Two-Dimensional Supersonic Jet Impingement on a Flat Plate

T.-F. Zien,* K.-Y. Chien,* and R.T. Driftmyer†
Naval Surface Weapons Center, Silver Spring, Md.

Abstract

IT has been demonstrated[1] that the basic mechanism responsible for the most severe case of shock-interference heating is the impingement of a supersonic jet on the surface. The purpose of the present study is to obtain some basic information on the jet-impingement flowfield for use in the study of shock-interference heating phenomena. In this paper, we report on the results of a study of the flowfield associated with a two-dimensional, supersonic jet impinging normally on a flat plate. Two wedge nozzles manufactured at the design Mach numbers of 1.75 and 2.75 were used to provide the jet. Results of some surface pressure measurements and the shock measurements of the impingement flow are presented and discussed. A brief description of an approximate theory based on the method of integral relations is also included, and the theory is used to compare with the experiment.

Contents

The theoretical computations will first be abstracted briefly here. More details are available in Refs. 2 and 3. The geometrical arrangement is a plane jet at normal impingement, with the origin of the coordinate system at the stagnation point of the flat surface. The problem is considered to be steady and two-dimensional, with x and y axes along and perpendicular to the plate surface, respectively, and the freestream jet flow is in the negative y direction. For simplicity, the gas is assumed to be inviscid and obeys the perfect gas law. Ahead of the shock wave, the jet is assumed to be uniform with constant static pressure equal to the ambient value.

Scheme III of the method of integral relations (MIR) was used in the formulation of the approximate theory. In the one-strip formulation, we have employed the modified continuity equation (obtained by combining the relation of constant entropy along streamlines and the energy and the continuity equations). Since the plate surface is a streamline, an algebraic relation between the surface pressure and the surface velocity can be obtained to replace the x momentum equation. The other governing equations are 1) the energy equation (which is algebraic), 2) the y momentum equation, 3) the geometric relation between the detachment distance of the shock wave (Δ_s) and the shock angle (σ_s), and 4) the geometric relation between the detachment distance of the wall jet (Δ_j) and the angle of the upper boundary of the wall jet (σ_j). All angles are measured relative to the jet direction. The flowfield can be divided into two regions, a shock-layer region ($0 \leq \tilde{x} \leq 1$) and a wall-jet region ($1 \leq \tilde{x} \leq \eta$), where $\tilde{x} \equiv x/R$ (R is the jet half-width) and $x = \eta$ is the location of the sonic point on the plate surface. The two regions are related by the requirements that, at $\tilde{x} = 1$, the flow variables are continuous, $\Delta_s = \Delta_j$, and σ_s and σ_j are governed by the Prandtl-Meyer expansion relation. The boundary conditions are the symmetry conditions at $\tilde{x} = 0$, the Rankine-Hugoniot conditions at $y = \Delta_s$, and the constant entropy conditions along $y = 0$ and $y = \Delta_j$.

By integrating first the y momentum equation and the modified continuity equation across the shock layer and then from $\tilde{x} = 0$ to $\tilde{x} = 1$, we obtain a system of nonlinear algebraic equatons. The procedure is repeated in the wall-jet region. A regularity condition at the surface sonic point is imposed to close the system. Note that the numerical difficulty of satisfying the regularity condition at $\tilde{x} = \eta$ peculiar to scheme I of MIR is completely avoided in the present scheme.

Two stainless steel wedge nozzles were manufactured at the design Mach numbers of 1.75 and 2.75 to provide the supersonic jets used in the experiment. The aerodynamic design of the nozzle was based on the simple inviscid, one-dimensional flow model for air (perfect gas, $\gamma = 1.405$). The nozzles have the same exit width of 3.81 cm (1½ in.) and the same exit area of 3.81 cm × 5.08 cm (1½ in. × 2 in.). The semi-wedge angle was 2 deg, 13 min for the Mach 1.75 nozzle, and 5 deg, 34 min for the Mach 2.75 nozzle.

The test plate was made of stainless steel, and instrumented with a row of five pressure taps evenly spaced across a 2.54-cm (1-in.) span in the central portion of the plate. The pressure taps were aligned in the depth direction of the nozzle block in order to determine the two dimensionality of the impingement flowfield in the experiment. Two glass ported side plates were rigidly fixed to the edges of the test plate to constrain the flow in order to achieve the desired two dimensionality.

