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A Study of the detonation wave shape inside confined explosive with a metallic copper liner

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Abstract: The behaviour of shock wave inside a shaped charge is so important that the detonation wave nature characterizes (determines) the degree of jet coherency at the liner interface. The detonation wave shape inside the shaped charge depends on the casing thickness, material, the liner material, geometry and the applied wave shaper geometry. In this paper, a series of numerical simulation models were performed to study the incident and reflected waves and to characterize the resulting shock wave front to evaluate its effect on the produced (generated) jet characteristics. The used code was Autodyn 3D based on non-linear dynamic analysis with jetting analysis model. Inert wave shapers (Lead, Aluminium and steel) and active ones (TNT and PETN) behaviour were studied. The liner type used in this study was copper with in which the apex angle of the liner cone was 40°. It was concluded that the wave front shape has an obvious influence on the characteristics of the jet formation and its properties such as mass of jet and velocities of its tip. Also, the bulk sound speed of the liner itself in addition to the collapse characteristics of the liner was discussed in this paper successfully.
Keywords: Liner, wave shaper, explosive shock wave, jetting, Autodyn code.

1. Introduction

Regarding to the theory of shaped charges, the explosive types and its energy affect the performance of the jet formed and its penetration-ability in addition to the type of the liner and its characteristics [1-3]. Several different energetic materials could be used for the charge filling [4, 5]. Trinitrotoluene (TNT) is one of the most useable explosive for filling of charges by casting method [6]. In addition, it might be used in mixture with other explosives to increase the penetration performance of the charges [7]. Different high energy materials can also be used such as pentaerythritol tetranitrate (PETN) and other advanced high performance explosives [8-10]. Therefore, it is essential to do the best use of the explosive mass by modifying the detonation wave at the interface of the liner wall [1]. The detonation wave head could be modified by placing of inert or active space part in the explosive itself [11]. This spacer can be placed in the explosive charge itself under the initiation point of the charge where it has the ability to delay the detonation wave head. This space part is named as wave shaper or explosive lenses [11]. The wave shaper is also used to decrease the head height of the hollow cavity by modifying the shock wave over short distance travel. Changing the incident angle of the DW could be performed and cause obvious change of the jet properties [12]. The successful and effective wave shapers that have been used were plastics, ceramics, metals and concrete [12].

The detonation wave moves in hemisphere shape inside the explosive charge where these hemispheres smoothly propagate through the whole explosive charge without any deflection away from the explosive boundaries and a metallic confinement. The coherent jet could be enhanced by

decreasing the collapse angle of the liner which depends mainly on the angle lies between the detonation wave front and the wall of the liner [13].

In this paper, several models of shaped charge models were studied and analyzed applying a selected hydro-code named Autodyn. The geometry of wave shaper in addition to the type of its material was studied. The effect of different parameters; tip velocity, collapse angle and the angle of its collapse in addition to the material of the confinement on the jet formed were investigated.

The used shaped charge in this study is a small caliber of 40mm outer diameter and a copper liner of uniformed thickness of 1.4mm and HMX explosive material of density of 1.8 g cm^{-3}. Steel was used as casing for the charge with 6mm thickness.

2. Description of the Studies Parameters

The influence of the shape of the detonation wave on the characteristics of jet produced is studied by changing the following parameters:

2.1. The wave shaper (W.S.) geometry

The time delay of detonation wave arrival until touching the liner material is so important that the produced jet velocity and its coherency is dependent upon the applied wave shaper configuration.

In this paper, four different wave shaper geometries applied inside the high explosive charge were tested as a time delay and so as the produced jetting characteristics such as jet tip velocity, flow velocity and collapse angle. These wave former shapes are cylindrical disc of thickness 3mm and 5mm radius, the hemispherical disc is of radius 5mm, arc disc of radius 7.5mm and inclined plate are used. The shaped charge configuration without wave shaper and its interior detonation wave is illustrated in figure 1; while other W.S. of different geometries and their detonation wave shape are illustrated in figures 2-5. The material of these wave lenses is Aluminium of density 2.7g cm^{-3}.
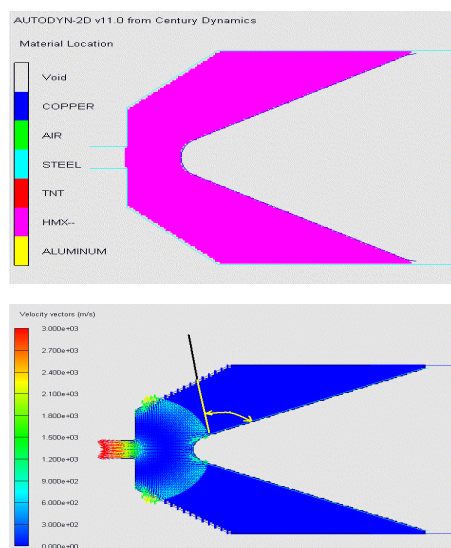

