A NOTE ON JET FORMATION BY EXPLOSIVES WITH LINED TRUMPET CAVITIES

by SAMPOORAN SINGH, *Defence Science Laboratory, Ministry of Defence, New Delhi.*

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Pugh, Eichelberger and Rostoker (1952) presented the nonsteady-state hydrodynamic theory of jet formation by explosives with lined conical cavities. By a simple extension of the above theory, recently Singh (1955) explained the successive stages of collapse, as observed by X-ray flash photography, of lined hemispherical 'shaped-charges'. The present is an attempt to explain jet formation by lined trumpet cavities.

The walls of the trumpet liners are assumed to have a fixed radius of curvature and the centre lies either in a plane through the apex and parallel to the base of the liner (Fig. 1*B*) or in a plane of the base of the liner (Fig. 1*C*). The corresponding conical liner having the same calibre and height as trumpet liners has an apex angle of 2α and is shown in Fig. 1*A*. The radius of curvature of the liners 1*B* and 1*C* is $R\left[=\frac{D}{4}\operatorname{cosec}^2\alpha\right]$, where D is the calibre.

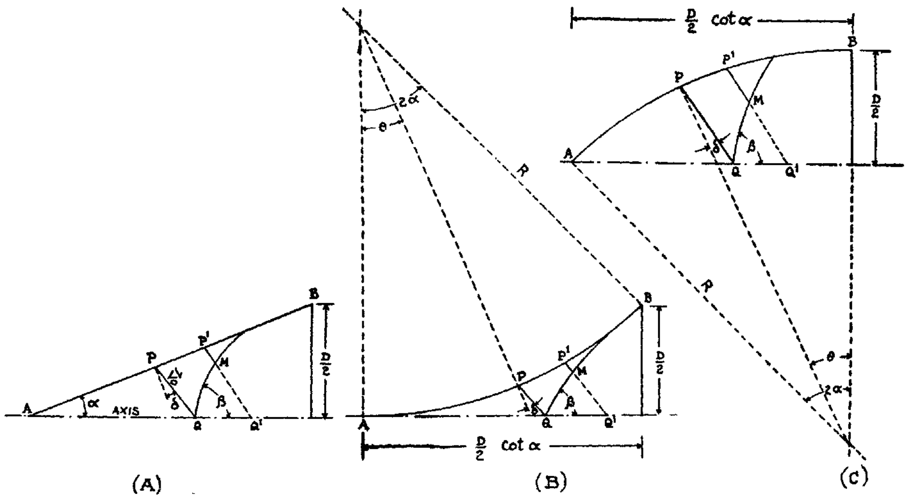

FIG. 1. Cross-sections showing the collapse processes in (*A*) conical liner, apex angle $= 2\alpha$, (*B*) trumpet liner having R as radius of curvature and the centre lies in a plane through the apex and parallel to the base of the liner, (*C*) trumpet liner having R as radius of curvature and the centre lies in a plane of the base of the liner.

Let us consider the trumpet liners to be divided into small elements and each element subtends an angle θ with the axis of propagation of detonation. The angle θ may also be defined as the angle between the plane detonation wave front and normal to the small element. The angle θ varies from (a) O at the apex to 2α at the base in liner $1B$ and (b) 2α at the apex to O at the base in liner $1C$.

As the pressures of detonation are very high compared to strength of metals, so each element could be treated as a perfect fluid. When a detonation wave sweeps from the apex to the base along the liners, each zonal element of mass dm collapses towards the axis with a velocity V_0, which remains constant until the axis is reached. Upon reaching the axis, this element divides into two elements of masses dm_s and dm_j, which proceed along the axis at the constant velocities V_s and V_j respectively.

The individual zonal elements are considered independent of one another and all the relations are derived by applying the laws of conservation of mass, momentum, energy and Bernoulli's theorem to individual zonal elements. The arguments given in the earlier papers (Pugh *et al.*, 1952 and Singh, 1955) then are valid and it can be shown that

$$V_o = \tfrac{1}{4} U_d (1+\sin\theta) \quad \ldots \quad (1)$$

$$V_o = 2U_d \sec\theta \sin\delta \quad \ldots \quad (2)$$

$$V_j = V_o \operatorname{cosec}\frac{\beta}{2} \cos\left(\theta+\delta-\frac{\beta}{2}\right) \quad \ldots \quad (3)$$

$$dm_s = dm \cos^2\frac{\beta}{2} \quad \ldots \quad (4)$$

where U_d is the velocity of detonation of the explosive, δ the angle between the direction of V_0 and the perpendicular to the original element and β the angle which the collapsing liner makes with the axis. The U_d is constant as the detonation wave travels from the apex of the liner to the thin belt of the explosive around the base of the liner.

