted backward was selected as a practical design. With the above estimation and the results of experimental studies so far done with various body configuration, the basic configuration of HST was derived as a combination of a highly swept-back delta-wing and a fuselage with a large slenderness ratio. In the joint research between University of Tokyo and the National Aerospace Laboratory, wind tunnel experiments have been conducted about the aerodynamic characteristics of four wing-body models of HST configurations (Fig.1). The experimental results are to be reported here.

Three-component force tests and study on the ambient flow were done about Model I of τ=0.12, for M=7 and Reynolds number Re=3.2×10^6. C_L =0.15 and L/D=3.6 are obtained at the angle of attack α=2°(1). Using this model, the three-dimensional flow on the upper side and the fairing and stabilization effects of the fences on the lower side were studied; and the shift of the center of the aerodynamic force depending on α was found to be small. Meanwhile, a simplified analysis for the estimation of aerodynamic characteristics was used, in which the surface pressure distribution is obtained through the combination of a simple Newtonian flow approximation and the shock-expansion method and this distribution is corrected for viscosity through the combination of the shock-expansion method and the flat plate boundary layer analysis. The obtained values of the lift coefficient C_L , the drag coefficient C_D and the pitching moment coefficient around the nose Cm were compared with their experimental values and it was confirmed that the numerical analysis is useful for the estimation and improvement of characteristics. Efforts to enhance the reliability of numerical analysis will be important even hereafter. The characteristics of Model I as such are found far from being fully satisfactory. Nevertheless the knowledge gained here and the related basic studies to be mentioned later have proved useful in setting the subjects for subsequent research.

In Fig. 2 are illustrated some of the vital problems of the aerodynamic characteristics and aerodynamic heating of the HST configuration. For the purpose of abating the wave drag, the nose of fuselage and the leading edge must be sharpened, but then it will be important to provide measures against local intensification of aerodynamic heating. It will be equally important to cope with local intensification of aerodynamic heating due to the interference of shock waves from several parts of the body(3). Since the frictional drag, among total drag, predominates in such a configuration, the aerodynamic performance is largely affected by the stability and transition of the boundary layer and the formation of vortices(1)(4). On the lower surface of the body, the shock wave-boundary layer interaction at the engine air intake is important, while in the other areas the flow is approximately parallel to the uniform flow. Accordingly, research on the three-dimensional viscous flow due to various causes on the upper surface of the body will be one of the problems to be solved for better performance of HST.

With Model II of τ=0.078, it was found that C_L=0.13 and L/D=4.2 at α=2° (Fig. 3). Observing the oil flow on the upper surface of I against the one over II (Fig. 4), it seems that the better performance of II comes partly from the improvement of the three-dimensional flow over the upper surface. The basic study mentioned in the next chapter was done using the configuration of Model II. The HST performance described above has been generally attained using the configuration of Model II. Model III shows the same characteristics as Model II.

Model IV, with τ=0.096, is designed to fair particulary the wing-body junction; in this Model, C_L=0.075 and L/D=5.5 were obtained at α=6.5°(Fig. 5). This value of L/D is worthy of note as a value obtained at hypersonic speed for the above τ. Models I~IV were tested for the aerodynamic characteristics with the wings attached at different angles. Therefore they are to be compared here, at the same value of C_L, say, 0.15. L/D in Models I, II and IV are respectively 3.6, 3.5 and 4.5. Here it is noted that the value of IV is high. Figure 6(a) shows the Cp distributions on Model IV at α=7.33° and it is seen that C_L depends mainly on the Cp distribution on the lower surface. As Cp on the lower surface can be estimated numerically except near the wing tip, it seems that the estimation of the pressure drag, based on Cp, is generally valid. It is seen, therefore, that for better performance of HST configuration it is important to study the correspondence in behavior between the configuration and the three-dimensional viscous flow.

Figure 6(a) also shows that Cp distribution on the upper surface is sufficiently predicted by the analysis except near the wing - body junction, where measured Cp is smoother than the prediction. This smoothing is visualized to be associated with the three-dimensional boundary layer flow (Fig. 6(b)). Thus the continuous pressure distribution of the external flow is desirable in the initial design so as to avoid the skewed boundary layer and the resultant skin friction increase. Further the influence of separation vortices from the strake or the main wing on Cp distribution is not evident in the present experiment.

3. Basic Research

Now basic works done on several problems in aerodynamics associated with the improvements stated in 2 are to be cited. The experiments were performed using the hypersonic wind tunnel (M=7) at the Department of Aeronautics, Faculty of Engineering, University of Tokyo; the Reynolds number was of the order of 10^6 , the same as in the experiment at NAL.

In the ambient flow field of HST, the

molecular effects, the phenomena associated with high temperature and the phenomena related to the turbulence make the problems difficult to approach .

3-1 Influence of Upper Surface Vortices on the Static Pressure Distribution and the Aerodynamic Heat Transfer Distribution.

Experiments were done on a flat double delta-wing; a straked delta-wing of Model II with the leading edge of 31° wedge on one side (lower side). Schlieren method, vapor screen method, and oil-flow method were proved to be useful means of observation to grasp the whole picture.

At a positive angle of attack, a bow shock wave stands off the lower surface (windward), while the swollen flow to the upper side (leeward) is re-compressed at midpart of the upper surface and flows out downstream. Thus with the three-dimensional external flow and compressed waves generated on the upper side, there emerge the complex interference with the viscous flow on the wall surface. Cross sectional picture of the flow reveals that in the boundary layer on the upper side of the wing with α of less than 12° a pair of imbedded vortices with their axes in the flow direction are generated and they increase the thickness of the boundary layer, thereby causing the downwash toward the center of the wing. In the case of the double delta-wing where the influence of the vortices from the strakes is significant, there is a tendency that the three-dimensional interference is intensified (Fig. 7).

