Investigating the interactions between an atmosphere and an ejecta curtain

2. Numerical experiments

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Abstract. The locus of ejecta excavated during an impact generates a debris curtain that expands outward. In an atmosphere this advancing curtain acts like a semipermeable barrier that displaces the surrounding gas. The generated flow separates near the top of the curtain to form a vortex ring whose strong winds entrain, transport, and deposit fine-grained ejecta, affecting the morphology of distal ejecta deposited on planets with atmospheres. We have investigated how the curtain width and velocity, particle concentration, size distribution and velocity parallel to the curtain, and the density, viscosity, and compressibility of the surrounding atmosphere controls the flow strength of these winds. Wind tunnel tests (Part 1 [Barnouin-Jha et al., this issue]) show that for an ejecta-like porous plate, the hydraulic resistance, a measure of energy losses for one-dimensional porous flow, governs the position along the curtain where it becomes effectively impermeable. Combined with suitable cratering models and published hydraulic resistance data, this information allows estimating the flow strength or circulation generated by an advancing curtain. The present study assesses the influence of atmospheric compressibility and particle motion parallel to the curtain surface on the curtain’s circulation in order to improve these estimates. Numerical experiments indicate that atmospheric compressibility has little effect on the circulation at Mach number below 0.5, consistent with analytical solutions. Analytical solutions show, however, that this flow circulation should increase significantly at higher Mach numbers. The numerical experiments also show that individual ejecta traveling parallel to the surface of the curtain enhance the induced circulation by 9% to 33%.

1. Introduction

An atmosphere significantly influences the entrainment and emplacement of ejecta in the laboratory and on the planets. During crater formation, excavated ejecta form an inverted cone-shaped curtain that expands outward nearly evenly [Gault et al., 1968; Oberbeck, 1975]. As the curtain advances, the surrounding atmosphere is forced around its lower thick portions. Flow separation at the top of this thick portion creates a vortex ring (Figure 1). Both laboratory and theoretical work indicate that the winds of the vortex entrain, transport, and deposit fine grained ejecta decelerated out of the curtain [Schultz and Gault, 1979; Schultz, 1992a; Barnouin-Jha and Schultz, 1996]. Such work also show that flow instabilities generated in the vortex account for the sinuosity or lobateness of distal ejecta facies observed at laboratory and possibly planetary scales [Barnouin-Jha and Schultz, 1998]. Furthermore, laboratory results [Schultz and Gault, 1979, 1982; Schultz, 1992a,b] indicate that these winds can mobilize and saltate target and large ejecta that are first deposited ballistically. The resulting ejecta morphologies resemble in many respects those observed on Mars, Earth, and Venus [Schultz and Gault, 1979,1982; Schultz and Singer, 1980; Schultz and Grant, 1989; Schultz, 1992a, b].

The flow strength or circulation of the winds generated by an advancing ejecta curtain controls most aspects of the atmospheric ejecta deposition process. This circulation is a function of the velocity and length of the curtain where it transitions from an impermeable to a permeable barrier to the atmosphere [Barnouin-Jha and Schultz, 1996]. These variables are easily determined during impact experiments using appropriate visualization techniques [see Barnouin-Jha and Schultz, 1996]. Such measurements, of course, cannot be made for planetary-scale impacts.

Two studies investigate how the physical properties of the ejecta curtain and surrounding atmosphere can be used to determine the circulation in curtain-derived winds. In a companion study [Barnouin-Jha et al., this issue] (hereafter Part I), we used a wind tunnel to investigate the flow field generated by both solid and porous plates. These tests indicate that hydraulic resistance (a measure of energy losses for one-dimensional porous flow) determines where along an ejecta-
Figure 1. Schematic of an ejecta curtain advancing through an atmosphere based on laboratory observations at the NASA Ames vertical gun range. The lower thicker portion is impermeable to the surrounding atmosphere, redirecting atmospheric flow through the ejecta curtain, thereby allowing flow separation to generate a vortex ring. Fine-grained ejecta are decelerated out of these semipermeable portions of the ejecta curtain and enter the vortex ring. Variables used in this theoretical model are indicated.

Figure 1. Schematic of an ejecta curtain advancing through an atmosphere based on laboratory observations at the NASA Ames vertical gun range. The lower thicker portion is impermeable to the surrounding atmosphere, redirecting atmospheric flow through the ejecta curtain, thereby allowing flow separation to generate a vortex ring. Fine-grained ejecta are decelerated out of these semipermeable portions of the ejecta curtain and enter the vortex ring. Variables used in this theoretical model are indicated.

like porous plate it becomes effectively permeable. Published data link hydraulic resistance to the thickness, porosity, and dominant particle size comprising a porous boundary, and atmospheric properties such as viscosity and density [Idelchik, 1994]. Such results can be combined with appropriate atmospheric and cratering models [e.g., Maxwell, 1977; Schultz and Gault, 1979; Orphal et al., 1980; Housen et al., 1983] to determine the length of the impermeable portion of the curtain and the time when it transitions from impermeable to permeable.

In the second study, reported here, numerical experiments extend the investigation to properties that affect the flow circulation but that cannot be studied easily at wind tunnel facilities, namely, atmospheric compressibility and the motion of particles parallel to the surface of the curtain. The numerical experiments required, first, calibrating its turbulence model using wind tunnel results and, second, testing numerical box sizes that satisfy the flow conditions in the wind tunnel while allowing rapid numerical convergence. Once appropriate numerical conditions are found, we report on how the circulation is affected by atmospheric compressibility and particle motion parallel to the surface of the curtain. Results from both the wind tunnel and the numerical experiments are then combined to provide a reasonably complete understanding of the flow field and flow strength generated by an advancing curtain. In a third contribution, this understanding allows developing a theoretical model of the evolution of an ejecta curtain in an atmosphere that will be tested against impact experiments [Barnouin-Jha and Schultz, 1999]. A future contribution will apply the model to larger planetary scales (see Barnouin-Jha [1998] for some preliminary examples).