(*a*) *Jet formation by liner* $1B$.—The position of an element in the parent liner is fixed by a length x ($x=R\sin\theta$) measured from the apex along the axis to the plane of the zonal element. When a detonation wave sweeps from apex to base along the liner, the elements P and P' move towards the axis with velocities V_o and V_0' respectively.

Let T ($T=x/U_d$) represent the time the detonation wave takes in travelling from the apex to the liner element P'; and t the time when P reaches the axis at Q and P' travelling in the direction $P'Q'$ reaches at M. Let the cylindrical co-ordinates of M be (r, z) and the co-ordinates of the original position P' of M in the liner be $[R(1-\cos\theta), R\sin\theta]$. Then

$$z = R\sin\theta + V_o(t-T)\sin A \quad \ldots \quad (5)$$

and

$$r = R(1-\cos\theta) - V_o(t-T)\cos A \quad \ldots \quad (6)$$

where $A = \theta+\delta$. Evaluating $\tan\beta$ by means of (Pugh *et al.*, 1952),

$$\tan\beta = \left[\left(\frac{\partial r/\partial\theta}{\partial z/\partial\theta}\right)_{\alpha,\, t}\right]_{r=0} \quad \ldots \quad (7)$$

we obtain

$$\tan\beta = \frac{\tan\theta + V_o\cos A/U_d + \left(A'\tan A - V_o'/V_o\right)(\sec\theta-1)}{1 - V_o\sin A/U_d + \left(A' + \tan A\, V_o'/V_o\right)(\sec\theta-1)} \quad \ldots \quad (8)$$

where $V_o' = \dfrac{\partial V_o}{\partial\theta} = R\cos\theta\dfrac{\partial V_o}{\partial x}$

and $A' = \dfrac{\partial A}{\partial\theta} = 1 + \dfrac{V_o'\cos\theta - V_o\sin\theta}{2U_d\cos\delta}$

(b) *Jet formation by liner 1C*.—Let us assume that in case of trumpet liner (Fig. 1*C*), the different parameters θ, V_0, V_j, dm_s, x, y, r, z and β have the same significance as discussed above. The quantities V_0, δ, V_j, and dm_s/dm are given by Eqs. (1), (2), (3) and (4). The expressions for x, r, z and β can be derived exactly in the same way and are as follows*:—

$$x = R(\sin 2\alpha - \sin\theta) \qquad (9)$$

$$z = R(\sin 2\alpha - \sin\theta) + V_o(t-T)\sin A \qquad (10)$$

$$r = \frac{D}{2} - R(1-\cos\theta) - V_o(t-T)\cos A \qquad (11)$$

$$\tan\beta = \frac{\tan\theta + V_o\cos A/U_d + \left(A'\tan A - V_o'/V_o\right)(\sec\theta\cos 2\alpha - 1)}{1 - V_o\sin A/U_d + \left(A' + \tan A\, V_o'/V_o\right)(\sec\theta\cos 2\alpha - 1)} \qquad (12)$$

