# Observations of Crosshatched Wave Patterns in Liquid Films

PHILIP R. NACHTSHEIM* AND JACK R. HAGEN†
*NASA Ames Research Center, Moffett Field, Calif.*

**This experimental approach, aimed at understanding the formation of crosshatched patterns in liquid films, eliminates differential sublimation or vaporization as a possible mechanism of pattern formation by introducing a liquid with an extremely low vapor pressure onto the surfact of a model in a supersonic (cold) wind tunnel. The results indicate that 1) moving crosshatched patterns can be obtained without sublimation or vaporization; 2) the motion of the liquid film can be characterized in sufficient detail to permit comparison between experiment and theory; and 3) the observed waves are consistent with the findings of a linear stability analysis.**

## Introduction

CROSSHATCHED surface patterns have been observed on recovered flight vehicles, hypersonic wind-tunnel models, and ballistic range models where the ablated plastic material (Lexan, Lucite, Teflon) existed in the liquid phase.[1-8]

The stability of a liquid film was analyzed[9] on a body adjacent to a supersonic stream in an attempt to describe the observed transient behavior of Lexan and Lucite reported by Larson and Mateer.[1] However, other analyses[10-14] have focused on mechanisms other than those associated with a melt layer. Some of the mechanisms cause differential ablation (sublimation or vaporization). These analyses primarily concerned gasdynamic effects that would explain the formation of crosshatched patterns regardless of the nature of the ablating surface. The analytic model of Ref. 14 does not incorporate ablation as a mechanism, but requires the surface respond as an anelastic solid.

In an effort to understand the formation of crosshatched patterns in liquid films, a study was conducted in a supersonic (cold) wind tunnel in which a liquid with an extremely low vapor pressure and known properties was introduced onto the surface of a model. The objectives were to determine if crosshatched patterns can be obtained without sublimation or vaporization, and to characterize any patterns obtained in sufficient detail to permit comparison between experiment and theory.

## Apparatus and Techniques

### Wind Tunnel

The test were performed in the Ames 1- by 3-Foot Continuous-Flow Supersonic Wind Tunnel at a freestream Mach number of 2.8, total pressure of 10 psia, and total temperature of 75°F.

### Models, Liquid, and Photographic Techniques

Initial tests used conical and concave metallic models, 6 in. long, with holes drilled into the tips for liquid injection. Subsequently, a 10° half-angle conical model was made of plexiglass with an improved liquid injection mechanism consisting of a slot near the tip. The base of the model, approximately 6 in. in diameter, was supported on a rod over which numerous felt washers were placed. The washers absorbed the liquid as it ran off the base of the model.

The liquids used were Dow Corning "200" silicone fluids (colorless with a wide range of viscosities). A desirable feature of the higher viscosity liquids is their low vapor pressure. For the 1000 centistoke fluid used in this investigation (for which patterns were obtained) the manufacturer states that the vapor pressure is negligible at temperatures as high as 200°C. To record the details of the surface patterns a white pigment, titanium dioxide, was added to the silicone fluid. The model was illuminated either from the top or from the front with the light source in the plenum chamber of the wind tunnel, and the camera viewed the surface of the model at right angles to the light source. The shadows cast by the crests of the waves on the white liquid were recorded in the motion pictures. Though adequate, this photographic technique did not bring out clearly the structure that was evident in the patterns observed visually.

### Test Technique

Supersonic flow was established over the model and then metered amounts of liquid were introduced through the slot near the nose of the model. The fluid interface as it flowed back over the surface of the model was timed, giving a measure of the mean film velocity. Measurements from motion pictures gave pattern angle and spacing.

## Results and Discussion

### Existence of Patterns in Liquids with Low Vapor Pressures

Primarily the experimental program was to determine if pattern formation requires ablation. The experimental approach eliminated differential vaporization or sublimation as a mechanism for pattern formation because of the low vapor pressure of the liquid used. The patterns photographed on the 10° half-angle cone are shown in Fig. 1 (light source located upstream of the nozzle throat). This result shows that crosshatched patterns in liquid films can be obtained without the mechanism of differential ablation (vaporization or sublimation). Several points of similarity exist between the patterns observed in this investigation and the crosshatched ablation patterns obtained in plactic materials observed by others[1,7,8] such as the existence of a liquid layer, the movement of the crosshatched wave patterns relative to the liquid layer, and at a point on the surface, a pattern angle greater than the Mach angle.