It is noticed that the increased value of -Cp in the double delta-wing favourably affects the lift (Fig. 8). Calorimetric and liquid crystal measurements reveal that the influence of vortices is also remarkable on the aerodynamic heat transfer distribution, and it is particlarly remarkable in the double delta-wing (Fig. 9). Boundary layer transition is noted near the trailing edge of the delta-wing when α is increased. Investigation of the aerodynamic heating in Model II attached with the body has indicated that the aerodynamic heating is intense at the nose, the leading edge of the wing, the side wall of the body where a separated flow from the wing stagnates, and the area where the shock waves interact and thus the important areas in thermal design have been identified.

3-2 Boundary Layer Transition

The mechanism of hypersonic flow transition, for all its importance, seems to remain in a very early stage of research. From a flight test at M=5, a transition Reynolds number $Ret=2\times 10^7$ is reported(5). In STS 1~3, the forward shift of the transition point due to the surface roughness is observed at α=33.3°, M=7.5~8.0, and $Re=8.9\times10^6$ (6). Meanwhile, basic studies point out the effects of the main flow turbulence, the pressure gradient and the heat transfer on Ret(7). All of these works are certainly of great interest, but the behavior of the boundary layer from instability to transition is still not clear. In view of the complexity of the process as suggested by the past works, the effects of shock boundary layer interaction, two-dimensional or three-dimensional surface roughness, separation and re-attachment, wall temperature, etc. on the boundary layer transition are being taken up as basic study subjects at University of Tokyo.

A study by using two orthogonally intersecting flat plates at hypersonic speed is performed for the understanding of flow interactions. Each plate can produce a combination of compression or expansion relative to the main stream. For instance, as seen from Fig. 10, the static pressure distribution on the wall surface comes closer to a definite value which is predictable from the two-dimensional flow, as it moves away from the junction, but the boundary layer induced by this pressure field becomes highly three-dimensional over a wide range, and longitudinal vortices are observed to grow. This fact is important in working for mitigation of wing-body interference and viscous drag in 2 and has been useful for improving the models from I to IV.

Further experiments with a backward step or a compression corner have shown that in the two-dimensional re-attachment region regular longitudinal vortices appear, but they do not lead the boundary layer to transition at $Re=3.2\times10^6$ or thereabout (Fig. 11). In the experiments on the interaction between shock wave and boundary layer, the incidence-reflection region and the region around the corner are invesitgated concerning the boundary layer transition and the non-linear interaction with the three-dimensional vortices. These are subtle phenomena, which make significant subjects of research even from a practical point of view.

3-3 Thermal Control of Flow

Hypersonic flow is concurrently a high-enthalpy flow and accordingly, the subjects of control in aerodynamics range from characteristics to aerodynamic heating. Apart from individual research on them, the control which involves the two is highly interesting. It has become clear that there are cases where the thermal control of the main stream is conducive to enhancing the aerodynaimc performance of HST. As applications of the basic analysis, detonation, combustion, and heat transfer, etc. are being considered to change the energy of the main stream. According to the past experience, it is possible to raise the wall pressure by about 50% by heating the flow close to the wall surface (Fig. 12). This technique is noteworthy as providing a means to secure the required C_L without modifying the configuration or the attitude of HST.

The effects of cooling the wall temperature Tw at the leading edge of the flat plate against the stagnation point temperature To upon the frictional force, the static pressure and the aerodynamic heat transfer near the leading edge are numerically simulated at speed ratio 15 by DSMC method. The effects of the cooled leading edge on the reduction of the aerodynamic force and on the state of the ambient flow can be predicted (Fig. 13)(8). This fact suggests that the active cooling of the leading edge as a countermeasure for aerodynamic heating favourably influences the aerodynamic characteristics. It will make one of the interesting subjects for future research.

4. Conclusions

Investigations for mitigation of drag are undertaken about HST configurations with Mach number 7, Reynolds number of the order of 10^6 and volume coefficient about 0.1. Slender configuration and blending of wing-body assembly are considered necessary.

L/D of about 5.5 is available. Various prospects are gained from basic studies; to cite one possibility, better performance is expected from thermal control of the flow.