2. Background

The wind tunnel study (Part 1) describes how the circulation of an advancing ejecta curtain is a function of

\[ \Gamma = f(\phi, w, d, \rho, \mu, U, u_p, c) \]

where \( \phi, w, \) and \( U \) are the porosity, width, and velocity of the curtain; \( d \) is the most common diameter of individual particles within the curtain; \( \rho, \mu, \) and \( c \) are the density, viscosity, and sound speed of the surrounding atmosphere; and \( u_p \) is the velocity component parallel to the curtain surface (Table 1). The wind tunnel tests indicate that the circulation can be rewritten as

\[ \Gamma = f(u_p/U, M) \]

where the hydraulic resistance \( \zeta \) is given by

\[ \zeta = f(Re_d, \phi, d/w) \]

The Reynolds number \( Re_d = \rho U d/\mu \) is the ratio of inertial to viscous forces acting on the particles comprising the ejecta curtain as atmosphere flows through the porous curtain.

The present study investigates the influence of the Mach number \( M = c/U \) and \( u_p/U \) on \( \Gamma \). The Mach number of the curtain measures the effects of atmospheric compressibility on the ejecta curtain as it advances in an atmosphere. Because the velocity of an ejecta curtain increases with increasing crater size, atmospheric compressibility may influence \( \Gamma \) at large scales. The term \( u_p/U \) provides a measure of the shear stress the atmosphere feels by the motion of particles within the curtain. Since the curtain consists of particles that initially travel along ballistic trajectories, the velocities of the particles change with respect to the curtain surface. Resulting shear stress can either increase or decrease \( \Gamma \) [Barnouin-Jha and Schultz, 1996]. Furthermore, the effectively impermeable curtain length and hence \( \Gamma \) can be influenced by the magnitude and direction of \( u_p \).

3. Numerical Procedure

The investigation of both atmospheric compressibility and the velocity component \( u_p \) of individual particles traveling parallel to the surface of the curtain were done using FIDAP [Fluent, Inc., 1993], a commercially available finite element code. FIDAP possesses a two-equation \( \kappa-\varepsilon \) model for turbulent flow (see Gatski [1996] for more details) that must first be calibrated against wind tunnel results. With appropriate values for the coefficients \( \kappa \) and \( \varepsilon \), we investigate the influence of mesh resolution and choose a suitable numerical box size that satisfies the flow conditions in the wind tunnel while ensuring rapid numerical convergence. The effects of \( M \) and \( u_p \) on \( \Gamma \) were investigated once appropriate numerical conditions were found.

