A new technique for producing high-velocity liquid-like jet

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Abstract
A new technique is presented by which lateral outflows of material , from an oblique impact collision between wax projectile and a rigid surface , are collected to form a high speed single jet. This jet has been shown to be capable of producing cavities in semi-infinite target of wax in a manner similar to that produced in a hypervelocity impact situation. The produced jet capability of penetration is found to be maximum at higher velocities of impact , lower values of standoff and with projectiles having angle of obliquity in the range (β=20-25^o). A preliminary theoretical model is also presented in an attempt to describe the process of jet creation and jet characteristics. The present technique is proved to be promising in simulating penetration of semi-infinite targets by the impact of high speed jet .

Keywords : impact , hypervelocity , penetration , jet , wax .

Introduction :

A high-speed jet is widely used to refer to the well-known energetic jet produced from a shaped charge liner. A typical shaped charge jet may have a tip velocity which exceeds Mach 25 in air , and may be used in cutting , tank defeating , mining , …etc.[1] .

Jets of liquid were also produced for both laboratory and field purposes. Bowden and Brunton[2] used a slug fired from a gun to act as a fast moving piston in order to accelerate a small amount of liquid contained in a small chamber. The liquid was extruded through an orifice of as small as (1mm) diameter . The main function was to simulate high speed impact of liquid jets against solid specimens. On the other hand , liquid jets produced by special pumping devices under pressures of up to (30000psi) or more , are commonly used for boring subway tunnels, coal and ice breaking and tree cutting [3].

The type of jet most relevant to the present work is the so-called sideways (lateral) jetting which is almost produced in an oblique impact between two surfaces. In explosive welding , for example, a high velocity metallic jet may also be created since an oblique collision of metallic plates is also occurring .The jetting material , in the case of oblique collision of two different materials , consists mainly of the softer material[4].

In an oblique impact between two surfaces , the occurrence of jetting depends upon several parameters like the velocity of impact , angle of obliquity, and the physical and mechanical properties of the two impacting surfaces [5].

Even when a liquid drop impinges normally on a rigid surface , a stage of compressible fluid flow where no sideways jetting can occur. Later, when a point is reached and the second stage of releasing the impact waves commences, sideways jetting will take place[6]. The lateral or sideways jetting velocity may be as much as (2–5) times the impact velocity [2,7].

Recently , a series of tests where liquid- like (wax) cylindrical projectiles impact normally on target plate of Aluminum ; limiting values of (V_0 and β) necessary for jetting occurrence were performed[8].

To the authors best knowledge, collection of accidental sideways jetting had never been attempted before; presently, this is achieved and a high velocity single jet is formed by driving negative conical-ended wax projectiles to impact against a plane rigid surface . Moreover, a mathematical model which describes the different stages of the jet creation is also presented to gain a deeper insight of the process .

Analytical model :

Fig.(1A) shows a negative conical-ended projectile of wax just before impacting a rigid plate with velocity (V_0). Because of the conical cavity in the projectile leading end, inwards sheet-like jets emerge from the inner periphery of the contact annulus of the projectile. These jets emerge at the same time, as they should, at some angle (Φ), see **Fig.(1B).** Later , when all of the jets reach a point at the axis of the projectile, they collide, coalesce and then bifurcate ; the one flowing in the same direction of the projectile being the main jet while the one which moves in opposite direction is the secondary jet ,see **Fig.(1C).** The process of jetting and emergence of the main jet is continued till the whole material of projectile forming the cavity is consumed .

Many assumptions have to be made to simplify the mechanics of this complex nature of jet creation . These are :

1-Compressibility effects are neglected .
2-Jetting is confined to the inner periphery of the contact annulus .
3-The projectile is long enough so that the rarefaction waves do not interfere with the incident waves .
4-The whole volume of the conical cavity contributes into the jetting process , and
5-The secondary jet has no effect on the projectile .

Referring to **Fig.(1B)** , the mass flow rate of the inward sheet-like jet can be easily deduced , from considerations of the projectile front geometry and its speed , as :

$$m^0 = \rho . V_o . \pi \left[R^2 - (R - \frac{V_o t}{\tan \beta})^2 \right] \tag{1}$$

This jetting has a velocity given by the sum of the velocity of the contact perimeter and the flow velocity relative to this perimeter [2] , i.e. :

$$V_1 = \frac{V_0}{\tan(\beta / 2)} \tag{2}$$

Moreover , the jetting emerges at an angle (Φ) which depends on the physical and mechanical properties of both the projectile and the impact surface as well as the angle of obliquity (β) .

These jettings emerge simultaneously from the periphery of the contact annulus, and later they collide at a point on the axis of the projectile where they form two circular jets . Because this point of collision is not stationary, it is useful to use a system of coordinates moving with the collision point. In this stationary picture of collision, the continuity equation implies that :

$$m^o = m_m^o + m_s^o \tag{3}$$

whereas the linear momentum conservation equation is :

$$m^o . V_1 . \sin \phi = m_s^o . V_1 - m_m^o . V_1 \tag{4}$$

The mass flow rate of both jets can be determined by solving Eq.s(3) & (4) as follows :

$$m_m^o = \frac{1}{2} m^o (1 - \sin \phi) \tag{5}$$

$$m_s^o = \frac{1}{2} m^o (1 + \sin\phi) \tag{6}$$

Since it is an axisymmetric case of jetting , the main and the secondary jets are of circular cross-section . Moreover, the mass flow rate of the most interesting main jet is equal to :

$$m_m^o = \rho . V_{1} . \pi . r_j^2 \tag{7}$$

Thus, equating Eq.s(5) &(7) with the aid of Eq.(1) yields :

$$r_j = R\sqrt{\frac{1}{2}(1 - \sin\phi)\tan(\beta/2)\left(1 - (1 - \frac{V_o t}{R.\tan\beta})^2 \right)} \tag{8}$$