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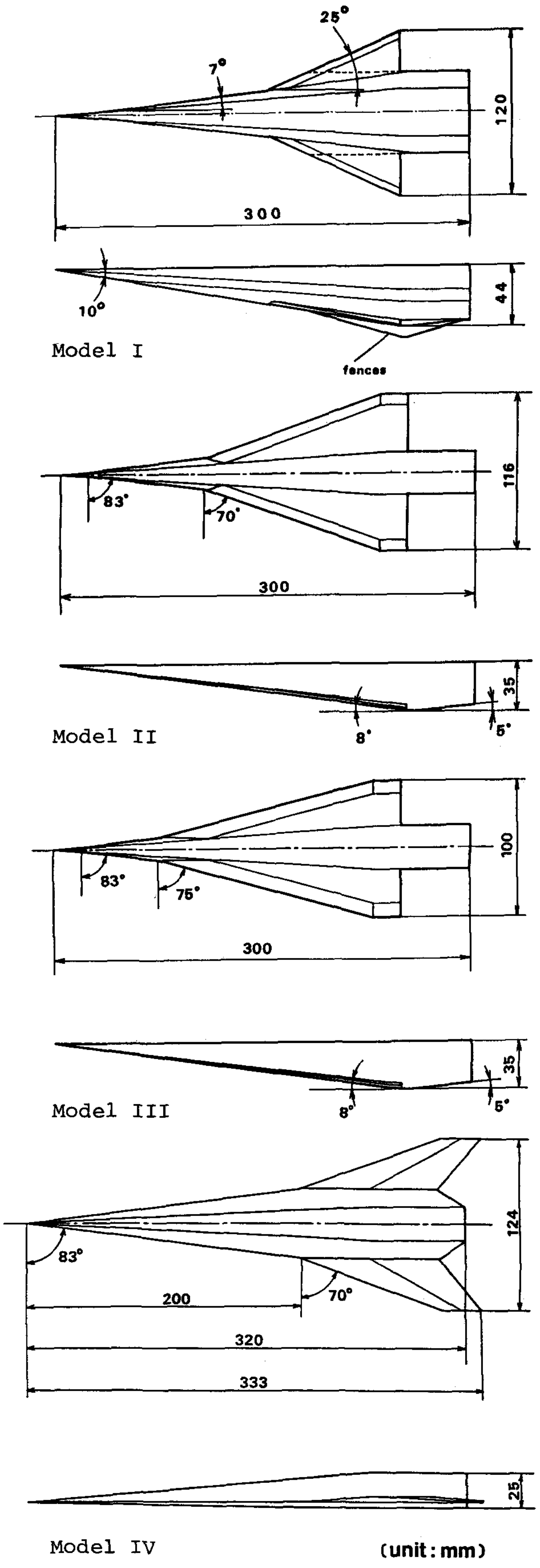


Fig. 1 Wind tunnel Models I~IV.

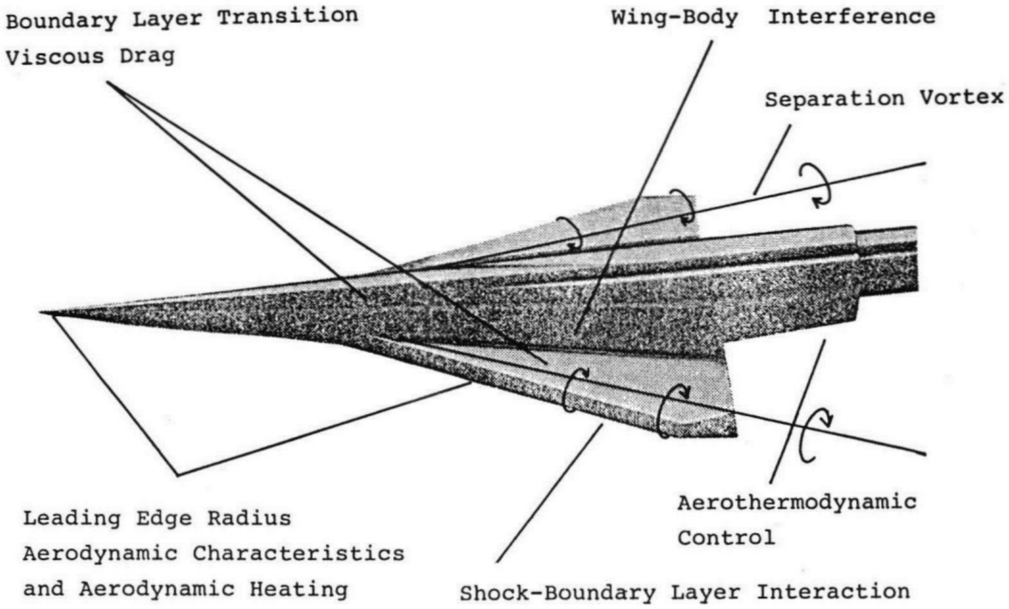
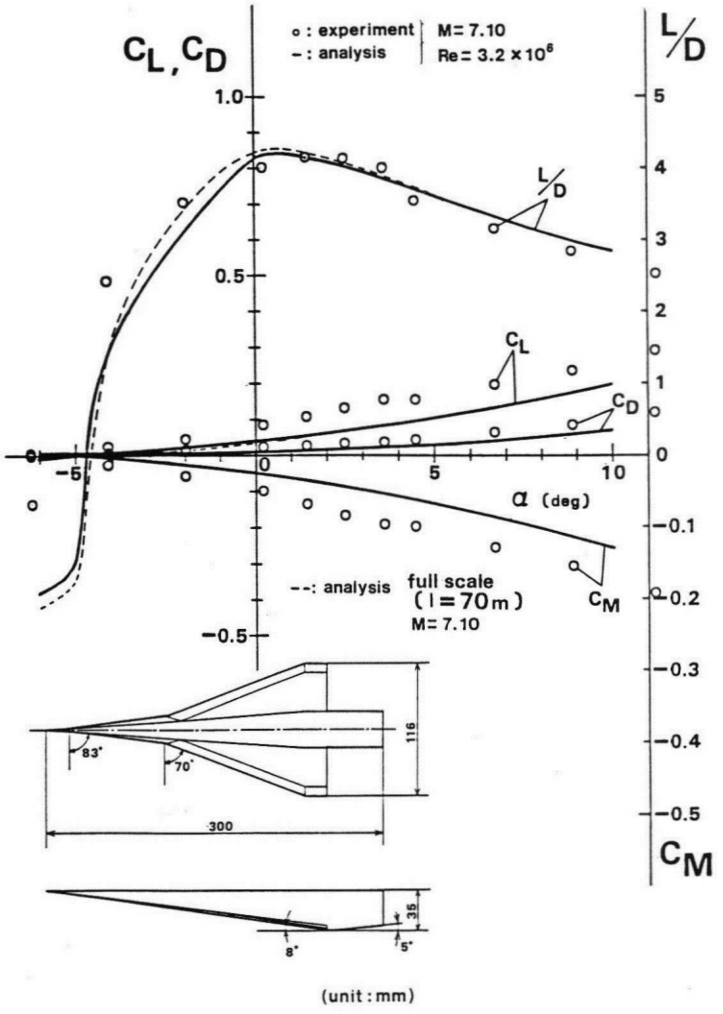
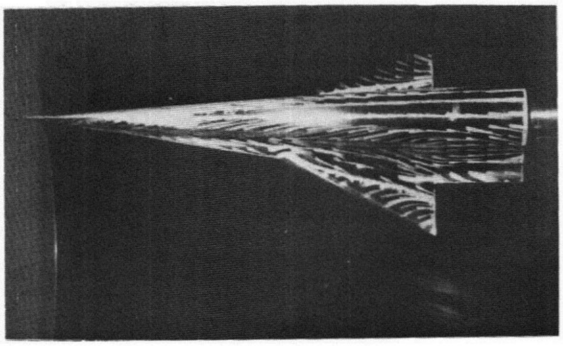