3.1. Calibrating \( \kappa \) and \( \varepsilon \)

Turbulent flow conditions prevailed during the wind tunnel investigations, consistent with the flow conditions achieved by a rapidly advancing ejecta curtain at both laboratory and planetary scales [Barnouin-Jha and Schultz, 1996]. In such flow conditions, turbulent flow in the boundary layers dissipates energy more efficiently than in the laminar flow case. To compensate for such losses, FIDAP requires two coefficients (\( \kappa \) and \( \varepsilon \)) that help ensure that reasonable energy losses occur at both the surfaces and edges of obstacles under
Table 1. Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>$\Gamma$</td>
<td>circulation (m²/s)</td>
</tr>
<tr>
<td>$\Gamma_c$</td>
<td>circulation due to flow separation only (m²/s)</td>
</tr>
<tr>
<td>$\Gamma_p$</td>
<td>circulation generated in numerical calculations behind the different plates analyzed (m²/s)</td>
</tr>
<tr>
<td>$\Gamma_T$</td>
<td>circulation due to flow separation and energy losses in the semipermeable sections of an ejecta curtain (m²/s)</td>
</tr>
<tr>
<td>$\Gamma_{ic}$</td>
<td>circulation generated in an incompressible flow (m²/s)</td>
</tr>
<tr>
<td>$\Gamma_r$</td>
<td>circulation generated in a compressible flow (m²/s)</td>
</tr>
<tr>
<td>$\Gamma_{max or min}$</td>
<td>maximum and minimum circulation generated by an advancing ejecta curtain (m²/s)</td>
</tr>
<tr>
<td>$U$</td>
<td>curtain velocity (m/s)</td>
</tr>
<tr>
<td>$U_c$</td>
<td>incoming or upstream flow velocity equal to curtain velocity $U$ with change of reference (m/s)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>curtain porosity; for porous plate this is the ratio of open to closed cross-sectional area</td>
</tr>
<tr>
<td>$w$</td>
<td>width of an ejecta curtain or a porous plate</td>
</tr>
<tr>
<td>$d$</td>
<td>dominant or nominal particle diameter in ejecta curtain (m)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>atmospheric density (kg/m³)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>atmospheric viscosity (kg/(ms))</td>
</tr>
<tr>
<td>$u_p$</td>
<td>component of velocity parallel to surface of the ejecta curtain (m/s)</td>
</tr>
<tr>
<td>$c$</td>
<td>atmospheric speed of sound (m/s)</td>
</tr>
<tr>
<td>$M = U/c$</td>
<td>Mach number of ejecta curtain</td>
</tr>
<tr>
<td>$Re_d$</td>
<td>Reynolds number of dominant particle comprising the ejecta curtain</td>
</tr>
<tr>
<td>$u$</td>
<td>local flow speed (m/s)</td>
</tr>
<tr>
<td>$u_{avg}$</td>
<td>average interstitial flow speed in a porous obstacle with porosity $\phi$ (m/s)</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>hydraulic resistance of a porous obstacle in 1-D channel flow</td>
</tr>
<tr>
<td>$\zeta_{cr}$</td>
<td>critical hydraulic resistance</td>
</tr>
<tr>
<td>$H$</td>
<td>vertical height of plates investigated (m)</td>
</tr>
<tr>
<td>$L^*$</td>
<td>effectively impermeable ejecta-like plate length (m)</td>
</tr>
<tr>
<td>$L$</td>
<td>solid plate length (m)</td>
</tr>
<tr>
<td>$Re_h = \rho(U_{inf}H)\mu$</td>
<td>Reynolds number of plates investigated</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>measure of turbulent energy in upstream flow</td>
</tr>
<tr>
<td>$T$</td>
<td>averaging period taken to be longer than any significant period of the turbulent fluctuations themselves (s)</td>
</tr>
<tr>
<td>$U_{inf}(t)$</td>
<td>instantaneous upstream flow velocity (m/s)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>numerical energy dissipation for turbulent flow modeling</td>
</tr>
<tr>
<td>$\delta$</td>
<td>normalized characteristic width of shear layer behind inclined solid plate</td>
</tr>
<tr>
<td>$u_x$</td>
<td>horizontal component of flow velocity in computational box (m/s)</td>
</tr>
<tr>
<td>$u_y$</td>
<td>vertical component of flow velocity in computational box (m/s)</td>
</tr>
<tr>
<td>$u_{max}$</td>
<td>maximum flow speed in recirculation zone behind plates investigated (m/s)</td>
</tr>
<tr>
<td>$P_{inf}$</td>
<td>ambient atmospheric pressure (Pa)</td>
</tr>
<tr>
<td>$P_0$</td>
<td>stagnation pressure in front of an obstacle (Pa)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>ratio of specific heats of ambient atmosphere</td>
</tr>
<tr>
<td>$u$</td>
<td>velocity vector of fluid intersecting a curve C</td>
</tr>
<tr>
<td>$t$</td>
<td>unit tangent vector of C</td>
</tr>
<tr>
<td>$ds$</td>
<td>length of a line element along C</td>
</tr>
<tr>
<td>$C$</td>
<td>curve enclosing recirculation zone behind the plates investigated</td>
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</tbody>
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The dimensionless $\kappa$ term is a measure of turbulent energy in the incoming flow and is defined by

$$\kappa = 1.5I^2 = \frac{1}{U_{inf}} \sqrt{\frac{1}{T} \int_0^T (U_{inf}(t) - U_{inf})^2 dt}$$

where $I$ is the intensity of turbulence, $U_{inf}(t)$ is the instantaneous flow speed, $U_{inf}$ is the mean flow speed impinging on the plate in the wind tunnel, and $T$ is an averaging period taken to be longer than any significant period of the turbulent fluctuations themselves. The intensity of turbulence $I$ is measured from inlet flow conditions at the wind tunnel. The $\varepsilon$ term measures the energy dissipation generated by turbulence at the surfaces and edges of the obstacle investigated. A first guess at $\varepsilon$ can be obtained by using

$$\varepsilon = \frac{\kappa}{0.18}$$

where $\delta$ is the characteristic width of the shear layer behind the inclined plate normalized by the scale height $H$ of the inclined plate (Figure 2). The wind tunnel experiments also provide $\delta$.

Fine-tuning $\varepsilon$ is achieved by matching wind tunnel data for the size of the separation pocket behind, and the flow profile near, an inclined plate. The best values of $\varepsilon$ are obtained by performing numerical calculations in a computational box that exactly replicates the wind tunnel geometry (Figure 2a). Wind tunnel data for the solid inclined plate should provide an accurate estimate of $\varepsilon$ even for a porous plate because the energy losses at the perforations of such a plate resemble...
those generated at the top sharp edge of an inclined solid plate. All the sides present in the computational box were held fixed and matched exactly the boundary conditions present in the wind tunnel.

For \( \kappa = 3.75 \times 10^{-3} \) defined by the incoming flow, the numerical calculations best duplicate the wind tunnel results when \( \varepsilon = 1 \times 10^{-4} \) (Figure 3). The calculated flow-speed profiles both in front and behind the solid plate match the wind tunnel data remarkably well. Furthermore, the reattachment points of the numerical and wind tunnel flows coincide at \( x^* = 13.5 \), well within the 20% difference commonly accepted for \( \kappa-\varepsilon \) models [Nallasamy, 1985].

3.2. Mesh Resolution

Having established suitable values of \( \kappa \) and \( \varepsilon \), we investigate the influence of mesh resolution. FIDAP [Fluent, Inc., 1993] possesses an adaptive mesh generator where the nodes at the flow boundaries are designated by the user. A very fine mesh is constructed in the sensitive regions of the flow where the boundary layer forms and flow separation occurs. In the other regions the constructed mesh is significantly coarser (Figure 4). Increases by a factor of 2 and more in the number of mesh nodes, especially in the sensitive regions of the flow, changed the flow structure by less than 1%, indistinguishable from the convergence error of the calculation. Such a result is common in steady state flow where gradients are small. We assume therefore that the mesh used to determine \( \kappa \) and \( \varepsilon \) was sufficiently discrete and reached grid convergence. This grid resolution was used in all of the following calculations.