It should be emphasized that in the ablation experiments, these features only appeared momentarily, early in the run, and could be referred to as transient. After the initial transient phase, the scale of the patterns increased markedly, the patterns became stationary, and the pattern angle changed and became approximately equal to the Mach angle. With further increase in time, the grooves in the surface became irregularly spaced and quite deep to the extent that the melted plastic flowed in these grooves. The transient behavior should not be discounted as having no practical significance for, as shown in Ref. 7 in Teflon (an ablator

Presented as Paper 71–622 at the AIAA 4th Fluid and Plasma Dynamics Conference, Palo Alto, Calif., June 21–23, 1971; submitted August 10, 1971; revision received June 12, 1972. The helpful advice provided by J. B. McDevitt of Ames Research Center on the design of the slotted liquid injection mechanism is gratefully acknowledged.
Index category: Material Ablation.

* Assistant Chief, Thermal Protection Branch. Member AIAA.
† Test Engineer, Thermal Protection Branch.

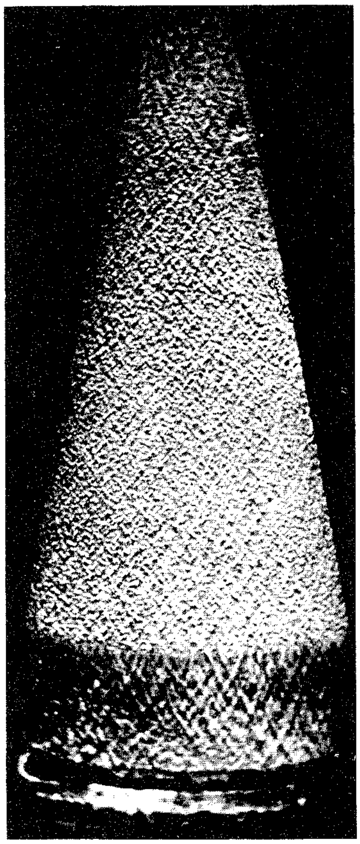

Fig. 1 Crosshatched patterns on conical model.

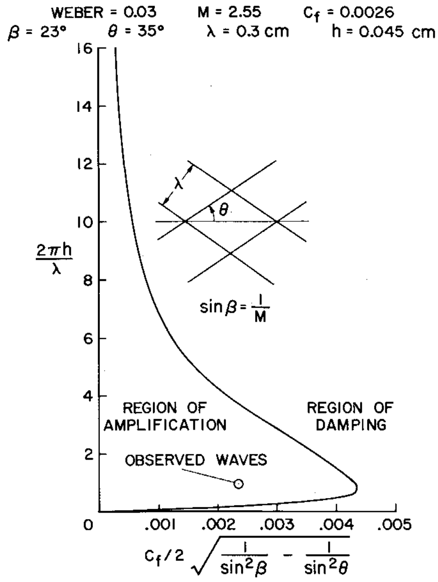


Fig. 2 Cutoff wave numbers.

that melts prior to vaporization), elimination of the transient phase suppresses pattern formation.

The crosshatched patterns that occur in charring ablators[2] resemble patterns that occur in plastic ablators exposed to the hot stream for a long time in that the pattern angle approximately equals the Mach angle with irregular spacing of the grooves. The distinction between the patterns that occur in charring ablators and the patterns that appear momentarily in plastic melt layers was made previously.[7]

## Characterization of Observed Patterns and Comparison with Theory

An additional objective of the experimental program was to characterize any pattern formed in the liquid film in sufficient detail so that a comparison could be made with the predictions of a linear stability theory.[9] From the procedures and the measurements indicated in the "Test Technique" section, and with the known properties of the liquid, the crosshatched pattern could be characterized in sufficient detail to permit comparison of the observations with the theory. The data reduction scheme is based on a liquid layer analysis that is exact for a linear velocity profile and approximate for other profiles; the main assumptions are that the boundary layer is turbulent and that the presence of the liquid film does not alter the turbulent boundary-layer velocity profile. The analysis is presented in the Appendix where numerical results are also given for the patterns shown in Fig. 1.

The test conditions corresponding to the patterns shown in Fig. 1 are compared with the predictions of a linear stability analysis in Fig. 2. The point labeled "observed waves" corresponds to the patterns shown in Fig. 1. The calculated curve in this figure is similar to one presented in Ref. 9, for a different Weber number. The ordinate represents a dimensionless wave number and the abscissa a modified friction coefficient. According to the linear stability analysis, the coordinates of any amplified and therefore observed wave for a given Weber number should appear in the region enclosed by the curve (i.e., to the left of the curve shown). For a Weber number of 0.03 corresponding to the patterns shown in Fig. 1 the coordinates of the observed wave are in the region of amplification.