According to Eq.(8) , the maximum radius of the jet is attained when the contact perimeter reaches the orifice ,i.e at a time (t =T) where :

$$T = \frac{(R - r_o)\tan\beta}{V_o} \tag{9}$$

Thus: $$r_{j\max} = R\sqrt{\frac{1}{2}(1 - \sin\phi).\tan(\beta/2)\left(1 - \left(\frac{r_o}{R}\right)^2\right)} \tag{10}$$

In order to allow for the complete emergence of the jet through the orifice , the radius of the orifice is selected such that ($r_{jmax} = r_o$) and substituted in Eq.(10) to give :

$$r_o = R\sqrt{\left[1 + \left(\frac{1}{2}(1 - \sin\phi)\tan(\beta/2)\right)^{-2}\right]^{-1}} \tag{11}$$

The absolute velocity of the main jet is the sum of its velocity relative to the collision point (V_1) and the velocity of that point (V_c) , i.e. :

$$V_j = V_1 + V_c \tag{12}$$

The velocity of the collision point (V_c) is determined in view of the current concept of jet creation . This point , where axisymmetric jetting meet or collide , is seen to travel in the same direction of the projectile during the impact process . By considering the first and the last locations of the travel of that point , as well as the time taken by that point to travel between these two locations , it can be deduced that :

$$Vc = \frac{R\tan\phi}{\frac{R\tan\beta}{V_o} - \frac{R\sec\phi}{V_1}} \tag{13i}$$

,which can be written using Eq.(2) as :

$$Vc = V_o \frac{\tan\phi}{\tan\beta - \tan(\beta/2).\sec\phi} \tag{13ii}$$

Thus , using Eq.(2) and Eq.(13ii) , Eq.(12) becomes

$$V_j = V_o[\cot(\beta/2) + \frac{\tan\phi}{\tan\beta - \tan(\beta/2).\sec\phi}.] \qquad (14)$$

In the same manner the absolute velocity of the secondary jet is :

$$V_S = V_1 - Vc \qquad (15i)$$

,which can be written using Eq.(2) and Eq.(13ii) as :

$$V_S = V_o[\cot(\beta/2) - \frac{\tan\phi}{\tan\beta - \tan(\beta/2).\sec\phi}.] \qquad (15ii)$$

Experimental work:

The apparatus used in the present work was constructed by Kiter [9] and is presently modified to allow a thick target of wax to be impinged by a high speed jet of wax, see **Fig.(2)**. The jet is created by the impact of negative conical-ended projectiles of wax against rigid plate as shown in **Fig.(3).**

Different projectiles of different angle of obliquity were fired at different velocities against semi-infinite targets standing off at different distances from the upper surface of the plate. The projectiles were made of Paraffin wax of density (ρ=825 kg/m^3); these are (6gr) of mass , (17.8 mm) in diameter and of different angles of obliquity .

Thick cylindrical targets of Crystalline wax of density (ρ=876kg/m^3); these are (104mm) in diameter and (70mm) in thickness .The elastic wave speed in the material of wax was measured using a (sonic viewer) instrument with electro- acoustical transducers . Different frequencies of the transducers were used and values in the range of (1568–1579 m/s) were recorded at a constant temperature of (28 ^{o}C) .

In each test the impact velocity of the projectile is measured using electronic counter timer with a (0.1 microsecond) resolution connected to an R-C circuit . Depth of penetration, diameter and the volume of the crater produced by the jet , are also measured ; all measurements of the experimental program are listed in **Table(1)** .

Results and Discussion :

Penetration cavities were found to be roughly conical in shape and almost of an apex angle less than (90^o) , see **Fig.(3A,B,C)**.

In view of the orifice diameter made in the anvil plate being less than (4 mm) which represents the maximum diameter of the produced jet , a (21 mm) diameter of crater is an evidence that a hypervelocity jet impact has occurred . It is believed that the jet , as it penetrates the target , is deflected laterally and push the target material aside . In doing so , high circumferential stresses are induced in the target which manifest itself by deep radial cracks observed at the rim of the target.

Due to the difficulties associated with measuring the velocity of the produced jet , a lower bound of (1568 m/s) is based on the assumption that a hypervelocity jet s one of a velocity which exceeds the elastic wave speed in the material of wax .

It is important to say that this technique depends largely on the precise dimensions of the projectile as well as the precise normality of impact . Unfortunately a slight deviation may occur in a sudden failure in jet creation and hence target penetration . However, the simple and cheap design of this technique , compared with that of the shaped charge or water cannons , makes it attractive in simulating hypervelocity impact situations.

Although further work is needed on the characteristics of the produced jet, the following results are hoped to give a preliminary picture of the jet produced in this work. **Fig.(5)** shows that the depth of penetration is steadily increasing with increasing of the projectile velocity provided that other parameters (like S and β) are unvaried. This result, although logical in the field of penetration of semi-infinite targets [1,3,10], it still confirms the resemblance of the presently-produced jet with high-speed jets of the shaped charge and other similar jets. Moreover, that the higher speed of projectile produces a deeper crater is also an evidence of a higher speed of jet; an indirect agreement although qualitatively with the widely-cited works in the relation between the impact velocity and the resulting lateral outflow[2,7].

Fig.(5) also manifests the inverse relation between the depth of penetration and the target stand-off values . This relation indicates the similar behavior of the presently-produced jet with other high-speed jets in that they lose their capability of penetration due to spreading or dispersion usually encountered with higher values of stand-off .

It is important to mention that the minimum value of stand-off (15mm) is governed by the thickness of the anvil plate ; should this thickness be reduced , the depth of penetration would be increased as implied by the trend of **Fig.(5)**.