The nozzle-plate assembly was installed in the test section of the Supersonic Wind Tunnel No. 2 at the Naval Surface Weapons Center. The existing vacuum capacity of the tunnel was used to control the back pressure of the jet.

The experiment with each nozzle began with a pitot survey of the freejet using a pitot rake to establish the actual Mach number and to determine the quality of the two-dimensional jet. Detailed results of the pitot survey are given in Ref. 2, and we only note here that the average Mach numbers for the freejet were determined to be 1.85 and 2.77, respectively, for

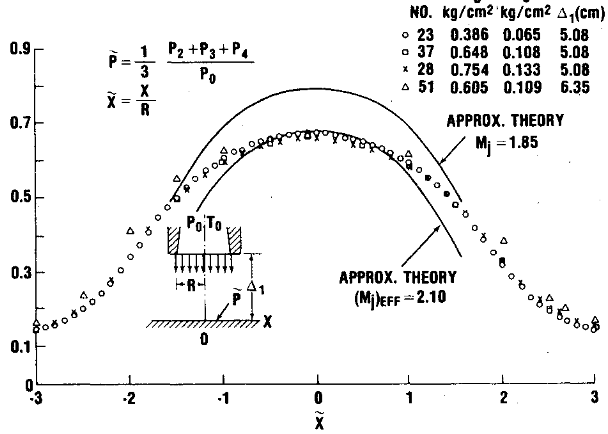

Fig. 1 Surface pressure results: $M_j = 1.85$.

Presented as Paper 78-208 at the AIAA 16th Aerospace Sciences Meeting, Huntsville, Ala., Jan 16–18, 1978; submitted Feb. 8, 1978; synoptic received June 6, 1978; revision received July 31, 1978. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Supersonic and Hypersonic Flow.

*Research Aerospace Engineer. Applied Mathematics Branch. Associate Fellow AIAA.

†Aerospace Engineer, Aerodynamics Branch. Member AIAA.

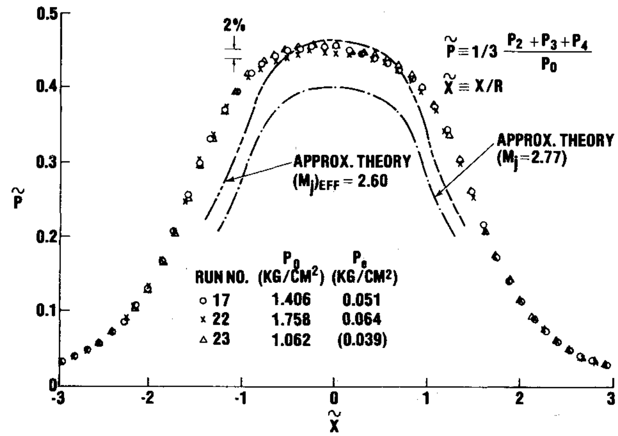

Fig. 2 Surface pressure results: $M_j = 2.77$.

the two nozzles, compared to the design values of 1.75 and 2.75. The freejet was found to be uniform in both width and depth directions to about 5% or better for both nozzles. Note that the survey was conducted without the test and side plates.

The surface pressure results for nearly isentropic jet impingement are shown in Figs. 1 and 2, corresponding to the Mach 1.75 nozzle and Mach 2.75 nozzle, respectively. The surface pressure was measured by five pressure taps, P_1 through P_5, along the depth of the nozzle. However, the readings of P_1 and P_5 were disregarded because of the apparent three-dimensional effects, and the average readings of P_2, P_3, and P_4 were used for the surface pressure data. This was the procedure used in the data analysis for both nozzles. In Fig. 1, the pressure data of the three different runs with $\Delta_l = 5.08$ cm are seen to agree very closely, and the expected symmetry in the data with respect to the nozzle symmetry plane is clearly visible. The data with $\Delta_l = 6.35$ cm are also included in Fig. 1 to indicate the effect of Δ_l on the surface pressure distribution. The effect of Δ_l on surface pressure apparently becomes more pronounced for an underexpanded jet.[2] As can be seen in Fig. 2, the expected symmetry of the pressure distribution and the close agreement among the data for different P_0 continue to exist for the Mach 2.75 nozzle.