Variations of tunnel Mach number and total pressure altered the visually observed patterns slightly. Alterations of the patterns caused by injecting liquids with viscosities greater than 1000 centistokes were not significant. However, injecting a liquid with a much lower viscosity (3 centistokes) resulted in no visually apparent patterns. This absence of patterns at a large liquid layer Reynolds number is consistent with the predictions of Ref. 9 (i.e., damping occurs at large film Reynolds numbers). Further, it should be stated that patterns were obtained in the liquids without the addition of any pigment but they were not visible in the photographs.

## Additional Observations Related to the Mechanism of Crosshatching

The iteraction of the waves in the liquid with the freestream observed in this investigation is of considerable interest in describing the mechanism of crosshatching. The shadowgraph in Fig. 3 clearly shows the spacings of the Mach waves emanating from each of the waves in the liquid on the surface of the concave model. Evidently the surface waves interact directly with the supersonic stream, indicating a near lack of viscous attenuation in the thin turbulent layer.

One further observation indicates the importance of surface tension as a mechanism in the formation of the crosshatched patterns. Exploratory tests were performed in a blow-down wind tunnel that could be shut down quickly. After shutdown, the pattern persisted momentarily and then gradually disappeared as the surface tension pulled the surface of the liquid taut. The behavior of the film was similar to that of newly applied wet paint in which the brush marks disappear gradually.

### Hydraulic Analogy to Crosshatching

A hydraulic analogy to crosshatching was developed during this investigation to identify the essential mechanisms of pattern formation. In Fig. 4 the photograph on the left shows a porous skinned conical model in which honey under pressure is being exuded through the surface pores. The photograph on the right shows the patterns that result when water flows supercritically over the surface of the honey. The honey exuded through the pores corresponds to a liquid film, and by the classical hydraulic analogy, the supercritical water flow corresponds to inviscid supersonic flow. The quantities being simulated in the honey demonstration that are thought ot be essential to the formation of crosshatched patterns are as follows: 1) supersonic flow; 2) viscous liquid film; and 3) surface tension of the liquid film. Another mechanism common to both experiments is the lack of viscous attenuation across the turbulent boundary layer in the wind tunnel experiment, and across the water boundary layer in the honey demonstration. The lack of viscous attenuation in the first case depends on the existence of a thin turbulent boundary layer. In the second case, since the water flow is supercritical, the classical hydraulic analogy can be invoked, where, as is known, viscous effects in the water flow are unimportant.[15]

The crosshatch pattern arises from the viscous damping of the supersonic pressure disturbances by the liquid film. For an extremely viscous film, these two quantities balance exactly at the gas-liquid interface.[9] The physical properties (viscosity and surface tension) of the liquid film determine the wavelength of the patterns. In the demonstration with honey, as in the wind-tunnel tests, the wave pattern moved relative to the mean motion of the liquid film.

In Ref. 16 several experiments were performed using the hydraulic analogy to study the effect of streamwise vortices on pattern formation. Hence, a different mechanism was being examined in Ref. 16 as opposed to the mechanisms identified above. The role of streamwise vortices as a crosshatching mechanisms was recently clarified in Ref. 17 by performing a definitive experiment. In Ref. 17 it was concluded that streamwise vortices are not necessary for crosshatching to exist.

## Conclusions

1) Moving crosshatched patterns can be obtained without the mechanism of ablation (vaporization or sublimation). 2) The motion of the liquid film introduced onto a surface in a conventional supersonic wind tunnel was characterized in sufficient detail to permit comparison between experiment and theory. 3) The observed waves are consistent with the findings of a linear stability analysis of the motion of a liquid film on a solid surface adjacent to a supersonic stream.

## Appendix: Film Analysis and Reduction of Data

The two quantities of primary interest in describing the liquid film are the film height $h$ and the film velocity at the gas-liquid interface $V$. These quantities can be obtained from a mass balance equation and an equation balancing the shear at the interface as

$$Q = \pi r h V$$

$$\tau = (c_f/2)\rho_g V_g^2 = \mu V/h$$

where $Q$ is the measured quantity of the liquid introduced per unit of time, $r$ is local cone radius, $c_f$ is turbulent skin-friction coefficient, $\frac{1}{2}\rho_g V_g^2$ is dynamic pressure of gas on cone surface at boundary-layer edge, and $\mu$ is viscosity of liquid. The turbulent skin-friction coefficient was computed by means of the modified Blasius flat-plate formula: $c_f/(c_f/c_{f_{inc}}) = 0.058/[(Re_c/2)^{0.2}]$ where $Re_c$ is the local Reynolds number on the cone. This formula differs from the Blasius formula given in Ref. 18 in that the Reynolds number is divided by 2. This factor was introduced by Van Driest[19] to account for conical flow. The term $(c_f/c_{f_{inc}})$ can be correlated in terms of the Mach number alone[20] for an adiabatic wall.