The volume of the craters produced are also plotted in the same way , see **Fig.(6)**. Again the efficiency of the jet to penetrate a semi-infinite target , is increased by increasing the projectile velocity and/or decreasing the value of the standoff keeping of course the angle of obliquity unvaried . The similar behavior of **Fig.(5)** and **Fig.(6)** represents the consistency of the roughly-conical shape of the craters produced by the present jet .

In order to find out the effect of variation of the angle of obliquity on the penetration capability of the jet , the so-called (penetration capability) parameter is proposed . This parameter is simply defined as the volume of crater produced per unit joule of the kinetic energy of the projectile , i.e. ($V/(1/2)MV_o^2$) ; values of this parameter are calculated using the data of **Table(1)** for each test , averaged for each combination of (S and β) , inserted in **Table(2)** and finally graphed in **Fig.(7)** . As shown in this figure , the most capable type of projectile is that which has an angle of obliquity in the range ($\beta = 20^o$ -25^o) for all values of stand-off . Once again , the minimum value of angle of obliquity used in this work is based on the work of Kiter & Salem[8] who found that below a value ($\beta = 20^o$) , the outwards radial jetting is drastically reduced and eventually ceased below a value ($\beta=15^o$) . Of course, the value ($\beta=0$) refers to the flat-ended projectile in which case no jetting can take place, rather an extruded mass of wax of negligible effect on the target, is produced, see **Fig.(3D).**

Conclusions :

The main conclusions that may be drawn are:

1- The present technique succeeded in producing a high velocity jet made by collecting sideways jetting produced in an oblique collision of wax projectile and a rigid plate .

2- The produced jet of wax is capable of penetrating a semi-infinite target of wax and producing conical cavities or craters .

3- The type of impact is classified as a hypervelocity jet impact as suggested by the dimensions of the craters produced .

4-The penetration capability of the produced jet is maximized by increasing the projectile velocity, reducing the standoff distance and using an angle of obliquity in the range ($\beta=20^o$ -25^o).

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Notation :

(D) Diameter of crater
(L_j) Length of the main jet
(m^o) Mass flow rate of radial outflow
(m_m^o) Mass flow rate of the main jet
(m_s^o) Mass flow rate of the secondary jet
(P) Depth of penetration
(R) Radius of projectile
(r_j) Radius of the main jet
(r_{jmax}) Maximum radius of the main jet
(r_o) Radius of orifice
(S) Stand off
(t) Time
(T) Total time for oblique collision
(V) Volume of crater
(V_1) Velocity of radial outflow or jetting
(V_C) Velocity of collision point
(V_S) Velocity of the secondary jet
(V_0) Impact velocity of projectile
(V_j) Velocity of the main jet
(β) Angle of obliquity
(ϕ) Angle of jetting emergence
(ρ) Density of wax projectile

Table(1): Experimental program

β deg	S = 15 mm				S = 20 mm				S = 25 mm			
	V_o m/s	P mm	D mm	V mm^3	V_o m/s	P mm	D mm	V mm^3	V_o m/s	P mm	D mm	V mm^3
20	320	16	15	1040	420	14	13	680	360	8	8.5	170
	665	20	19	2190	680	16	15	1040	640	11	12	460
	750	23	21	2920	940	19	17	1580	920	14	13	680
25	440	19	14	1070	480	13	12	540	290	9	9	210
	620	21	17	1750	570	15	14	850	560	12	11.5	460
	810	24	21	3050	805	18	17	1500	810	15	12.5	680
30	320	17	12.5	770	405	12	10.5	380	330	8	7	110
	560	19	14	1070	710	15	12.5	680	510	10	9	230
	760	22	15.5	1520	925	17	14.5	1030	920	14	11.5	530
35	320	16	11	560	240	11	7.5	170	320	8	5	60
	660	18	12.5	810	570	13	10	370	590	10	7	140
	940	20	15	1300	880	16	11.5	600	920	13	9	300
40	300	14	9	330	240	9	6.5	110	400	7	4.5	40
	750	17	11	590	635	12	8	220	810	11	6	110
	960	18	13	880	915	15	10	430	990	13	8.5	270

Table(2) : Average values of the penetration capability .

β Deg	S = 15 mm	S = 20 mm	S = 25 mm
20	2.25	0.88	0.36
25	1.64	0.81	0.55
30	1.51	0.54	0.28
35	0.98	0.54	0.15
40	0.63	0.33	0.08