Figure 1. The tested shaped charge without wave shaper (top) and SW propagation inside the explosive (bottom)
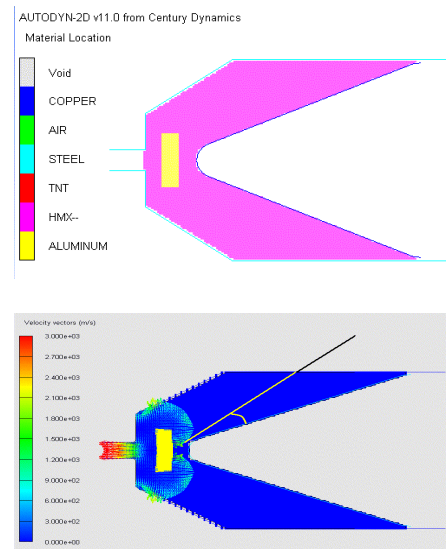

Figure 2. The tested shaped charge Al disc (top) and its SW propagation inside the explosive (bottom)

2.2. The wave shaper material (Al, lead steel, TNT and PETN)

One design of wave shaper is used to investigate the effect of different materials on the performance of this shaper on the jet characteristics. The used shaper is the inclined one using the different inert materials (Al, lead and steel) and Active explosive materials (TNT and PETN). The post detonation jet

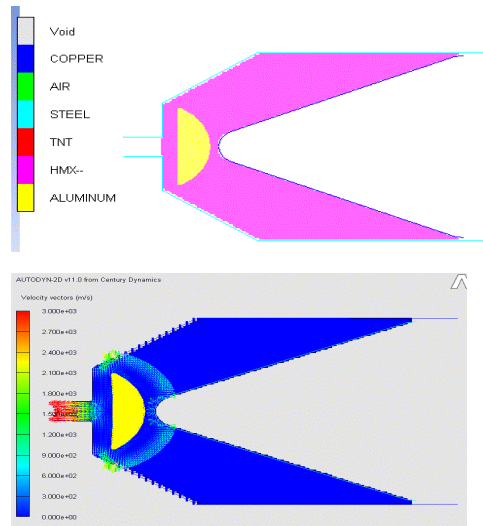characteristics are considered to compare between the produced jet properties for these different materials.

Figure 3. The tested shaped charge Al hemisphere (top) and its SW propagation inside the explosive (bottom)
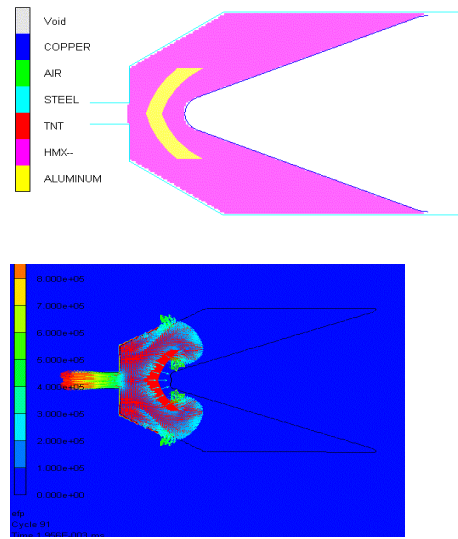
Figure 4. The tested shaped charge Al Arc disc (top) and its SW propagation inside the explosive (bottom)