In the comparison of the surface pressure results (Figs. 1 and 2), it is seen that the agreement is rather unsatisfactory if the theoretical results are based on the average freejet Mach numbers, $M_j = 1.85$ and $M_j = 2.77$, respectively, determined from the pitot surveys. In particular, the measured surface pressures at the stagnation point ($x = 0$) do not correspond to the total pressures behind the normal shock at the respective freejet Mach numbers. This discrepancy suggests the introduction of an "effective" jet Mach number, $(M_j)_{\rm eff}$, in the impingement flow. $(M_j)_{\rm eff}$ is based on the measured surface pressure at the stagnation point, assuming isentropic flow between the plate and the downstream side of the shock caused by the plate. In fact, Gummer and Hunt[4] based the determination of their jet Mach number on such a pressure measurement in their axisymmetric jet impingement experiment, in the absence of a pitot survey of the freejet. The "effective" jet Mach number was found to be 2.10 in the experiment with the first nozzle and 2.60 in the experiment with the second nozzle. The theoretical surface pressure distributions based on $(M_j)_{\rm eff}$ show reasonably good agreement with the measured distributions, especially near the stagnation point where the most severe heating is expected to take place.

In view of the uncertainties and nonuniformities existing in the ambient conditions of the experiment, notably the difficulty in maintaining a uniform back pressure in the semiconfined configuration used in the surface pressure measurement, it is difficult to expect that the impinging jet had a constant and uniform Mach number equal to that of the freely expanding jet. Other complications such as viscous effects, which could become more pronounced in a confined space than in an open space, could also contribute to the deviation of the Mach number of the jet from its free expansion value. Therefore, the use of $(M_j)_{\rm eff}$ in lieu of M_j in the comparison between theory and experiment does not seem unjustified. Note that $(M_j)_{\rm eff}$ differs from M_j only by about 7% in the Mach 2.77 experiment, although the difference is in the reversed direction relative to that in the Mach 1.85 experiment.

Results of shock measurements are given in Ref. 2. We only note here that the considerable scatter in the data precludes any definitive comparisons between theory and experiment.

In conclusion, we enumerate the following observations based on the present study: 1) the simple wedge nozzles appear adequate for providing two-dimensional freejets of good quality; 2) the two-dimensionality of the plate pressure distribution in the jet-impingement experiment was achieved in the central portion of the plate in the present semiconfined configuration; 3) the semiconfined configuration apparently caused the Mach number of the impinging jet to deviate from its value based on the free expansion condition, and the "effective" jet Mach number of the impinging jet could be determined from the surface pressure at the stagnation point; and 4) the simple approximate theory seems adequate to predict the pressure distribution on the plate surface.

Acknowledgment

This work was supported by Naval Air Systems Command, AIR320C, under the cognizance of W.C. Volz, whose encouragement is greatly appreciated. The authors also gratefully acknowledge some enlightening discussions with B.L. Hunt of the University of Bristol, England.

References

[1] Edney, B., "Anomalous Heat Transfer and Pressure Distributions on Blunt Bodies at Hypersonic Speeds in the Presence of an Impinging Shock," The Aeronautical Research Institute of Sweden, Stockholm, FFA Rept. 115, 1968.

[2] Zien, T.-F., Chien, K.-Y., and Driftmyer, R.T., "Two-Dimensional Supersonic Jet Impingement on a Flat Plate," AIAA Paper 78-208, Huntsville, Ala., Jan. 16-18, 1978.

[3] Chien, K.-Y., "Normal Impingement of a Supersonic Jet on a Plane—A Basic Study of Shock-Interference Heating," Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, Md., NSWC/WOL/TR 75-195, 1975.

[4] Gummer, J.H. and Hunt, B.L., "The Impingement of a Uniform, Axisymmetric, Supersonic Jet on a Perpendicular Flat Plate," *The Aeronautical Quarterly*, Vol. 22, Nov. 1971, pp. 403–420.