Fig. 2 Some aerodynamic problems of HST.

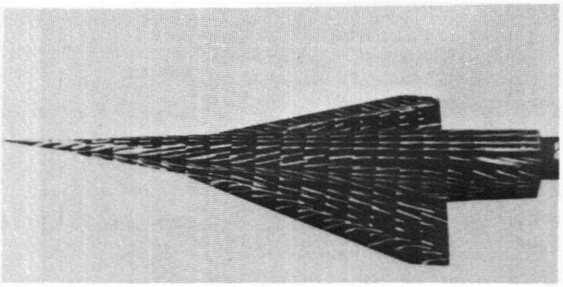


volume coefficient = 0.078

Fig. 3 Aerodynamic characteristics of the HST Model II. M=7.1. Re=3.2×10⁶.

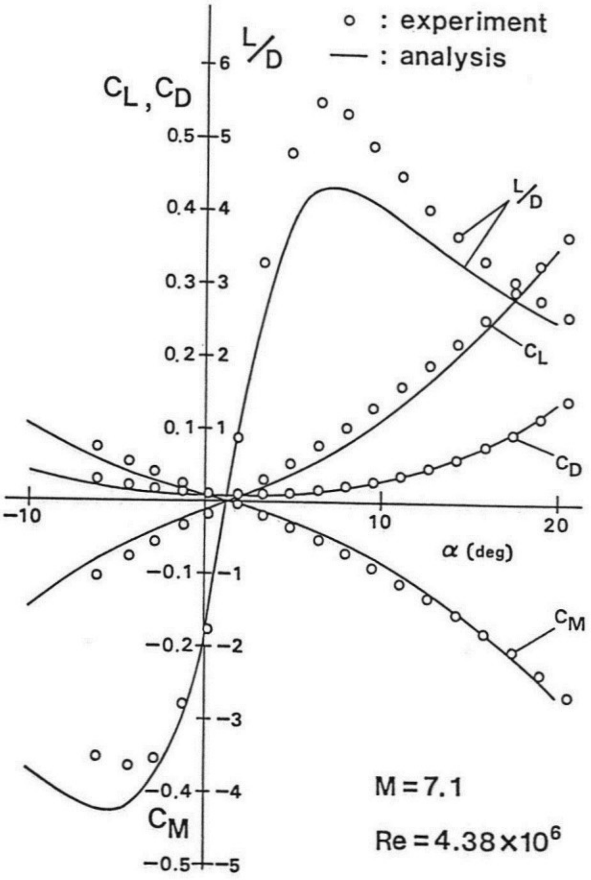


Model I
(α=0°)



Model II
(α=0°)

Fig. 4 Comparison of surface oil flow patterns of I and II.



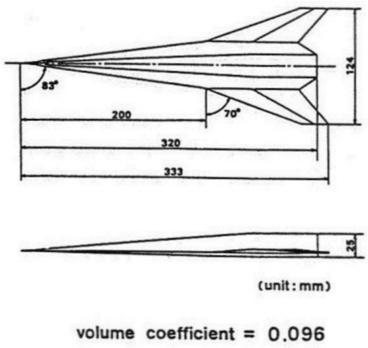


Fig. 5 Aerodynamic characteristics of the HST Model IV. M=7.1. Re=4.38×10^6.