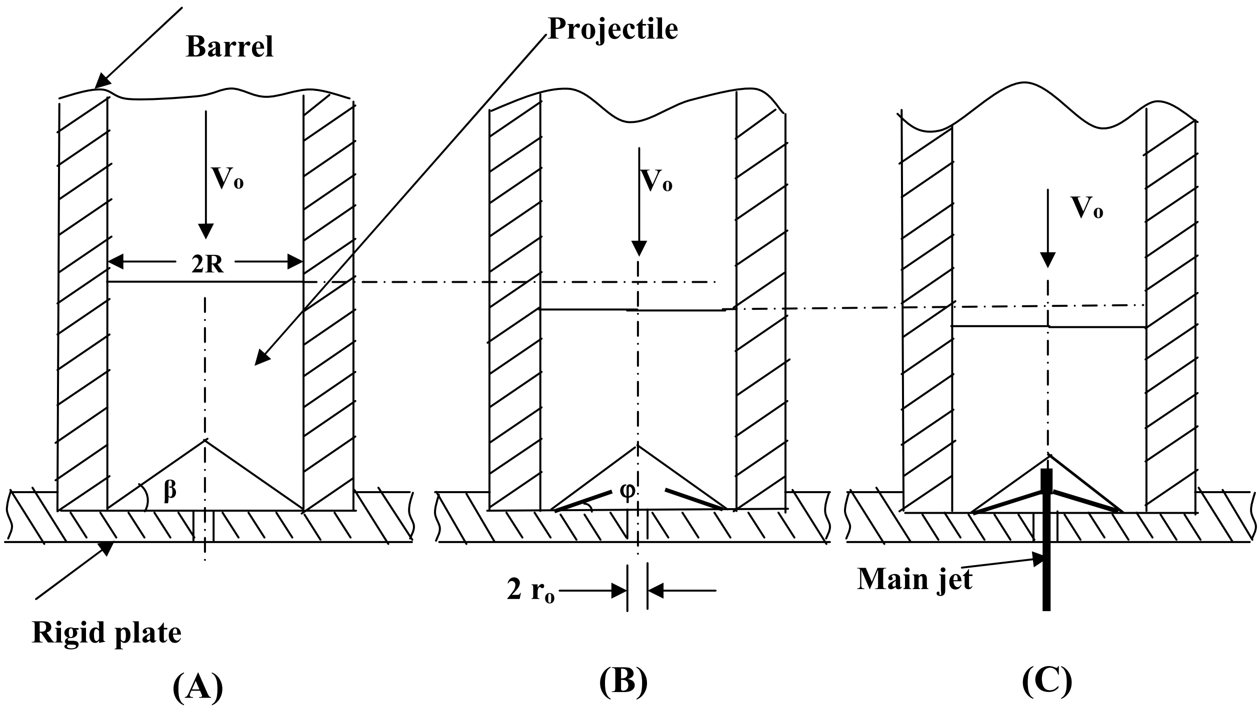


Fig. (1) : The process of jet creation: (A) Instant of impact (t = 0)
(B) Lateral jetting (t > 0) (C) Collision and emergence of the main jet (0< t< T).

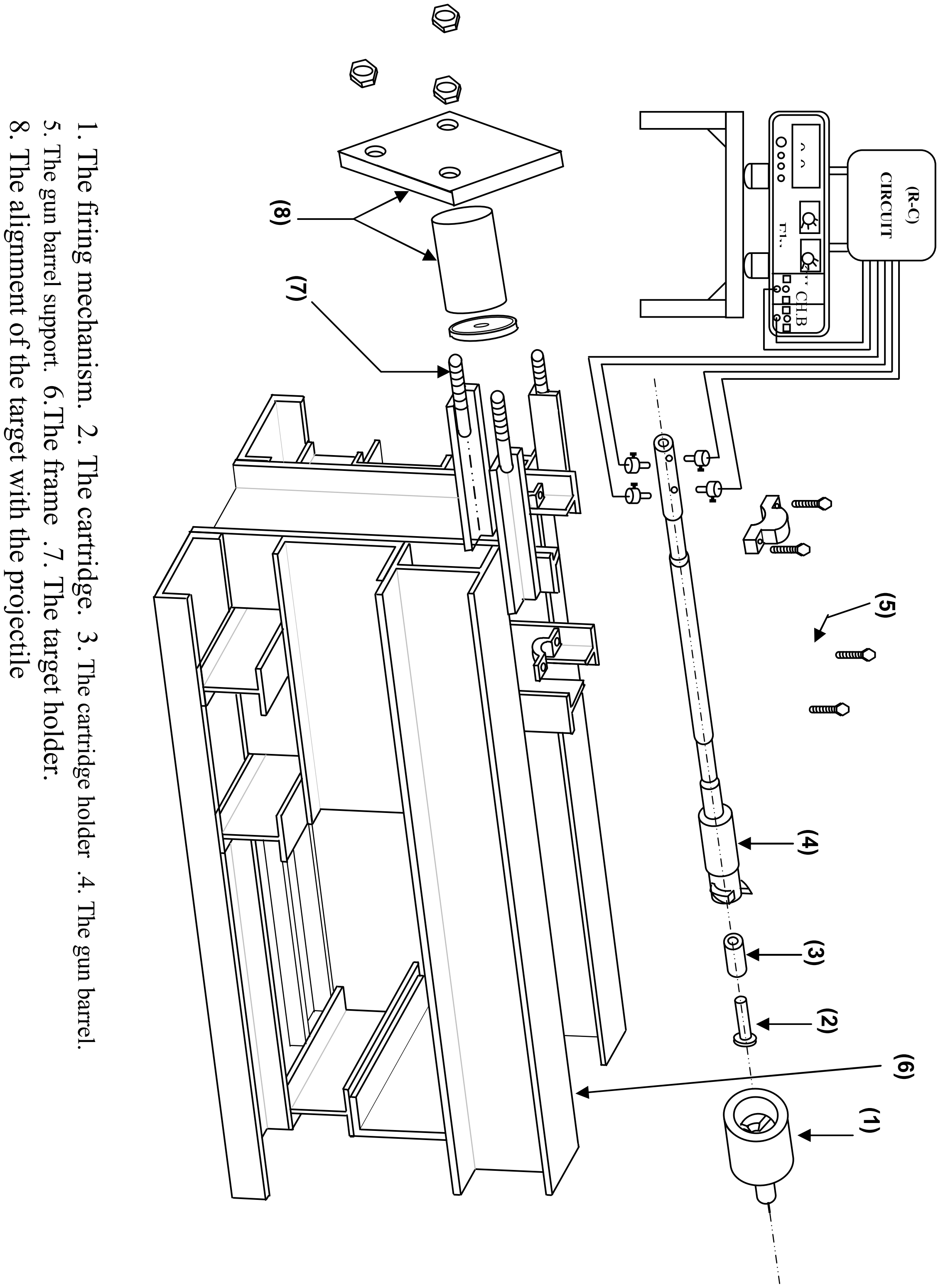


Fig. (2) : Schematic diagram of the apparatus.(Scale:1:7)
1.Firing mechanism 2.Cartridge 3.Cartridge holder 4. Gun barrel
5.Gun barrel support 6.Frame 7.Target holder 8.Alignment parts.