The test conditions for the photograph in Fig. 1 were freestream Mach number 2.8, cone half-angle 10°, total pressure 10 psia, total temperature 75°F, and freestream Reynolds number $1.8 \times 10^6$ ft$^{-1}$. For a station 6 in. from the tip (where the measurements will be compared with the theoretical predictions), the Mach number at the cone surface is 2.55, $Re_c$ is $1.14 \times 10^6$ (taking recompression into account), and the term $(c_f/c_{f_{inc}})$ for this Mach number is 0.65. These conditions give $c_f = 0.0026$. Since the pressure coefficient on the cone surface was 0.095 and the dynamic pressure $(\frac{1}{2}\rho_g V_g^2)$ $0.172 \times 10^6$ dynes/cm$^2$ (0.172 atm), the shear stress $\tau$ was 423 dynes/cm$^2$.

The film height $h$ and velocity $V$ could be calculated for the given conditions and the measured value of $Q$ (0.48 cm$^3$/sec)

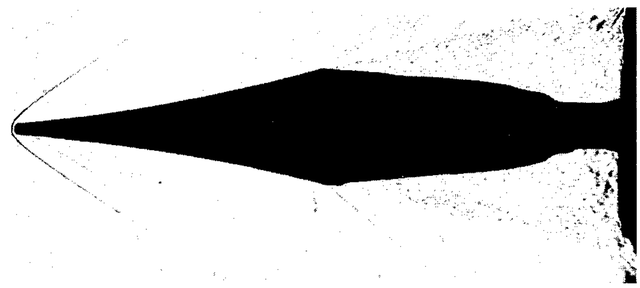

**Fig. 3 Shadowgraph of concave model.**

along with the known properties of the fluid. Unfortunately, the viscosity of the fluid ($\mu$) was not known precisely because of the addition of the white pigment to the 1000 centistoke fluid. Titanium dioxide was added until the desired degree of opacity was obtained. The viscosity of the slurry (fluid plus pigment) was then measured with a Brookfield Viscometer. The addition of the pigment caused the slurry to exhibit non-Newtonian behavior, and the measured viscosity ranged from 1450 to 3000 centistokes, depending on the rotor speed. This difficulty was eliminated, fortunately, by the previously mentioned experimental procedure that consisted of establishing the air flow over the cone surface and then introducing the liquid. The velocity at which the liquid interface moved rearward over the cone could be measured from the motion pictures to provide a measure of the average film velocity. This velocity was consistent with an effective viscosity of 1450 centistokes for the slurry at the test conditions. The variation of the viscosity with temperature did not prove to be a difficulty since the temperature of the fluid at the surface of the cone as measured by a thermocouple dropped only 25°F from its value in the room temperature reservoir. The viscosity of the Dow Corning "200" fluids is relatively insensitive to temperature changes of this magnitude.

Other liquid properties needed to reduce the data were obtained from the manufacturer. Specific gravity is approximately unity and the surface tension $T$ is 21 dynes/cm, assuming that adding the pigment did not alter the values of these properties significantly.

The measurements made from the motion pictures yielded 0.3 cm for the wavelength normal to the wave fronts, and 35° for the pattern angle. The mass balance equation and the equation for the shear given above can be solved for $h$ and $V$. In addition, the Reynolds number of the film $Re_f$ is given as $Re_f = \rho Q/\pi r \mu$. To summarize, at the station where $r = 2.7$ cm (approximately 15 cm from the tip) the pertinent pattern values are wavelength $\lambda = 0.3$ cm, pattern angle $\theta = 35°$, mach angle $\beta = 23°$. These values yielded: $h = 0.045$ cm, $V = 1.29$ cm/sec, and $Re_f = 0.004$. The film Reynolds number is extremely small. The Weber number $W$ to be used for comparison with the results of the linear stability analysis, valid for small Reynolds numbers, is based on the film velocity normal to the wave fronts, that is, $W = V \sin\theta(\rho h/T)^{1/2}$. The given values yield $W = 0.034$. The dimensionless wave number is given by $2\pi h/\lambda = 0.94$ and the modified friction coefficient[9] is $(c_f/2)[(1/\sin^2\beta) - (1/\sin^2\theta)]^{1/2} = 0.00235$ for the

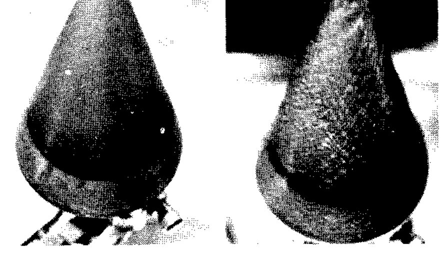

**Fig. 4 Hydraulic analogy to crosshatching.**

assigned values. The last two computed values are plotted on Fig. 2 where the analytic curve was calculated for a Weber number of 0.03.