2.3. The thickness of the shaped charge confinement

The shaped charge should have confinement of thin thickness (nearly 10% caliber of the charge[1]) made from light materials such as Aluminum or composite materials; but in case of oil perforation; the casing material should be thick and made from heavy materials such as steel in order to endure the downhole severe pressure and temperature conditions [14]. In this study, different models of jetting were studied using shaped charge of uniform liner thickness of 1.2mm with a cone apex angle of 40mm to determine the jet formation characteristics.
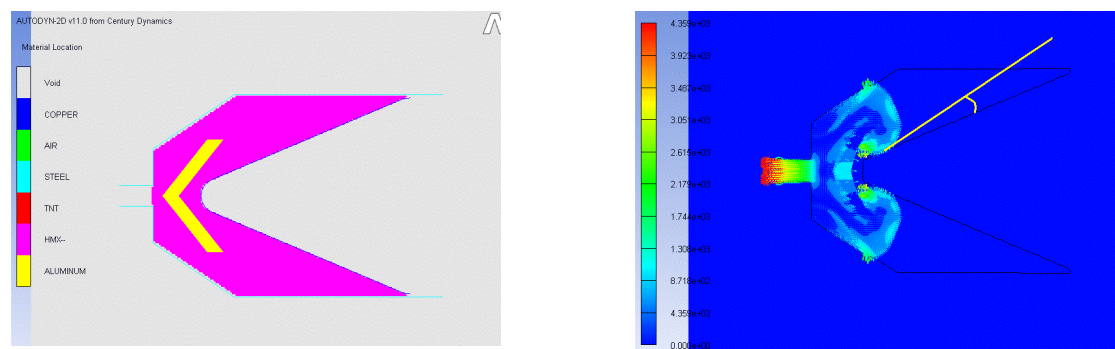

Figure 5. The tested shaped charge with inclined Al disc (left) and its SW propagation inside the explosive (right)

3. AUTODYN-3D code

The AUTODYN-3D program is non-linear dynamic analysis software developed by Century Dynamics. The program is general-purpose engineering software package that uses finite difference

technique for solving a wide variety of non-linear problems in solid, fluid and gas dynamics. This code is used to simulate the jetting phenomenon of designed shaped charge. It can predict velocity, cumulative jet mass, collapse angles, time of jet formation, particulization time, and jet mass characteristics.

Autodyn-2d-3d version of the numerical finite difference code Autodyn (AD), has a built in jetting routine which is coupled to the code in which PER –type calculation is performed when the collapse of the liner is complete [15, 16]. Lagrangian or Eulerian grids were applied to model the explosive charge while the liner was modeled as a shell in which specified mass points are used "jetting" points. A Lagrange grid was used to model the charge and wave shaper and shell segments were used to model the steel encasement. After the jetting of the specified points on the liner is complete, a history of the standard jetting analysis data is obtained together with the well known fitting curves such as cumulative jet mass and collapse angle with liner elements and liner initial position.

4. Results and discussions:

4.1. Wave shape geometry:

The jet characteristics data for the four different wave shaper configurations are listed in table 1. It was found that the jet mass for the five shaped charges is nearly constant but there is a significant difference in the velocity of the jet tip of these configurations. The shaped charge with an inclined W.S. configuration shows the highest tip velocity because the detonation wave around this barrier has been shaped to meet the liner wall with a very narrow angle between the normal to wave front and the liner wall. This angle is about 20° when the wave starts to meet the liner. The W.S. effect also appears when the collapse angle of the jet is considered. The minimum collapse angle in this configuration is 24° while it is 27.5^{o} in the case when Al disc W.S. is present. Therefore, a more coherent jet with higher tip velocity is expected when the inclined W.S. element is used.

Table 1. The different W.S. configurations jetting results of conical liner wall thickness of 1.2mm and cone apex angle 46° with HMX main explosive charge

Wave shaper Geometry	Al-Disc	Hemisphere	Arc disc	Inclined
Jet tip velocity (m/s)	6587.2	6703.4	6601.6	8808
Jet mass (g)	3.6157	3.5789	3.586	3.591
Jet K.E (kJ)	39.979	38.541	40.346	41.027
Min. Collapse angle B (deg.)	27.5	26.1	26.5	24
Max flow velocity (m/s)	3083	3151	3095	4190