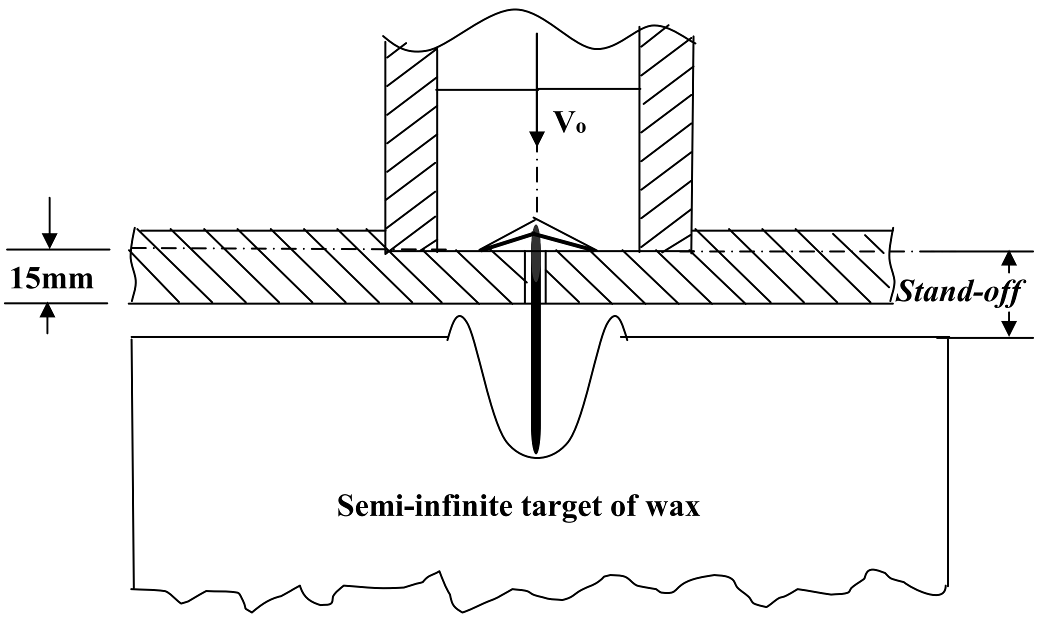


Fig.(3) : Penetration of semi-infinite target of wax by the presently-produced jet .

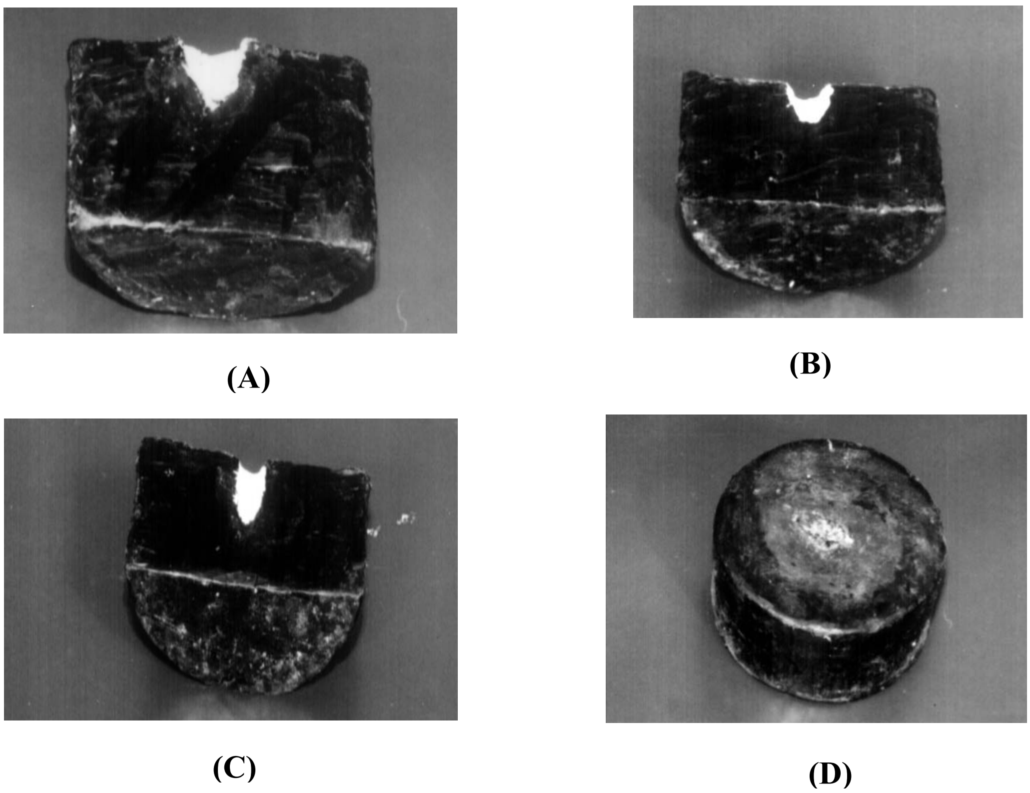
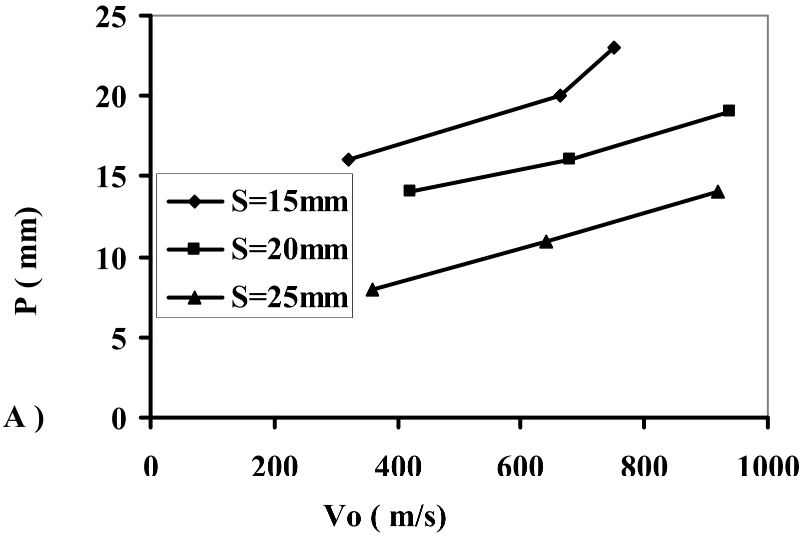
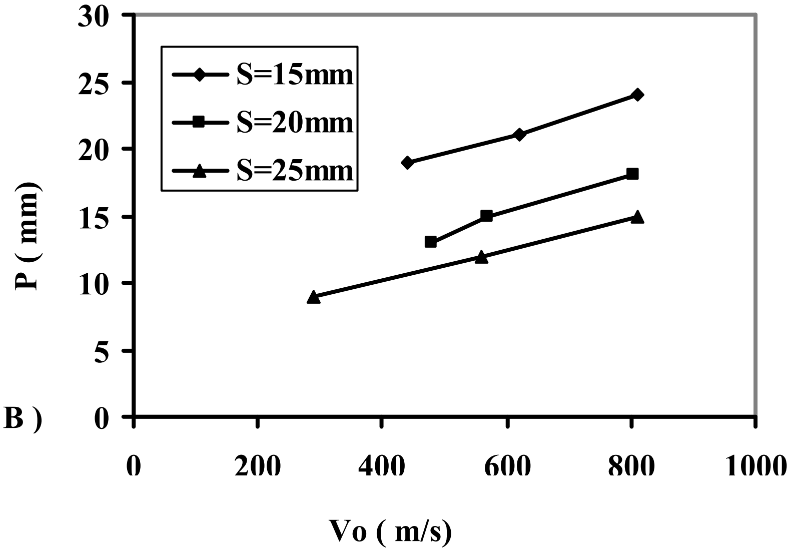