3.3. Numerical Box Size

The geometry of the computational box used to calibrate \( \varepsilon \) required large amounts of computational memory and time to obtain converged solutions. We therefore repeated these calculations in a smaller box that did not possess the flow field beneath the horizontal plate holding up the inclined solid plate (Figure 2b). The front ledge was also eliminated. It was replaced with stress-free boundary conditions in the horizontal flow direction (i.e., \( du/dy = 0 \)) and zero flow conditions in the vertical condition (i.e., \( u_y = 0 \)), analogous to the ejecta
Figure 3. Measured and numerical flow speeds at a variety of locations in front and behind a solid plate (see Figure 1 for origin of x-y axis, and Table 1 for normalizing factors) for identical Re_H (see Table 1 for definition of Re_H). The wind tunnel flow speeds are given by the black square symbols, while the numerical results for the entire tunnel are represented by gray circles, and the numerical results for the partially closed tunnel are represented by open diamonds. The flow speed is normalized by the incoming flow speed U. This comparison shows that a reasonably good match between the measured and computed results can be achieved when κ = 3.75x10^{-3} and ε = 1x10^{-4} (see text).

curtain case. The results are very similar to those obtained using the entire computational domain that calibrated ε (Figure 3). Again the measured and computed flow profiles match each other remarkably well, and the reattachment points occur at nearly the same position.

To increase the efficiency of the computations further, we opened the top of the small computation box. This approach ensured more rapid convergence because the turbulent wall boundary conditions at the top of the box are replaced by numerically more stable stress-free boundary conditions (i.e. du/du = dv/dx = 0). Such boundary conditions also resemble more closely the flow conditions encountered by an ejecta curtain and allow determining the flow accelerations that occur in the wind tunnel due to blockage by the test plates.

The computational results show that at identical Reynolds numbers (defined as Re_H = ρU_ωH/μ), both the maximum velocity and the general structure of the flow are not significantly affected by the assumed box, i.e., closed or open (Figure 5). This also implies that blockage by the test plate is not significant in the wind tunnel experiments. We therefore used the small open box configuration to investigate the effect of increasing M and varying u_p on the circulation of the ejecta curtain.

As for the wind tunnel tests (see Part 1), we investigate the
influence of both $M$ and $u_p$ on the circulation using a two-dimensional (2-D) rectangular flow geometry. Such a flow should be representative of the 2-D axisymmetric flow generated by an advancing ejecta curtain of a large crater because the size of the curtain-induced ring vortex is thin relative to the curtain length. We also investigate the influence of $M$ and $u_p$ using steady state flows because the velocity of the curtain changes gradually when significant flow separation begins usually after $-2/3$ of crater growth is complete as most ejecta are excavated.

3.4. Atmospheric Compressibility

For large impacts, atmospheric entrainment of excavated ejecta occurs predominately at the late stages of ejecta excavation near the end of crater growth when the surrounding atmosphere has mostly but not entirely recovered from the early-time impact blast [Schultz and Gault, 1979, 1982; Schultz, 1992a; Barnouin-Jha and Schultz, 1996, 1998; Part 1]. For such large events, the outward curtain speeds are sufficiently large that they can compress displaced atmosphere. For example, at the time when crater growth ceases, the curtain Mach number $M = U/c$ of a 30-km-diameter (rim-to-rim) crater will achieve 0.4 on Mars, 0.3 on Venus, and 0.4 on Earth. These Mach numbers increase to first order with the square root of crater radius. The magnitude of these Mach numbers can increase further after crater growth ceases because the curtain accelerates as it travels beyond the crater rim. Also, the atmosphere continues to cool while further recovering from the initial blast [see Sedov, 1993], reducing the speed of sound $c$ and, thereby, increasing the curtain Mach number.

To investigate the effect of $M$ on an ejecta curtain’s circulation, computations of flow behind a solid plate at identical $Re_{ij}$ but increasing Mach number were performed. Velocity vector plots for computations at $M = 0.001, 0.1$, and 0.2 show that the Mach number has little effect on the flow field and hence the circulation generated by the plate (Figure 6). In all three computations, little or no change in the maximum flow velocities occurred (Figure 6). Values of $M = 0.1$ and 0.2 correspond approximately to the curtain velocity at the end of crater growth generated by a 3 km and a 9-12 km (rim-to-rim) diameter crater traveling through ambient atmospheric conditions on Mars, Venus, and Earth. Computations beyond $M = 0.2$ (i.e., larger craters) were not achievable because the pressure solver of FIDAP generated numerical dissipation that led to solutions that were unrealistic.

These numerical results at low $M$ are consistent with theoretical expectations. The stagnation pressure $P_0$ in front of an inclined plate or ejecta curtain is

$$P_0 = P_{\infty} \left[ 1 - \frac{1}{2} (1 - \gamma) M^2 \right]^{1/(\gamma - 1)} \quad (6)$$

where $P_{\infty}$ is the ambient atmospheric pressure and $\gamma$ is the ratio of specific heats of the ambient gas. For $M$ up to 0.5, $P_0$ differs little from the value given by incompressible flow, and the flow field simply scales with curtain velocity. As $M$ increases beyond 0.5, $P_0$ is progressively greater than its value for incompressible flow, leading to proportionally greater separation velocities across an inclined plate or an ejecta curtain. Consequently, the curtain circulation should increase relative to the value for incompressible flow. In essence, the atmosphere acts more and more like a spring, releasing stored energy from compression in front of an inclined plate or an ejecta curtain. Such expectations are confirmed by theory for a thin airfoil at subsonic speeds, where the circulation in compressible flow ($\Gamma_c$) can be expressed in terms of the circulation in incompressible flow ($\Gamma_{ic}$) [Landau and Lifshitz, 1987]:

$$\Gamma_c = \frac{\Gamma_{ic}}{\sqrt{1 - M^2}} \quad (7)$$

Equation (7) shows that $\Gamma_c$ increases by 15% at $M = 0.5$ and 60% at $M = 0.8$. This formulation is not valid for transonic flow conditions (i.e., $M > 0.8$, or craters exceeding about 100 km rim-to-rim diameter).