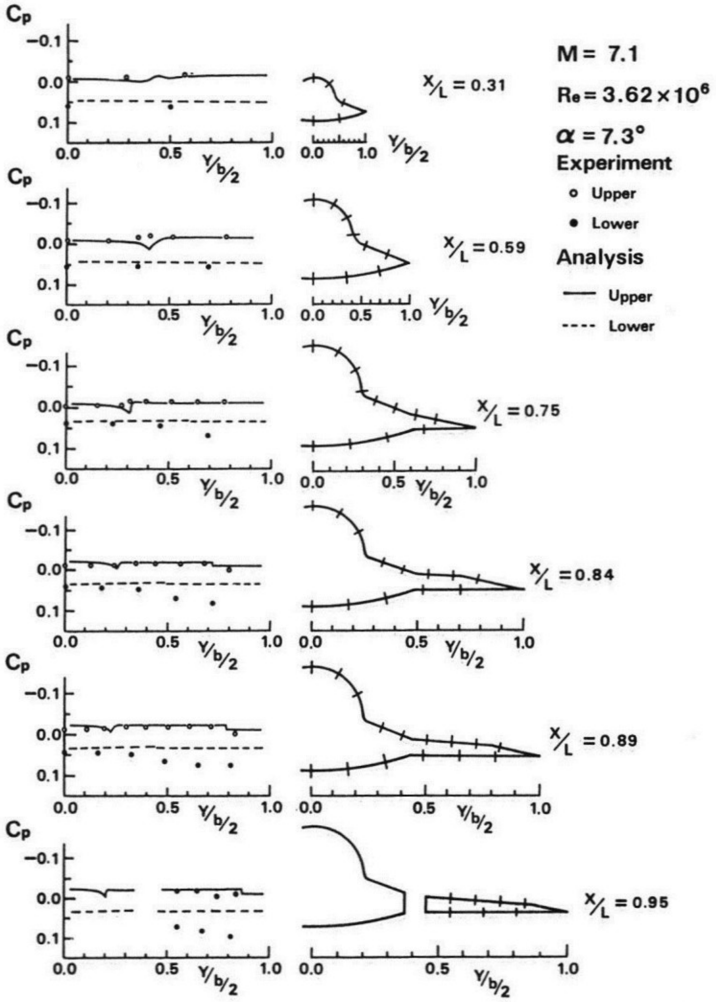


Fig. 6(a) Cp distributions on Model IV.

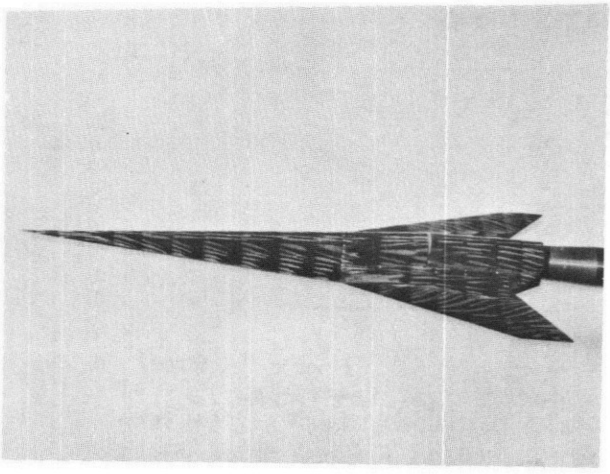
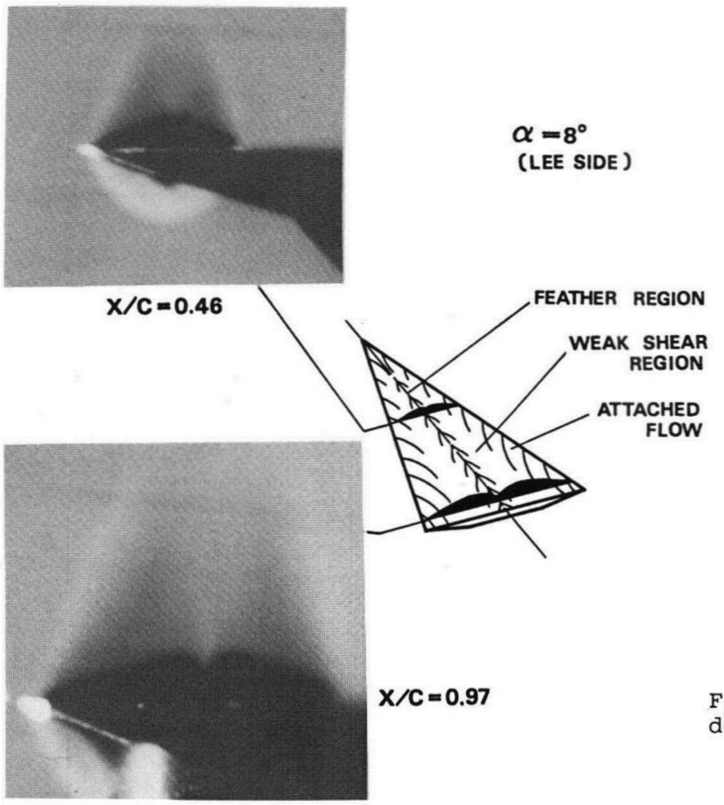


Fig. 6(b) Surface oil flow pattern of Model IV. M=7.1. Re=3.62×10^6. α=7.33°.



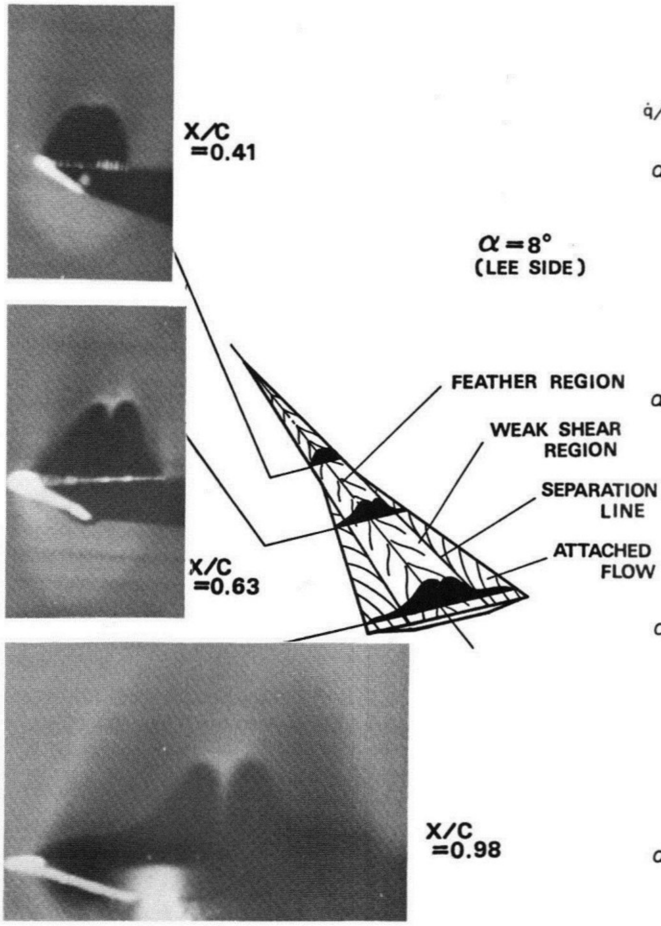


Fig. 7 Development of viscous layer on delta-wing and double delta-wing. M=7. Re=3.6×10⁶.