Figure 6 illustrates an abnormal jump in the jet flow velocity near the apex angle of the cone, this may be attributed to the very narrow angle between the normal to wave front and liner wall in case of inclined W.S., which in turn accounts for the increase in the jet tip velocity in figure 7. The collapse angle of the inclined W.S. Figure 8 also indicates small angles close to the apex after which the collapse angle of the different shapers nearly have the same pattern.
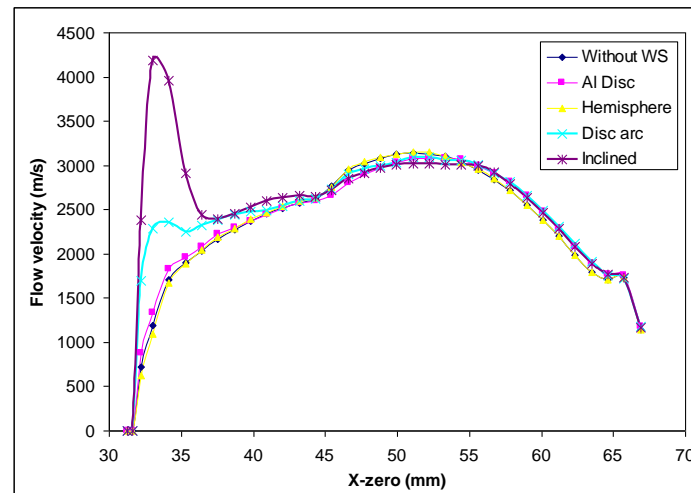
Figure 6. The flow velocity of different W.S. with initial x-position of the liner
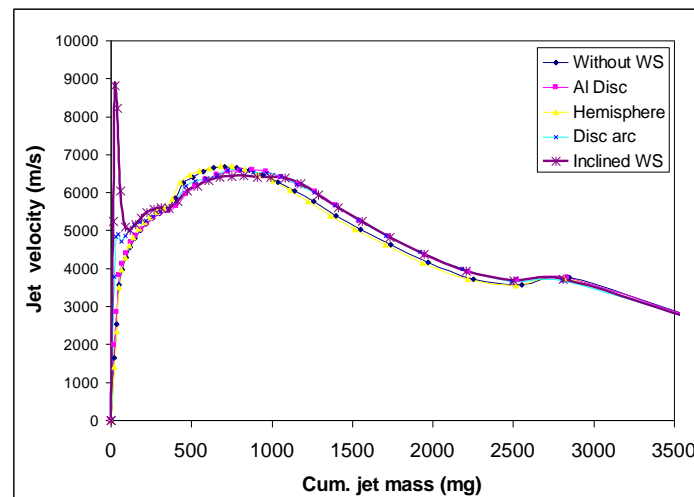

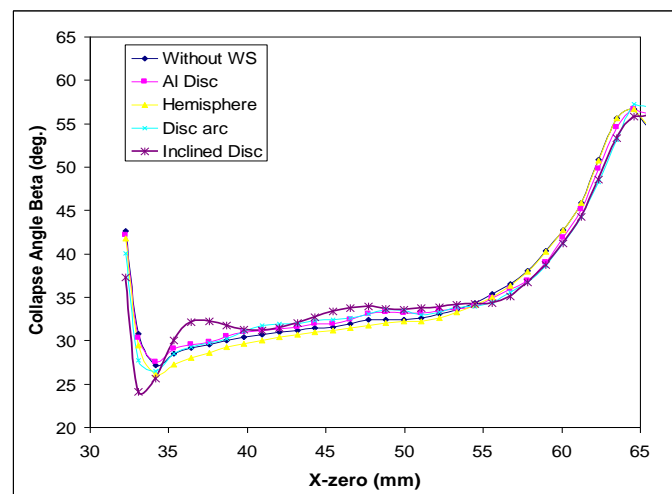**Figure 7.** The jet velocity of different W.S. with cumulative jet mass

Figure 8. The collapse angle of the jet of different W.S with
initial x-position of the liner

4.2. Wave shaper material

Table 2 lists the jetting output data for different W.S. materials. The inclined WS configuration is used with both active and inert W.S. tested shaped charges. It was found that Al W.S. is better than Lead and steel in the produced jet velocity but the collapse angle is greater than those of the Lead and steel. This means that the coherence of the jet in case of steel and Lead W.S. is better than that of Al W.S. but the relevant kinetic energy in case of Al is much higher than that of the others. Hence the predicted penetration depth is higher in case of Al W.S. The reason why the Al WS exhibits the best performance may be attributed to shock parameters where the detonation wave speed in case of Al is much lower than that of Lead and Steel, therefore the elapsed time for a shock wave to pass through Al barrier may be smaller than that of the two others.

The effect of explosive is also obvious in both shapers TNT and PETN. Both of these shapers resulted in much faster jet than without WS. The reason is the difference in the detonation velocity between these explosives and main charge HMX explosive. The detonation velocity of the three high brisant explosives TNT, PETN and HMX ($\rho=1.89$ g cm^{-3}) at the previously mentioned densities are 6930, 5170 and 9110 m s^{-1} respectively.