An ejecta curtain travels at a steep angle with respect to the incoming flow and, consequently, acts more like a blunt body
Figure 5. Streamline, dimensionless speed (u/\(U_\infty\)) and dimensionless pressure (p/\(pU_\infty^2\)) contour plots for incompressible flow in a (a) closed and (b) open simulation of a portion of the wind tunnel. For the open wind tunnel results, stress-free boundary conditions are prescribed at the top boundary of the numerical box (see text). Other than some slight differences at the top of the box, streamline, speed, and pressure values for both cases are very nearly identical, with differences that cannot be distinguished within the accuracy of the numerical calculations. These calculations demonstrate that the test plates do not significantly block the cross-sectional area of the wind tunnel test section. As a result, measured flow accelerations are not due to area changes within the wind tunnel, and open simulations of the wind tunnel should suffice for the numerical experiments.
rather than a thin airfoil. Therefore, a better quantitative analog for the effect of increasing Mach number on curtain-induced circulation may be obtained by analyzing flow past a sphere. Experiments show that the drag coefficient of spheres steadily increases with increasing $M$ above 0.5. Indeed, this drag coefficient increases by 50% at $M = 0.8$ [Charters and Thomas, 1945]. For blunt bodies the drag coefficient mainly measures the difference in pressure across the body. By Bernoulli's principal, a 50% increase in drag coefficient must require approximately a 70% increase in flow speed around the sphere. This should result in approximately a 70% increase in the circulation of the flow generated by the sphere (in the upper half space, say). This blunt body increase in circulation nearly equals that predicted by (7) for a thin airfoil.

The above-described increase in $\Gamma$ can be offset when the flow shed by the curtain becomes supersonic. The circulation generated by the advancing ejecta curtain will decrease because the flow undergoes shocks as it rushes over the top of the impermeable portion of the curtain. Such shocks reduce the maximum flow speed (and hence the circulation). These shocks, however, will not prevent the formation of the vortex ring behind the curtain; trailing vortices still form behind airfoils that travel at transonic and supersonic speeds. The induced drag for airfoils traveling at subsonic, transonic, and supersonic speeds provides evidence for the appearance of such trailing vortices [Liepmann and Roshko, 1956]. Furthermore, Merzkirch [1964] demonstrated how compressible vortex flows are generated by shock tube flow over a vertical wedge. The shock effects on the circulation of curtain-generated ring vortex will be examined in a future study.

3.5. Motion of Individual Ejecta Parallel to the Curtain Surface

Three sets of numerical experiments were performed to investigate how particles within an ejecta curtain, moving parallel to its surface, affect flow created by the ensemble of ejecta, i.e., the curtain. The first set of experiments considers a 50% porous plate with large perforations. When its boundary surface is stationary, these perforations allow sufficient

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Figure 6. Computed dimensionless contour speed plots (see Figure 4) for turbulent flow ($Re_H = 11,500.0$; see Table 1 for definition of $Re_H$) at Mach number $M = 0.001$, 0.1, and 0.2. No significant change in speed can be observed from one plot to the next. The maximum flow speed may be increasing slightly, although the range of values for this speed are of the order of the accuracy of the numerical calculations.
The first set of experiments illustrates how motion along the boundary surface of the curtain may significantly affect the induced flow field. With no motion, flow simply passes through the plate while losing some speed (Figure 8a), consistent with corresponding wind tunnel tests (Figure 9). When

Figure 7. Normalized component of ejecta velocity \( u_p \) parallel to the surface of the ejecta curtain at the time of crater formation \( T \). The velocity \( u_p \) is normalized by the advancing velocity \( U \) of the ejecta curtain, while the position along the curtain is normalized by the curtain length \( L \) which is estimated by the transition from continuous to discontinuous ejecta on the Moon and Mercury (see Barnouin-Jha and Schultz [1998] for further explanation). \( u_p \) is computed using a modified Z-model [Maxwell, 1977; Schultz and Gault, 1979]. The average velocity along the length of the curtain at the time of crater formation equals 1.64\( U \).

flow through to prevent recirculation behind the plate. The second set of experiments also considers a 50% porous plate, but with small perforations. Unlike the first plate, these small perforations prevent significant flow through at low \( \text{Re}_H \). Consequently, in this flow regime a recirculation pocket forms behind the plate when its surface boundary is stationary. The third set of experiments considers flow past a solid plate. In all three sets, we compared the flow field and circulation generated by the plates when their surfaces were first stationary and then moving. The speed of both the upwind and downwind boundary surfaces of the plate were set equal to twice the incoming flow velocity, in an upward direction parallel to the surfaces. This velocity is slightly greater than the mean velocity along the surface of an ejecta curtain when crater growth ceases [Maxwell, 1977; Schultz and Gault, 1979] (Figure 7). Roughly speaking (within a factor of 2), the end of crater growth is equal to the time when the ejecta curtain becomes permeable.