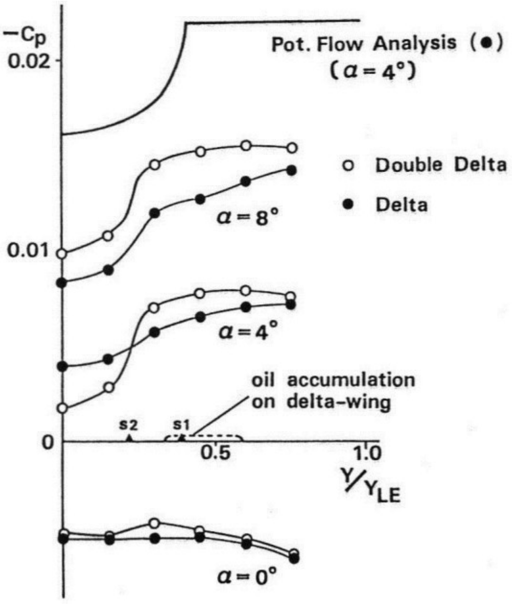


Fig. 8 Cp distributions on delta-wing and double delta-wing. M=7. Re=3.6×10⁶.

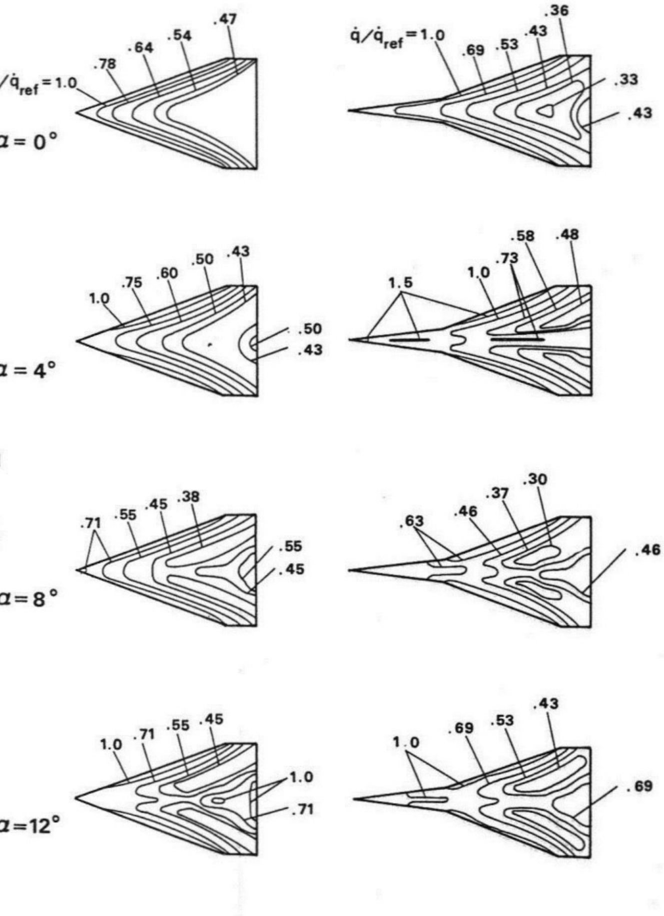


Fig. 9 Heat transfer distributions on delta-wing and double delta-wing. M=7. Re=3.6×10⁶.