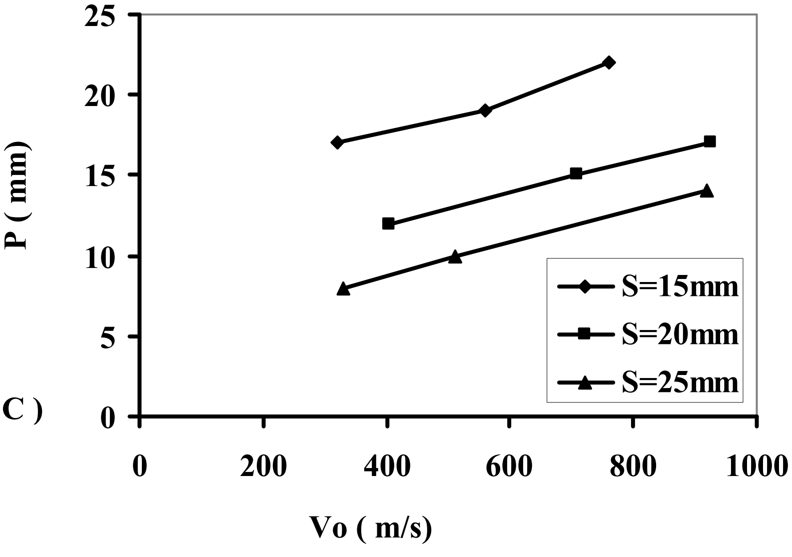
Fig.(4) : Photographs of sectioned impacted targets of wax by the presently-produced jet:
(A) $\beta = 25^o$, $V_o = 810$ m/s , S = 20 mm (B) $\beta = 40^o$, $V_o = 990$ m/s , S = 20 mm
(C) $\beta = 25^o$, $V_o = 810$ m/s , S = 15 mm (D) $\beta = 0$, $V_o = 900$ m/s , S = 15 mm


P (mm)
Vo (m/s)
S=15mm
S=20mm
S=25mm

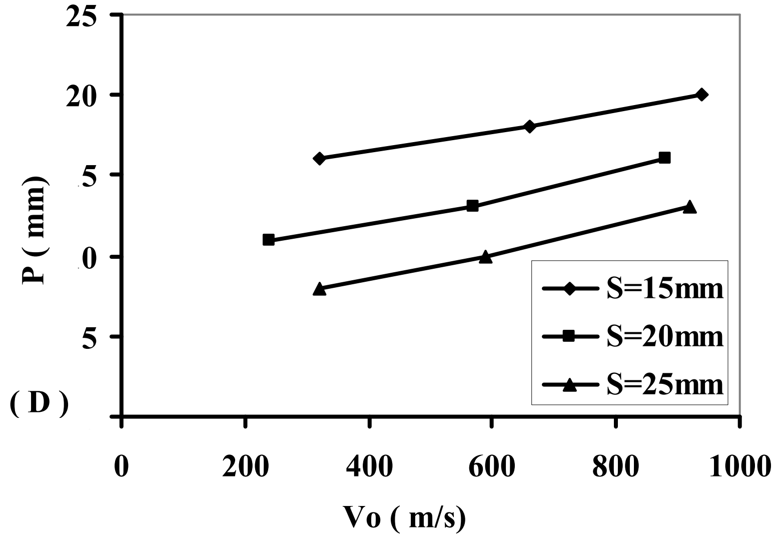
(A)


P (mm)
Vo (m/s)
S=15mm
S=20mm
S=25mm

(B)


P (mm)
Vo (m/s)
S=15mm
S=20mm
S=25mm

(C)