Table 2. The jetting output data for different W.S. materials of inclined configuration of conical liner wall thickness of 1.2mm and cone apex angle 46° with HMX main explosive charge

Wave shaper Material	Inert			Active (Explosive)	
	Al ($\rho=2.8$ g cm^{-3})	Lead ($\rho=11.35$ g cm^{-3})	Steel ($\rho=7.8$ g cm^{-3})	TNT [17] ($\rho=1.63$ g cm^{-3})	PETN [18] ($\rho=1.7$ g cm^{-3})
Jet tip velocity (m s^{-1})	8808	6570	6535	9872	9408
Jet mass (g)	3.5914	3.481	3.53	3.631	3.583
Jet K.E (kJ)	41.027	39.74	40.144	41.52	40.94
Min. Collapse angle B (deg.)	24	22.57	23.73	24.3	23.244
Max flow velocity (m s^{-1})	4190	3083.7	3068.8	4680	4485

4.3. Casing thickness effect

The jetting output data for the studied casing thicknesses effect on the jet characteristics are listed in table 3. This effect of casing material on the jet characteristics is attributed to the reflected detonation waves on the casing surface inside the explosive itself, which meet the liner with different incidence angles between the detonation front and liner wall axis.

The subsequent reflected waves from the casing surface can produce regions of high pressure on the liner surface resulting in a jet with higher tip velocity [19]. This was verified by adding 7 gauge points to the shaped charge, shown in figure 9. It can be observed that both the obtained pressure-time histories shown in figure 10-a,b for the two cases (i.e. 1 and 8mm casing thicknesses) have nearly the same pattern However, the impulse-time history in figure 11-a,b explained the reason why the jet tip velocity for 8mm case is higher than that for 1mm case. This velocity is preferred to be as much as

possible provided being under a certain critical value defined by Mach limit. The Mach number limit for the coherent jet is calculated according to the equation [20]:

$$Ma = \frac{v_f}{c_o} < 1.23$$

where v_f is the flow velocity of the jet and c_o is the sound speed in the liner material.
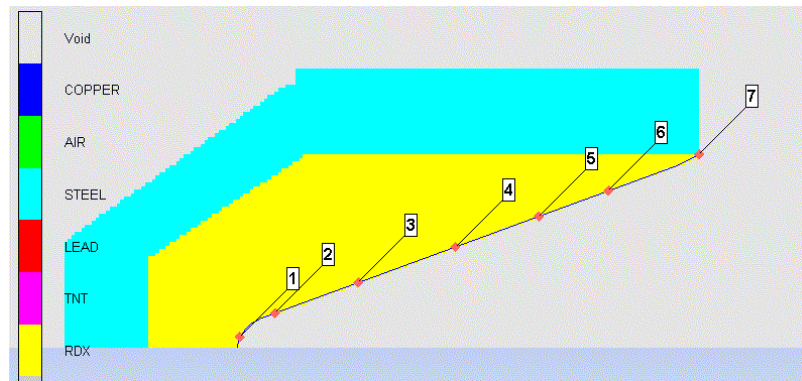

Figure 9. Different fixed target points along the liner axis to predict the p-t history of the DW inside the explosive charge using 8mm casing wall thickness

The Mach limit velocity of the copper material (v_f) is 4676 m s^{-1}. So, all the resulting jets are coherent because their collapse velocities are lower than the Mach number limit for the coherent jet calculated from bulk speed of sound of the copper material which is 3940 m s^{-1} [20] while the maximum collapse velocity for the highest velocity tip of casing 8mm model was 3748 m s^{-1}.

Table 3. The jetting analysis data obtained from the jetting analysis of OWP using RDX main charge with 1.4mm liner wall thickness and 40° cone apex angle and different confining thickness

Wave shaper	Casing thickness				
Casing thickness	1mm	2mm	4mm	6mm	8mm
Jet tip velocity (m s^{-1})	6489.4	6540.3	6790.5	7035.5	7232.8
Jet mass (g)	5.6449	5.6601	5.693	5.718	5.7567
Jet K.E (kJ)	35.6	39.1	43.3	49.2	54.1
Min. Collapse angle B (deg.)	22.42	22.42	22.42	22.42	22.42
Flow velocity (m s^{-1})	3115.4	3213.8	3549.3	3671	3748.1