Figure 8. Calculated dimensionless velocity vector \((u/U_\infty)\) plots of flow past a 50% porous perforated plate. When the surface (sides) of the plate is (are) stationary (Figure 8a), flow perforates the plate but loses speed. When the plate surface is set into motion (Figure 8b), flow still passes through the plate, but now acquires a significant flow component upward that induces recirculation. For the latter calculation, the velocity of the plate sides is set equal to twice the incoming flow velocity, in an upward direction parallel to the surfaces. This velocity is slightly greater than the mean velocity along the surface of an ejecta curtain when crater growth ceases [Maxwell, 1977; Schultz and Gault, 1979] (Figure 7). Roughly speaking (within a factor of 2), the end of crater growth is equal to the time when the ejecta curtain becomes permeable.
Figure 9. Wind tunnel measurements of the normalized flow speed obtained downstream of a 58% porous plate (see Part 1) for a range of $Re_H$ (see Table 1 for definition of $Re_H$). These measurements and stringlets placed behind the plate are consistent with numerical results obtained (Figure 8a): in both cases the flow simply slows as it passes through the plate, but does not re-circulate downstream. The schematic in the upper left-hand corner illustrates the flow in the wind tunnel reconstructed from both the stringlets and wind speed measurements.

The second set of experiments investigates a 50% single porosity plate with smaller perforations. These perforations prevent significant flow through at low $Re_H$ and result in the formation of a recirculation zone behind the plate (Figure 10a). Such conditions replicate more closely the situation for an ejecta curtain, particularly in the upper sections of the curtain near where significant flow through the curtain exists. The maximum flow speed behind this plate when its boundary surfaces are moving is 35% greater than when its boundary surfaces are stationary (Figures 10a and b). Circulation $\Gamma_p$ can be computed along identical curves $C$ enclosing the recirculating zone behind the plate, using the closed line integral

$$\Gamma_p = \oint_C \mathbf{u} \cdot d\mathbf{s}$$

where $\mathbf{u}$ is the velocity vector of the fluid intersecting the
Figure 10. Calculated dimensionless velocity vector, flow speed (see Figures 4 and 7), and streamline contour plot for a 50% porous perforated plate at low $Re_H$ ($Re_H = 100.0$; see Table 1 for definition of $Re_H$), which allows recirculation when its boundary surface is stationary (Figure 10a). When the surface (sides) of this plate is (are) set in motion at twice the incoming flow speed (Figure 10b), the maximum flow speed achieved behind the plate is about 34% greater than that calculated behind the stationary plate. This implies the circulation behind the moving plate has been increased by 34% (see text).
not all of the ejecta is stripped out of the curtain just above
flow will still be decelerated by the local perforations,
face boundaries. While the flow field generated by an ejecta
perforated plate that allows recirculation without moving sur-
ejecta curtain, the increase in the circulation felt by the mov-
motion and hence the strength of the circulation. For an impact
plate surface. This effect increases the height of flow separa-
tion processes dominate the strength of the flow gener-
the hydraulic resistance criteria $\alpha = 10$ (Part 1) given $\phi$,
and the time when the curtain becomes impermeable. A more
precise estimate of $\Gamma$ can be computed by modifying $\Gamma_s$,
and the effects due to energy losses by flow through the curtain,
compressible flow effects and the speed of the curtain bound-
ary surface.

The impermeable curtain length $L$ is readily estimated us-
ing the hydraulic resistance criteria $\zeta_p = 10$ (Part 1) given $\phi$,
$w, d, \rho$, and $\mu$ along the length of the ejecta curtain based
on ejecta scaling rules [e.g., Schultz and Gault, 1979; Housen
et al., 1983], atmospheric conditions, and assumptions on the
ejecta size distribution. This value approximately scales the
flow through a porous plate as if it were a solid plate of
length $L$ (Part 1). The velocity $U$ of the ejecta curtain is well
predicted by the Z-model [Maxwell, 1977; Schultz and Gault,
1979], which describes the position of ejecta excavation as a
function of time.

The time when the curtain becomes fully permeable must
be known in order to estimate the initial circulation of the
curtain-derived vortex that ultimately controls ejecta deposi-
tion. Experiments show that this transition depends upon the
dominant grain size of the target present in the ejecta. For
impacts in coarse sand [Barnouin-Jha and Schultz, 1996, 1999]
is this transition occurs slowly, while for fine-grained
pumice the transition occurs quickly: significant sized holes
are observed through the curtain near the time when crater
growth ceases [Barnouin-Jha and Schultz, 1998]. The rapid-
y of the transition suggests that two processes compete in
determining when the curtain becomes permeable: (1) uni-
form winnowing of ejecta by through flow, (2) Raleigh-

### Table 2. Circulation and Maximum Flow Velocity

<table>
<thead>
<tr>
<th>Plate Setup</th>
<th>$U_f/U_{\infty}$</th>
<th>Circulation $\Gamma$</th>
<th>$U_{\max}/U_{\infty}$</th>
<th>$Re_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perforated</td>
<td>0.0</td>
<td>32.0 m$^2$/s</td>
<td>1.46</td>
<td>100</td>
</tr>
<tr>
<td>Perforated</td>
<td>2.0</td>
<td>42.8 m$^2$/s</td>
<td>1.97</td>
<td>100</td>
</tr>
<tr>
<td>difference, %</td>
<td>-</td>
<td>-</td>
<td>33.4</td>
<td>34.9</td>
</tr>
<tr>
<td>Solid</td>
<td>0.0</td>
<td>34.1 m$^2$/s</td>
<td>1.53</td>
<td>11500</td>
</tr>
<tr>
<td>Solid</td>
<td>2.0</td>
<td>37.1 m$^2$/s</td>
<td>1.66</td>
<td>11500</td>
</tr>
<tr>
<td>difference, %</td>
<td>-</td>
<td>-</td>
<td>8.8</td>
<td>8.5</td>
</tr>
</tbody>
</table>

curve $C$, $ds$ is the length of a line element along $C$, and $t$ is the
unit tangent vector of $C$ [e.g., Panton, 1984]. This circulation
varies nearly with the maximum flow speed, increasing by
33% for the moving boundary case relative to the fixed
boundary case (Table 2).

