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Streamwise Directed Vortices and Crosshatched Surfaces of Re-Entry Vehicles

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RECENTLY systems of streamwise directed vortices and crosshatched surfaces of re-entry bodies have attracted a good deal of attention. The streamwise directed vortices appear to play an important role in various flow situations involving curved flow, and they give rise to important physical phenomena within practical heat transfer and ablation situations. This note draws attention to some results obtained by means of a water jet in exploring these phenomena.

The experiments were made in an apparatus which delivered a vertical water jet through nozzles of three different sizes. The jet velocity could be regulated with great accuracy within the range 7–32 fps. The models consisted of a 30° cone, a 90° cone and a flat plate which were coated with paint and exposed axisymmetrically to the jet. M. Scherberg at Aerospace Research Labs. Wright-Patterson Air Force Base, suggested that the experiments might also be used to exhibit the cross-hatching process connected with ablation, an idea that has been substantiated by the latest findings of the author.

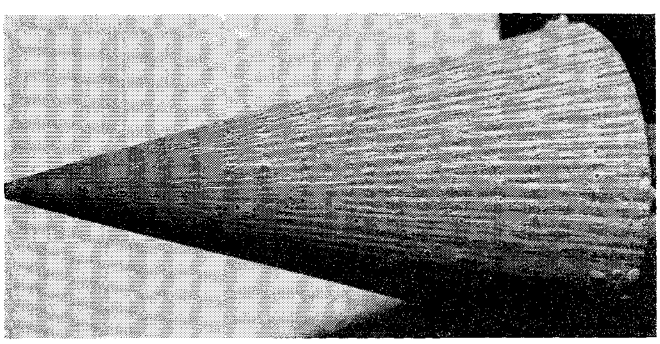

Fig. 1 Striations on a 30° cone model.

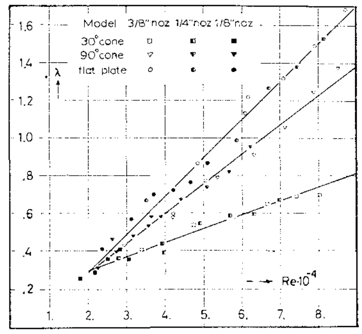

Fig. 2 Number of striations vs jet Reynolds number.

When the models were coated and exposed to the jet with the paint still wet, striations would occur in the coat as exemplified by the 30° cone model shown in Fig. 1. These striations show such a remarkable regularity and correlate so well with the parameters of the flow as to suggest that the striations are indicative of a three-dimensional flow close to the surface, which may be characterized as streamwise directed vortices. The regularity of the striations is clearly brought out in Fig. 2 where the number λ of striations per degree angle as function of the Reynolds number of the jet is plotted for the three different models with three nozzle sizes. A detailed report on these experiments[1] is at present in print and further work is in progress to recorrelate the data making them directly applicable to flight vehicles.

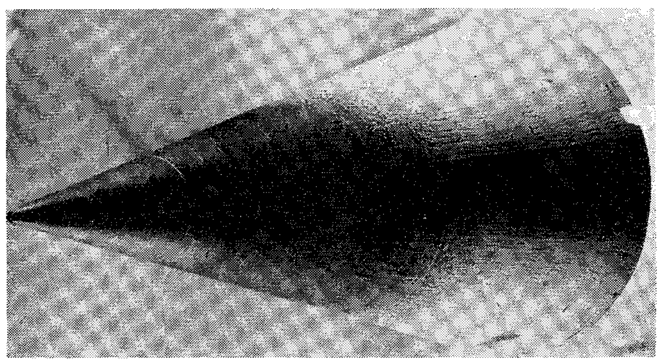

Fig. 3 Re-entry vehicle in the Sparta program (Chrysler Corporation).

Through the courtesy of the Chrysler Corporation, Missile Division, a good deal of material from their Sparta program was placed at the author's disposal. Figure 3 shows one of their recovered re-entry vehicles in the form of a 27° cone, and the striations found in the surface of this cone show a remarkable similarity to those found in the model in Fig. 1. Superimposed on the Sparta streamwise pattern one finds a crisscross pattern which is exhibited in Fig. 4 showing details from rubbings (a paper is wrapped around the model and rubbed) of other Sparta cones.