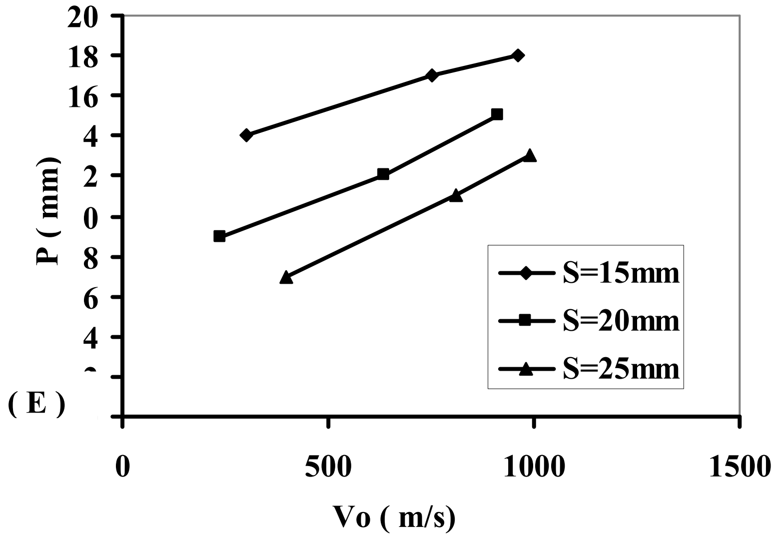
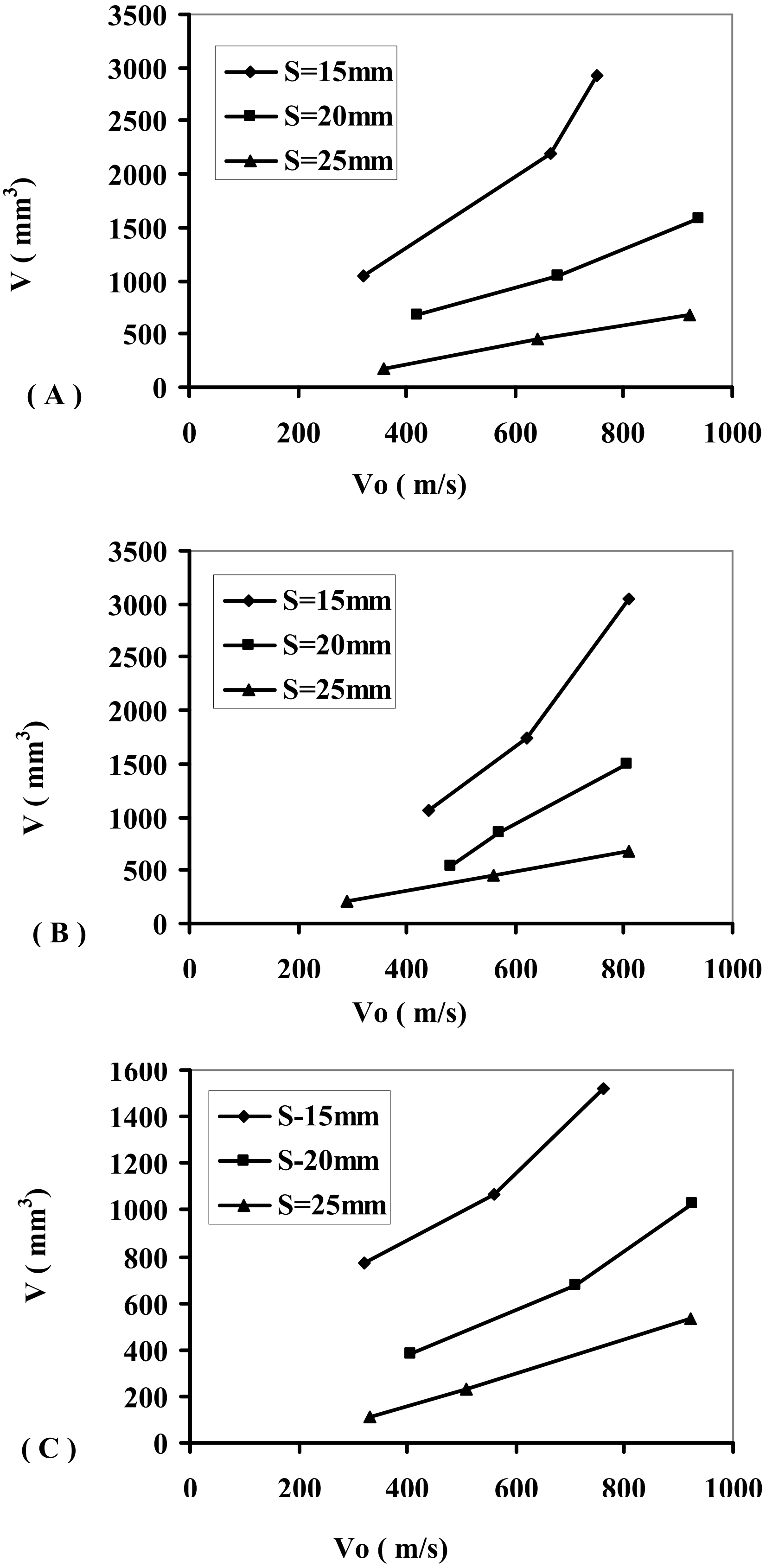


Figure5: The depth of penetration vs. the impact velocity (Vo) for different values of standoff (S) : (A) β =20 ^{o} (B) β =25 ^{o} (C) β =30 ^{o} (D) β =35 ^{o} (E) β =40 ^{o}