The third set of experiments considers flow past a solid plate. Laboratory evidence shows that a significant portion of
the ejecta is removed by flow through the portions just above
the impermeable section of the curtain. Wind tunnel tests
showed that the flow field of an ejecta-like plate (whose po-
rosis decreases with increasing height) with impermeable
length $L^*$ is nearly identical to that for a solid plate with an
equivalent solid length $L$ (Part 1). For both these reasons, a
solid plate should provide a good quantitative measure of the
effects of a curtain's moving surface boundaries on its circu-
lation. The numerical experiment reveals that the velocity
(and circulation) behind the solid plate with moving bounda-
daries is about 9% greater than when its boundaries are station-
ary (Figure 11, Table 2).

A solid plate with a moving boundary surface induces a
different flow pattern in front of the plate compared with the
other cases studied. At some distance in front of the plate, the
upward and incoming flow velocities balance each other out
to create a basal vortex (Figure 11b). Such a vortex has actu-
ally been observed in shadowgraphs of an advancing ejecta
curtain in laboratory experiments [Schultz and Gault, 1982]
and in numerical simulations of impacts into the ocean (D.

Summarizing, the numerical experiments indicate that flow
separation processes dominate the strength of the flow gener-
cated in curtain derived-flows while motion along the curtain
plays a second-order role. The results are consistent with pre-
vious assumptions and observations [Barnouin-Jha and Schult,
1996]. Furthermore, the numerical experiments indi-
cate that the moving edges more effectively change the flow
field of the curtain when it allows flow through. Apparently,
flow through the plate reduces its inertia sufficiently that it
readily gains an upward velocity component from the moving
plate surface. This effect increases the height of flow separa-
tion and hence the strength of the circulation. For an impact
ejecta curtain, the increase in the circulation felt by the mov-
ing edges must lie somewhere between the solid and the 50% perforated plate that allows recirculation without moving sur-
face boundaries. While the flow field generated by an ejecta
curtain resembles to first order that of a solid plate, much but
not all of the ejecta is stripped out of the curtain just above
where flow rushes through the curtain. As a result, the pass-
ing flow will still be decelerated by the local perforations,
Figure 11. Calculated dimensionless velocity vector, flow speed (see Figures 4 and 7), and streamline contour plot for a solid plate in turbulent flow ($Re_H = 11,500.0$; see Table 1 for definition of $Re_H$) when its surfaces are (a) stationary and (b) moving upward at twice the incoming flow speed. The maximum flow speed achieved behind the moving plate surface is about 8% greater than that calculated behind the stationary plate. This implies the circulation behind the moving plate surface also increased by 8% (see text). A small but distinct vortex is formed in front of the solid plate that was not observed in the porous plate calculations. It is the result of a balance between the deceleration of the incoming flow by the plate and the shear drag of fluid upward by the boundary surface.
Taylor or Kelvin-Helmholtz instabilities [e.g., Chandrasekhar, 1981]. The above experimental evidence indicates that when the size of pore space in the curtain is large (as in the case of the coarse-grained ejecta) uniform winnowing dominates slowly eroding the curtain top downward. However, when the size of pore space is small, more pressure is exerted on the interface where the atmosphere impinges on the advancing curtain surface, leading to the growth of Raleigh-Taylor or Kelvin-Helmholtz instabilities that would punch holes through the curtain.

A third factor could influence when and where an ejecta curtain becomes permeable: the presence and distribution of large rocks in the ejecta curtain. If these rocks are located in regions of the curtain where their diameter exceeds the thickness of the curtain, impinging atmosphere will deflect locally around these protruding rocks. This deflected atmosphere travels at a greater velocity relative to the impinging atmosphere and could punch holes through the curtain around the protruding rocks. Although the resulting jets are most likely to form in the regions where the curtain is thinnest, these could in some cases lead to erosion at other locations where solid-like rocks exist. The continuous solid-like nature of the curtain could be broken up, possibly disrupting flow separation and vortex formation.

Because commonly cited estimates for block sizes formed during cratering [Gault et al., 1963] are unlikely to exceed the curtain thickness of most large craters. The blocks located well within a curtain will not influence the flow generated by a curtain because the permeability of the curtain is primarily controlled by the hydraulic resistance, which is defined in terms of the curtain’s most common particle diameter \(d\). The large blocks will be important only at the curtain top, where the curtain is thinnest, or after significant time when large amounts of curtain material are eroded away to expose the blocks. In the latter case, the vortex flow should be well established, entraining the fine-grained material away from around the blocks that continue on ballistic paths [Schultz and Gault, 1979; 1982; Schultz, 1992a].