It turns out that the present water analogy experiments are very well suited for investigations of the ablation process.

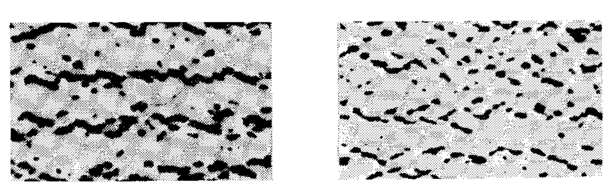

Fig. 4 "Rubbing" from recaptured re-entry cones (Chrysler Corporation).

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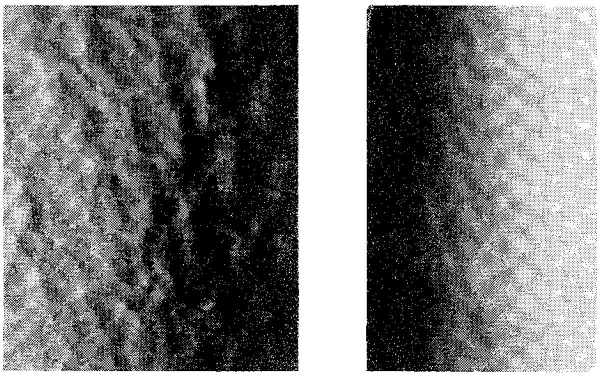


a) b)

Fig. 5 Patterns observed in the paint coat, a) 90°cone, b) 30°cone.

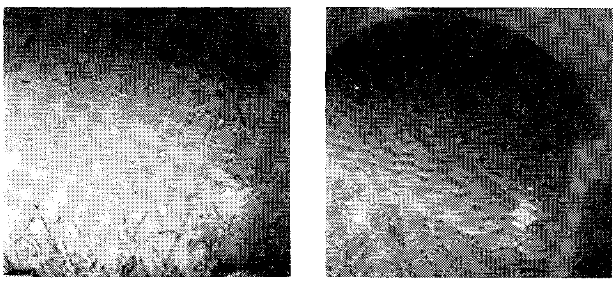
From the various cases of criss-cross patterns observed in the paint coat on the models Fig. 5 shows two examples. Although the investigations are being continued and a complete report is in preparation, some results will be presented here.

The first result from a series of test runs is that the criss-cross patterns do not necessarily appear as a result of one unique physical phenomenon. One type of criss-cross has been observed as a result of local separation. This is the case in Fig. 6a where the pattern is seen to appear at the equator of the sphere being used as a model. In that case the pattern was "engraved" along the separation line in a coat which had been allowed to dry so long that the attached flow made no impression on it. This leads to the conclusion that local separation induces a situation where the mechanical forces exerted on the coat are much greater than what they are in the attached regions.

Another type of criss-cross pattern is observed in Fig. 6b where "wedges" or "bow-waves" are formed in the coat as a result of disturbances in the form of particles in it. These can easily be seen in the picture.

A third observation was made which seems to be highly relevant to the formation of the pattern. The slightest amount of eccentricity seemed to render a most favorable situation for the formation of the pattern described in Fig. 5. It is possible to create a situation whereby separation and the type of criss-cross shown in Fig. 5 appear simultaneously. In that case the lines of the criss-cross pattern are not parallel to the separation line. For a closer examination of this point the reader is referred to the complete text in preparation.

A few additional remarks seem to be appropriate on the ablation process itself as compared with the experimental method used here for its exploration. The seemingly crucial difference is found in the absence of heat production and heat transfer in the water analogy experiment. It can however be demonstrated how the depth of the melted layer (thickness of the paint coat) seems to hold the key to this problem because most of the observed ablation patterns can be understood on this basis.



a) b)

Fig. 6 Criss-cross on a sphere, a) caused by separation, b) caused by disturbances.