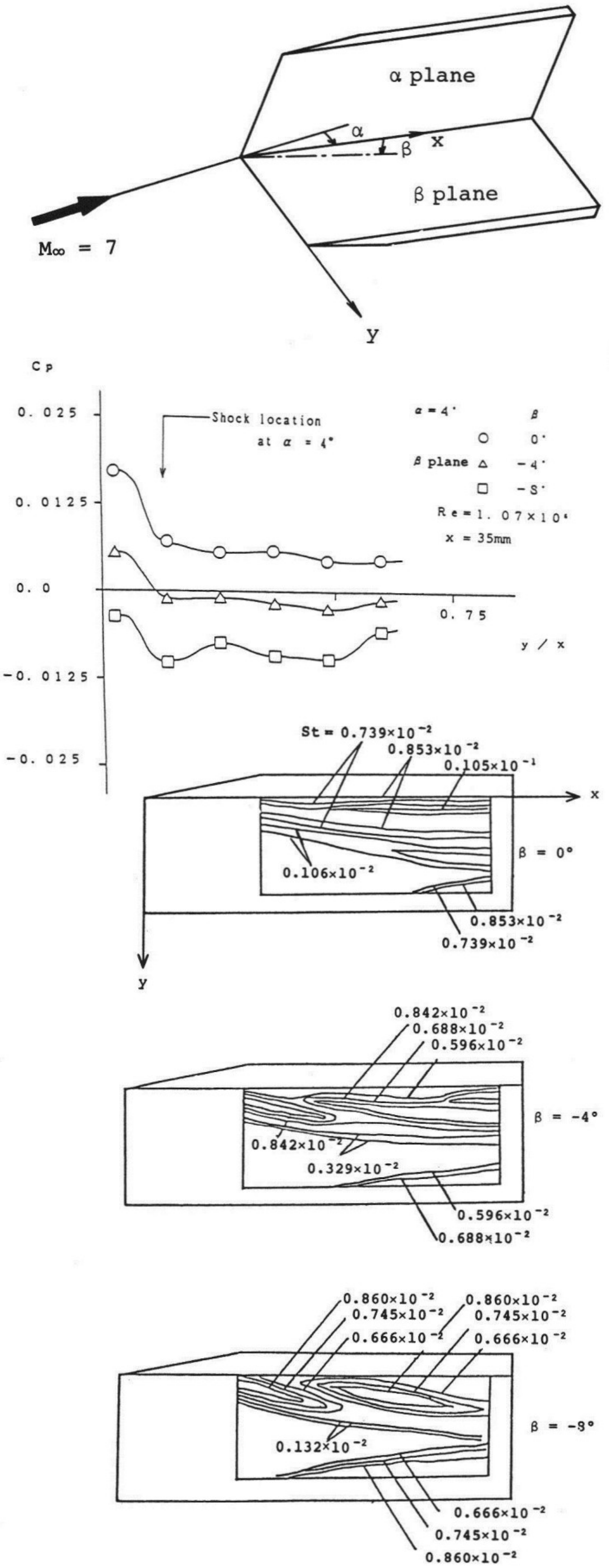


Fig. 10 Pressure and heat transfer distributions near the rectangular corner. M=7. Re=3.2×10⁶.

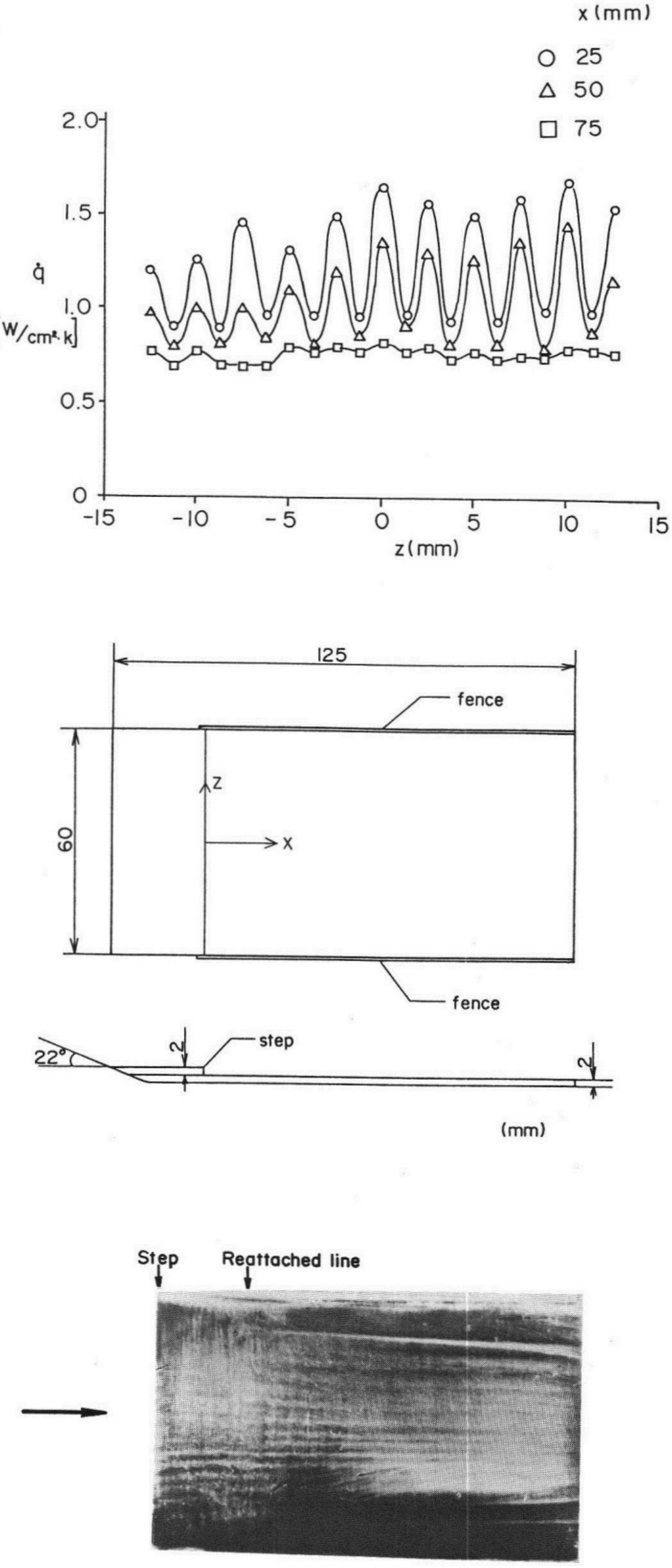


Fig. 11. Three-dimensional behavior of the boundary layer in the separation-reattachment region. M=7. Re=3.2×10⁶.