## References


[1] Larson, H. K. and Mateer, G. G., "Crosshatching—A Coupling of Gas Dynamics With the Ablation Process," AIAA Paper 68-670, Los Angeles, Calif., 1968.

[2] Laganelli, A. L. and Nestler, D. E., "Surface Ablation Patterns: A Phenomenology Study," *AIAA Journal*, Vol. 7, No. 7, July 1969, pp. 1319–1325.

[3] Williams, E. P., "Experimental Studies of Ablation Surface Patterns and Resulting Roll Torques," *AIAA Journal*, Vol. 9, No. 7, July 1971, pp. 1315–1321.

[4] Canning, T. N., Wilkins, M. E. and Tauber, M. E., "Ablation Patterns on Cones Having Laminar and Turbulent Flows," *AIAA Journal*, Vol. 6, No. 1, Jan. 1968, pp. 174–175.

[5] Larson, H. K. and Nachtsheim, P. R., "Cross-Hatching," *Compressible Turbulent Boundary-Layers*, NASA SP-216, 1968, pp. 381–388.

[6] Winkler, E. M., Madden, M. T., Humphrey, R. L. and Koenig, J. A., "Supersonic Ablation Studies With Teflon," TR-69-125, Oct. 1969, Naval Ordnance Lab., White Oak, Silver Spring, Md.

[7] Nachtsheim, P. R. and Larson, H. K., "Crosshatched Ablation Patterns in Teflon," *AIAA Journal*, Vol. 9, No. 8, Aug. 1971, pp. 1608–1614.

[8] McDevitt, J. B., "An Exploratory Study of the Roll Behavior of Ablating Cones," *Journal of Spacecraft and Rockets*, Vol. 8, No. 2, Feb. 1971, pp. 162–269.

[9] Nachtsheim, P. R., "Stability of Crosshatched Wave Patterns in Thin Liquid Films Adjacent to Supersonic Streams," *The Physics of Fluids*, Vol. 13, Oct. 1970, pp. 2432–2447.

[10] Tobak, M., "Hypothesis for the Origin of Cross-Hatching," *AIAA Journal*, Vol. 8, No. 2, Feb. 1970, pp. 330–334.

[11] Inger, G. R., "Discontinuous Supersonic Flow Past an Ablating Wavy Wall," Rept. DAC-62375, Sept. 1968, McDonnell-Douglas Corp., Santa Monica, Calif.

[12] Mirels, H., "Origin of Striations on Ablative Materials," *AIAA Journal*, Vol. 7, No. 9, Sept. 1969, pp. 1813–1814.

[13] Donaldson, C. DuP, "A Study of the Modal Response Approach to Patterned Ablation Including Experiment Definition," TR-20-213, April 1970, SAMSO, El Segundo, Calif.

[14] Probstein, R. F. and Gold, H., "Cross-Hatching: A Material Response Phenomena," *AIAA Journal*, Vol. 8, No. 2, Feb. 1970, pp. 364–466.

[15] Cambel, A. B., "Compressible Flow," *Handbook of Fluid Dynamics*, edited by V. L. Streeter, McGraw-Hill, New York, 161, Sec. 8, pp. 67–70.

[16] Person, L. N., "Exploratory Experiments in Water on Stream-Wise Vortices and Crosshatching of the Surface of Reentry Bodies," Rept. 69-0160, Sept. 1969, Aerospace Research Labs., Wright-Patterson Air Force Base, Ohio.

[17] Stock, H. W. and Ginoux, J. J., "Hypersonic Low Temperature Ablation — An Experimental Study of Cross-Hatched Surface Patterns," Tech. Note 64, July 1971, von Kármán Institute for Fluid Dynamics, Rhode-Saint-Genese, Belgium.

[18] Hayes, W. D. and Probstein, R. F., *Hypersonic Flow Theory*, Academic Press, New York, 1959, pp. 328-329.

[19] Van Driest, E. R., "Turbulent Boundary Layer on a Cone in a Supersonic Flow at Zero Angle of Attack," *Journal of the Aeronautical Science*, Vol. 19, No. 1, 1952, p. 55.

[20] Leipmann, H. W. and Roshko A., *Elements of Gasdynamics*, Wiley, New York, 1957, pp. 338–343.