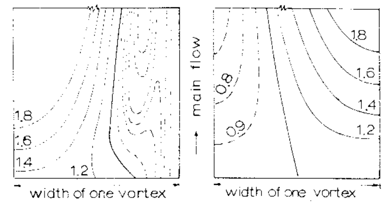


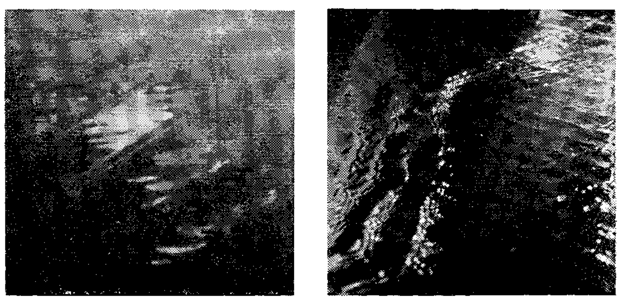
Fig. 7 Maps showing regions of increased and decreased heat transfer over the width of one vortex, a) high *Pr* number, b) low *Pr* number.

In an earlier report[2] the author demonstrated the influence of the streamwise directed vortices on the heat transfer from a wall for very high and very low Prandtl numbers. The effect of the presence of the vortices in the flow can be exhibited by the ratio between the local rate of heat transfer in the presence of the vortices and the same quantity computed under the assumption that the vortices are absent in the flow. This ratio will vary both in the streamwise and in the crosswise direction, and its variation is best demonstrated by a map over the width of one vortex where lines are drawn through points where the ratio is the same. This is done in Fig. 7 from which it is concluded that the vortices will give rise to a spanwise variation in the local rate of heat transfer. If this feature is carried over to the present situation one may infer that the depth of the melted layer during ablation may vary periodically in the crosswise direction. This concept of the situation may help in explaining the particular pattern from the Sparta cone in Fig. 4.

In the experiments mentioned so far the water has been used to simulate the outside flow and the phenomenon under investigation takes place in the paint coat simulating the melted layer. With the idea of a melted layer of transversely varying depth it is possible to simulate the flow in the melted layer by water running along a corrugated panel used as bottom surface in a water table. The flow is visualized by light reflected from the water surface. Figure 8a shows a pattern very similar to those observed on the Sparta cones, Fig. 4.

This experiment also gave additional information on the change in the criss-cross pattern when the depth of the melted layer becomes so great that its variation becomes less important. This takes place where the corrugated plate ends, and the pattern in Fig. 8b is observed. This is the same as that found on reentry bodies as described by A. L. Laganelli and D. E. Nestler[3] (Fig. 9).

One can now sum up the results as follows. The flow adjacent to the models or a re-entry body is such that streamwise directed vortices will be present in it. It follows that a transverse variation in heat transfer will also be present. In the model tests the striations shown in Fig. 1 are formed due to erosion when the paint coat is thin. In an actual case of ablation where the melted surface layer is thin the same phenomenon takes place only now the erosion process is "assisted" by the variation in heat transfer. Figure 3 gives an example where the striations are predominant and a criss-cross pattern is hardly present. When the melted layer is slightly thicker, the transversely varying depth becomes important



a) b)

Fig. 8 a) flow over a corrugated surface, b) and immediately downstream of that surface.

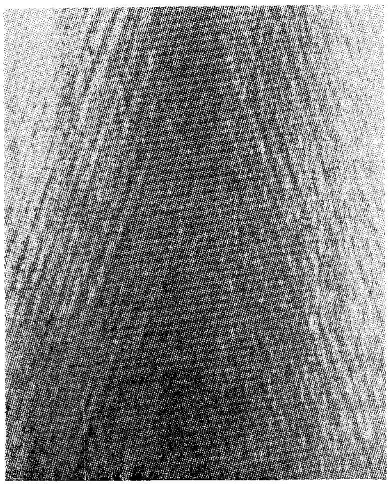


Fig. 9 Surface pattern from a re-entry body, reproduced from Ref. 3.