3500
3000
2500
2000
1500
1000
500
0
S=15mm
S=20mm
S=25mm
V (mm3)
(A)
0
200
400
600
800
1000
Vo (m/s)
3500
3000
2500
2000
1500
1000
500
0
S=15mm
S=20mm
S=25mm
V (mm3)
(B)
0
200
400
600
800
1000
Vo (m/s)
1600
1400
1200
1000
800
600
400
200
0
S-15mm
S-20mm
S=25mm
V (mm3)
(C)
0
200
400
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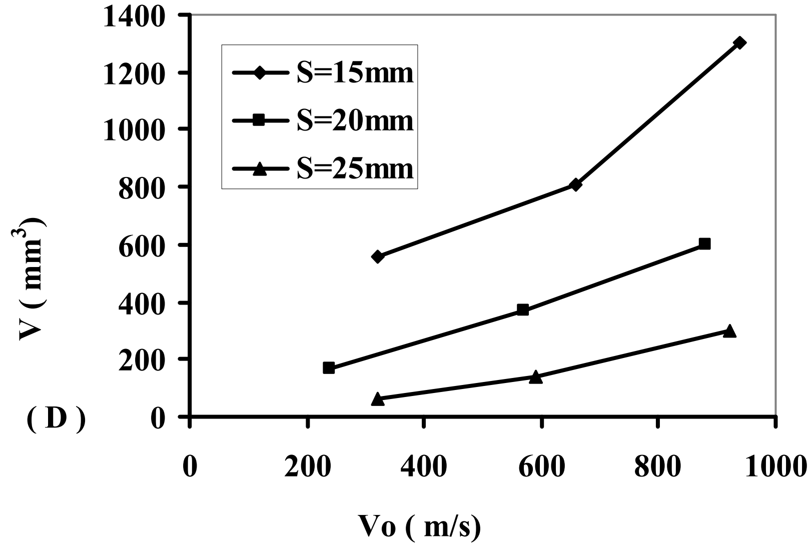
800
1000
Vo (m/s)



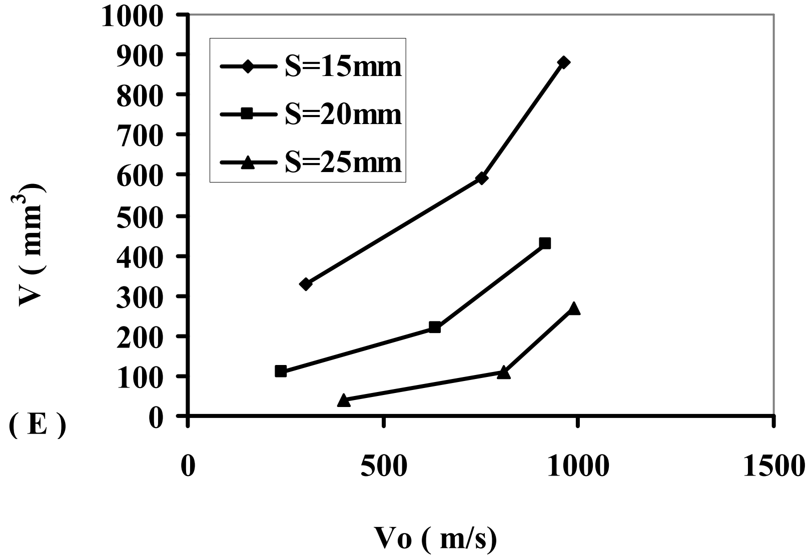


Figure6 : The volume of the crater (V) vs. the impact velocity (Vo)) for different values of standoff (S) : (A) β =20 ^{o} (B) β =25 ^{o} (C) β =30 ^{o} (D) β =35 ^{o} (E) β =40 ^{o}

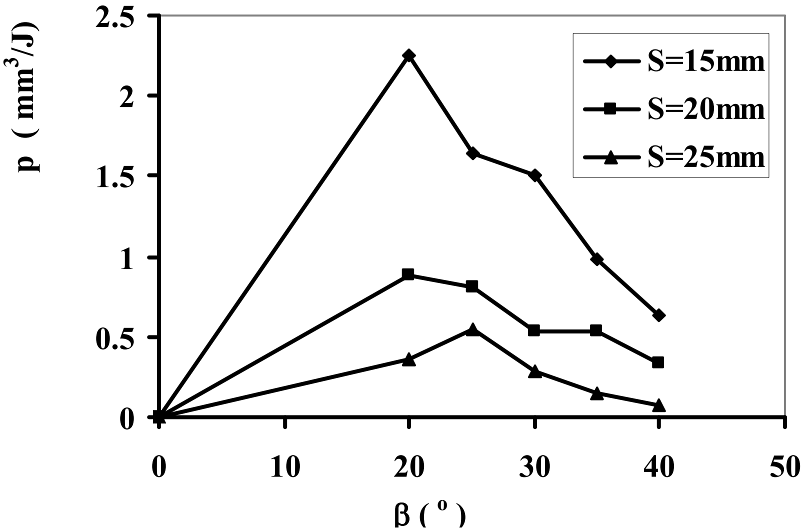


Figure7 : Effect of varying the angle of obliquity (β) on the penetration capability for different values of standoff (S) .

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طريقة جديدة لأنتاج نفث شبيه بالسوائل وعالي السرعة

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الخلاصة :يقدم هذا البحث طريقة جديدة وغير مسبوقة لأنتاج نفث شبيه بالسوائل وعالي السرعة وذلك باطلاق مقذوفات من الشمع ومجوفة مخروطياً من المقدمة وجعلها تتصادم مع صفيحة جاسئة .

وجد ان هذا النفث له القابلية على احداث فجوات في الاهداف السميكة المصنوعة من الشمع ايضاً وان هذه الفجوات شبيهة بتلك التي تنتج عن التصادم فائق السرعة . كما وجد ايضاً ان هذه القابلية تزداد بأزدياد سرعة المقذوفة وتقليل المسافة الفاصلة بين الهدف والصفيحة مع أستخدام تجاويف مخروطية للمقذوفة ذات زوايا (20^{o} - 25^{o}) .

قدم البحث ايضاً رؤيا نظرية تحليلية لوصف عملية انتاج هذا النفث والوقوف على خصائصه . أستنتج ايضاً ان هذه الطريقة واعدة لكي تستخدم في تطبيقات هندسية وخصوصاً في محاكاة التغلغل الحاصل في الأهداف السميكة نتيجة صدمها بنفث عالي السرعة .