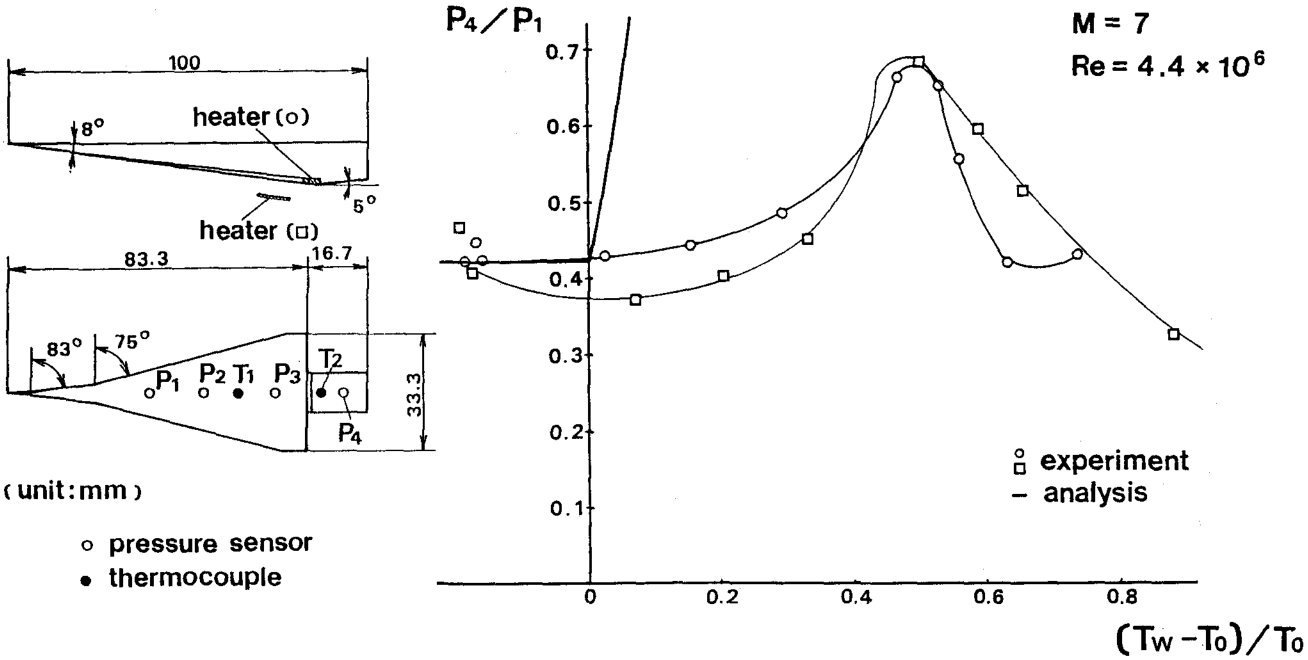


Fig. 12 Effect of heating on pressure increase. M=7. Re=4.4×10^6.

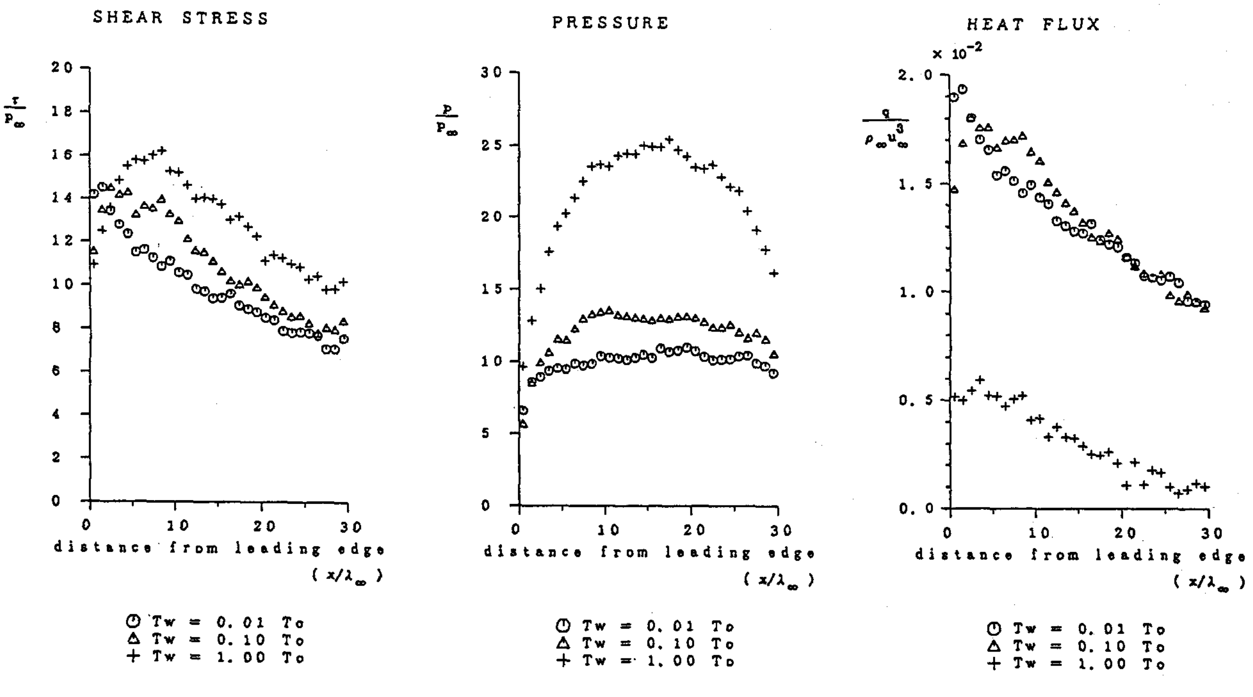


Fig. 13 Effects of surface cooling on skin friction, surface pressure and heat transfer near the leading edge of a flat plate. Speed ratio=15. λ_∞=mean free path of molecules in the external flow.