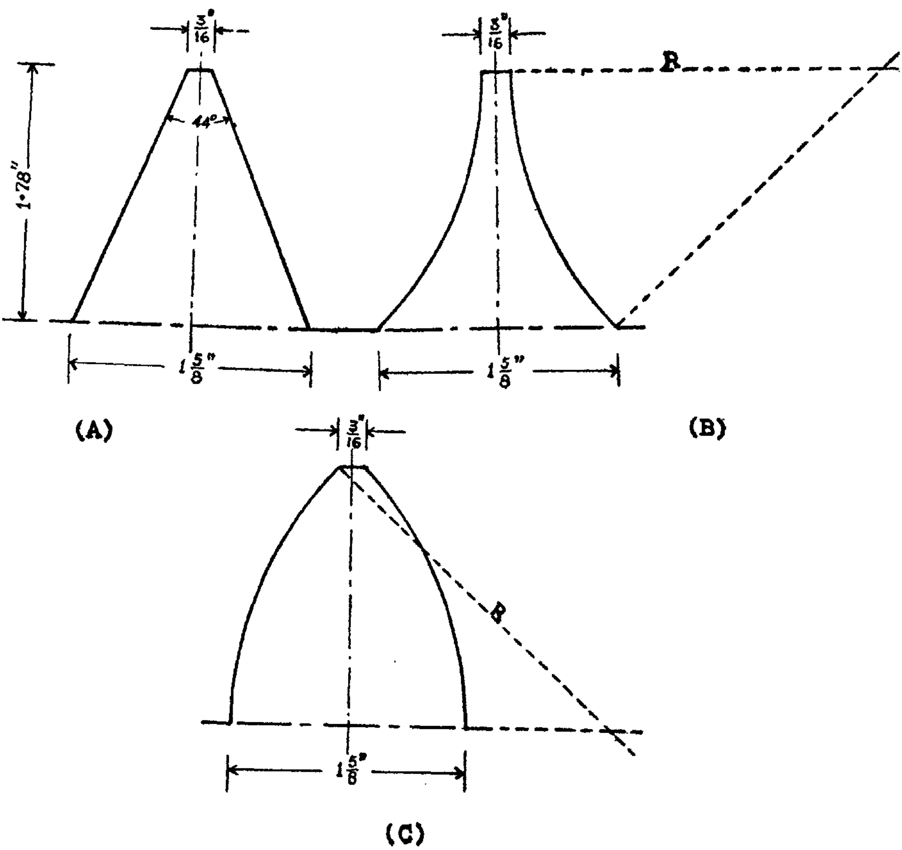

FIG. 2. Cross-sections of conical liner and trumpet liners.

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* A hemispherical liner is a special trumpet liner, where the angle 2α is equal to 90°. On substituting $2\alpha = 90°$ in eqs. (9) to (12), these reduce to the corresponding expressions for hemispherical liner.

where $V_o' = \frac{\partial V_o}{\partial \theta} = -R\cos\theta \frac{\partial V_o}{\partial x}$

and $A' = 1 + \frac{V_o'\cos\theta - V_o\sin\theta}{2U_d\cos\delta}$

The five variables V_0, δ, β, V_j and dm_s/dm are all functions of x or θ.

(c) Eichelberger (1955) published the curves of V_0, β and V_j as functions of x for a steel conical liner (reproduced as Fig. 2*A*) of $1\frac{5}{8}$ in. calibre and an apex angle of 44° ($\alpha = 22°$). For calculations, we take trumpet liners having the calibre and height to be $1\frac{5}{8}$ in. and 1·78 in. respectively, and are shown in Figs. 2*B* and 2*C*. The conical and trumpet liners have a flat apex (in the commercial production of these liners, it is impractical to make liners truly conical down to a pointed apex). From trigonometry in Fig. 2, the expressions for x, $(t-T)$, β, etc., can be slightly modified to take into consideration the flat apex.

Walsh, Shreffler and Willig (1953) showed that when the angle between a wedge is below a certain critical angle, the formation of jet does not take place. The 25° iron collision and 30° iron collision were found to be jetless and jet-forming respectively. In the trumpet liners, the elements having $\theta < 14°$ (elements near the apex in liner 2*B* and near the base in liner 2*C*) do not contribute towards jet formation.

In a trumpet liner, the increasing masses of liner elements and decreasing thickness of explosive from the apex to the base result in the decrease of collapse velocities* from the apex to the base. The resultant V_0 is a function of θ (given by Eq. 1), and mass of the liner element and thickness of explosive; but at this writing, it is not known how the two variables combine to give resultant V_0. As a first approximation, we assume that the resultant V_0 at any x (or corresponding θ) is given by the expression

$$\text{Resultant } V_o = V_o(\theta) - \epsilon(V_{o,1} - V_{o,2}) \quad .. \quad .. \quad .. \quad (13)$$

where $V_0(\theta)$ is given by Eq. (1), $V_{0,\,1}$ and $V_{0,\,2}$ are the values of V_0 published by Eichelberger at the apex ($x = 0\,52$ cm.) and the given x respectively and ϵ is a constant for a given value of θ. ϵ is some function of θ, but in the absence of any experimental data, ϵ is assumed to be unity in these calculations. This means that we are assuming the decrease of V_0 due to increasing masses and decreasing thickness of explosive from the apex to the base to be the same in case of conical and trumpet liners.

The calculated primary penetration (Singh, 1953) by liner 2*B* indicates that the liner is inferior in performance ($\sim 10\%$) to a conical liner, 2*A*, of the same calibre and height. In liner 2*C*, the jet appears to have a constant velocity and the primary penetration is of the order of the slant height of the liner. By static firings of shaped charges having conical and trumpet liners, we have confirmed that the trumpet liners are inferior in performance to the conical liner.

The calculated primary penetrations by different elements at the head of jet from the trumpet liner 2*B* are more than the corresponding elements of jets from the conical liner 2*A*. This, however, suggests the possibility of combining a conical and spherical liner having an overall superior performance to a conical liner of the same calibre and height.

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* This is analogous to collapse velocity gradient in case of conical liner (Eichelberger, 1955), where the collapse velocities for an element near the apex and an element near the base of a conical liner are 2,550 m./sec. and 1,500 m./sec. respectively.

Abstract

The jet formation by explosives with lined trumpet cavities has been explained by a simple extension of the nonsteady-state hydrodynamic theory of jet formation by lined conical cavity charges. It has been shown that the trumpet liners have a poorer performance as compared to a conical liner of the same calibre and height.

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