and the pattern in Fig. 4 occurs where the striations are predominant with a small scale criss-cross superimposed on them as in Fig. 8a. When the melted layer gets thicker, the variation in depth, if present, becomes unimportant and a pattern as shown in Fig. 9 from a re-entry body or in Fig. 5 on the model occurs. With the thin layer the viscous forces are the dominant ones; with the thick layer the viscous forces and the pressure forces are of equal importance. In both cases the presence of the vortices is a prerequisite for the phenomenon to take place. The present concept of the importance of the depth of the melted layer is supported by the observation in Ref. 3 to the effect that, in most cases, longitudinal grooves appeared upstream of the pattern. In light of the present concept this is due to the melted layer being thin upstream, whereas downstream the ablated material accumulates giving a thicker layer there.

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A Computerized Mass Spectrometer System for Spacecraft Ground Tests

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THE development of a dual-gas environmental control system for the Gemini B spacecraft required an instrument to monitor the composition of both cabin and suit atmospheres.

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During prelaunch, the Gemini B, on the pad with open hatches, has an earth atmosphere. After the hatches are closed, the cabin is purged, and a dual-gas (helium and oxygen) system supplies the cabin atmosphere on the pad. During launch and flight, a single-gas oxygen system supplies the cabin atmosphere. The atmosphere in the suits is oxygen during all mission phases.

System Description

A mass spectrometer was chosen to monitor the atmosphere in the cabin and space suits because this instrument is capable of detecting the five gases of interest (helium, water vapor, nitrogen, oxygen, and carbon dioxide) over a wide range of concentrations and, with the proper inlet system, can provide almost continuous monitoring.

The mass spectrometer system is shown schematically in Fig. 1. The gas transfer system provides gas samples from five locations in the spacecraft cabin, from three locations in each space suit, and from a common point, in the suit system. This system circulates gas, at a positive pressure, from the selected locations, past the inlet system, returning the gas to the spacecraft at a place corresponding to the sample location. This minimizes the mixing of gases in different parts of the spacecraft.

Test gases are admitted through one of two inlet systems. These inlets employ a capillary to reduce the pressure to 1 torr; a molecular leak admits the gas into the spectrometer chamber. This arrangement reduces the fractionation of the gas sample to a negligible amount. The capillaries are heated to reduce condensation of water vapor and carbon dioxide. Two inlets are used to isolate the cabin and suit environment control systems.

A diffusion pumped vacuum system was selected because of the large amount of helium in the gas mixture. The vacuum system consists of a 6-in. bakeable valve, a 4-in. liquid nitrogen-cooled trap, a 4-in. oil diffusion pump, and a 15-cfm two-stage mechanical pump. The system uses copper gaskets with sexless flanges, except for an elastomer O-ring between the diffusion pump and the trap. The 6-in. valve is used to isolate the chamber during the trap clean-up,[1] to provide a vacuum storage for the quadrupole during down time, and to provide a means of controlling the pressure in the chamber during analysis. The oil in the diffusion pump is Monsanto Sanovac 5. This oil was selected for its oxygen-compatibility[2] and to avoid the cracking problems associated with the silicone oils. The mechanical pump fluid is Monsanto MCS-585. This fluid, di-iso-decylphthalate, is also being used because it is oxygen-compatible and does not require special seals as does tricresyl phosphate.

The data acquisition system is comprised of a 100 channel analog signal conditioning unit, a test site control unit for multiplexing and digitizing, and a recording control unit which formats and records the digital data on magnetic tape. With this system, the digital formatted data at the central recording unit is made available to the computer. Also, analog signals monitored by the signal conditioning unit can be converted back to analog and displayed on the K-logger graph.

The test control system is made up of the computer, input/output (I/O) buffer, electrometer gain selection, five digital-to-analog converters (DAC) used for signal storage, and two DAC units used to supply mass selection voltages to the mass spectrometer.

The computer was programed to provide the five input voltages in sequence. Two commands were initiated for each input voltage desired. One command was sent to the "coarse" DAC. A second command was issued to the "fine" DAC. The sum of the coarse and fine DAC's appeared at the input to the gas analyzer and was monitored by the signal conditioning unit. In the event that the input voltage was not within the specified limits, the computer adjusted the fine