The wind tunnel tests indicate that the circulation will be reduced by 7% due to energy losses associated with flow through the upper semipermeable portions of an ejecta-like plate (Part 1). However, this should overestimate the losses because some winnowing of ejecta will actually occur. Thus the semipermeable circulation \(\Gamma_s\) generated by a real ejecta curtain should be at least

\[
\Gamma_s = 0.9\Gamma_c
\]

More likely,

\[
\Gamma_s = \Gamma_c
\]

The circulation change given by the blunt solid sphere traveling in subsonic flow conditions is very nearly identical to that predicted by the thin airfoil theory. For the blunt inclined ejecta curtain therefore the effect of atmospheric compressibility or curtain Mach number for \(M < 0.8\) also can be predicted reasonably by the thin airfoil theory, to give the compressible circulation \(\Gamma_c\)

\[
\Gamma_c = \frac{\Gamma_s}{\sqrt{1 - M^2}} = \frac{0.9\Gamma_s}{\sqrt{1 - M^2}}
\]

using equation (9). More likely,

\[
\Gamma_c = \frac{\Gamma_s}{\sqrt{1 - M^2}} = \frac{\Gamma_c}{\sqrt{1 - M^2}}
\]

using equation (10).

The effect of the motion of ejecta parallel to the surface of the curtain varies. For the plates where recirculation already occurs, the motion along the plate increases the total circulation \(\Gamma\) by 9% to 33%, depending on whether or not the plate is solid or perforated. These results are for moving surface conditions that most closely resemble those of an ejecta curtain at the time when crater growth ceases. The maximum increase in \(\Gamma\) by motion along the curtain is probably given by the 33% increase computed for the 50% porosity plate with recirculation. For this computation, no ejecta removal is accounted for, and the flow at the plate is laminar (Re \(H = 100\)). Both factors accentuate energy losses associated with porous flow through the plate, thereby enhancing the moving surface wall effect that easily redirects the flow upward. This effect completely overpowers the effect of energy losses due to flow through the curtain when the curtain edges are fixed. Hence the maximum curtain circulation \(\Gamma_{\text{max}}\) at this time can be given by

\[
\Gamma_{\text{max}} = (1.3)\Gamma_c = \frac{(1.3)(1.0)\Gamma_c}{\sqrt{1 - M^2}} = \frac{(1.3)\Gamma_s}{\sqrt{1 - M^2}}
\]

An ejecta curtain, however, remains relatively impermeable along most of its length until the critical value of \(\zeta_{cr}\) is achieved. Above this point, much of the ejecta is stripped away. Furthermore, the flow along its surface is turbulent. Thus the circulation generated by a curtain is more likely given by the minimum circulation \(\Gamma_{\text{min}}\):

\[
\Gamma_{\text{min}} = (1.1)\Gamma_c = \frac{(1.1)(1.0)\Gamma_c}{\sqrt{1 - M^2}} = \frac{(1.1)\Gamma_s}{\sqrt{1 - M^2}}
\]

The roughness (irregularities) of the curtain surface may accentuate \(\Gamma\) by dragging fluid around the curtain more effectively. However, this effect should not be very significant because the flow along the surface of the curtain is turbulent [e.g., White, 1986]. Laboratory data support this assertion [Barnouin-Jha and Schultz, 1996]. Within the uncertainties given, either equation (13) or (14) should provide reliable estimates of \(\Gamma\).

The above-derived equations do have some limitations. First, the Mach number of the curtain must not exceed \(M = 0.8\), and second, the flow speed in the vortex cannot exceed the speed of sound. If this flow speed does exceed this sound speed, shocks will form in the vortex, reducing its circulation. These effects have not yet been incorporated in equations (13)
and (14). Both these factors limit the applicability of the equation (13) and (14) to craters with rim-to-rim diameters of 39 km on Mars, 87 km on Venus, and 33 km on Earth, assuming ambient atmospheric conditions.

5. Concluding Remarks

The wind tunnel and numerical experiments reveal that a relatively accurate estimate of the flow conditions in the curtain-derived vortex can be achieved given the physical properties of the ejecta curtain and atmosphere. Flow separation essentially controls the vortex circulation. Effects due to through-flow energy losses, compressibility and curtain surface motion are second order. The key unknown is how to determine when and where the curtain becomes effectively impermeable as ejecta are winnowed out. In a future study the wind tunnel and numerical results will be combined with cratering [e.g., Schultz and Gault, 1979; House et al., 1982; Orphal et al., 1980] and atmospheric models in order to test against impact experiments, estimates of the flow conditions and time the curtain becomes impermeable [Barnouin-Jha and Schultz, 1999]. When we establish confidence in our approach at small scales, we will apply it at broad scales [e.g., Barnouin-Jha, 1998]. Our approach will allow us to consider realistic atmospheric conditions (i.e., a shock-heated atmosphere recovering from an initial blast, and a naturally occurring atmosphere whose density decays with height).

Estimates of the flow conditions in the curtain-derived vortex should provide a means to determine the entrainment capacity of ejecta by this vortex. This entrainment capacity controls the dusty flow conditions that ultimately determine the manner in which the vortex deposits ejecta. Such an understanding provides a basis for using ejecta run-out and ejecta sinuosity [Barnouin-Jha and Schultz, 1998] to assess atmospheric and target contributions (including presence of volatiles) in the vortex at the time when the curtain becomes permeable.

Acknowledgments. We would like to thank E. Marc Parmentier, Martin Maxey, and Jack Mustard for their helpful comments while preparing this manuscript. Much of this work would not have been possible without J.-C. Tatinclaux, who made it possible to use the wind tunnel facilities at the CRREL. We would also like to thank Buck Sharpton and an anonymous referee whose reviews helped improve the text. This study was made possible by the NASA Graduate Student Researchers Program and NASA grants NAGW-705, NAGS-3877, and NAGW-4979.

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