Figure 12 illustrates the profile of flow velocity with the initial liner element position. This means that all the selected casing thicknesses are suitable to produce a coherent jet. But, an optimization for this casing should be done in accordance with the lowest casing thickness that is capable of confining the oil well perforators (OWP) explosive charge and protecting it against premature explosion. Both the jet velocity with cumulative jet mass; figure 13 and collapse angle with the initial liner position; Figure 14 exhibit the same pattern for the different casing thicknesses although a significant difference between them illustrates how much the casing thickness will affect the jet characteristics.
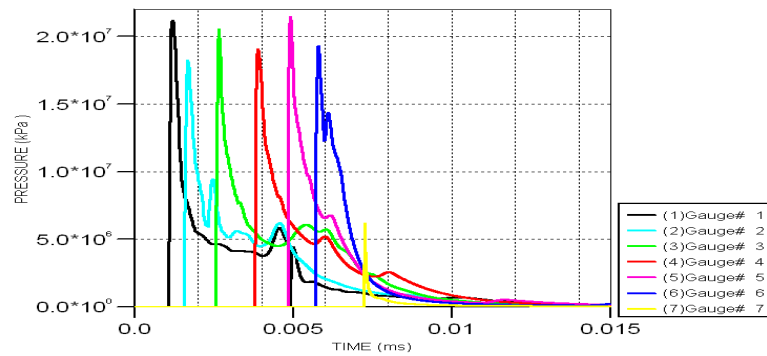
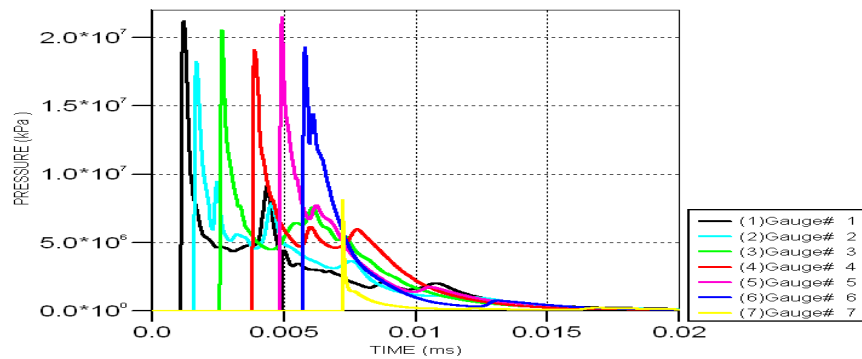**Figure 10 (a)** P-t history of OWP with 1mm casing thickness

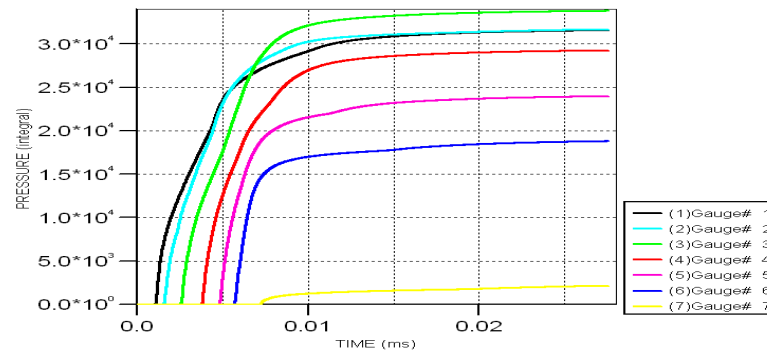
Figure 10 (b) P-t history of OWP with 8mm casing thickness

Figure 11 (a) Impulse –t history of OWP with 1mm casing thickness
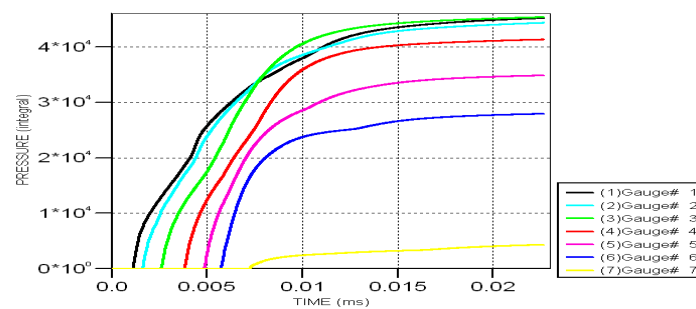

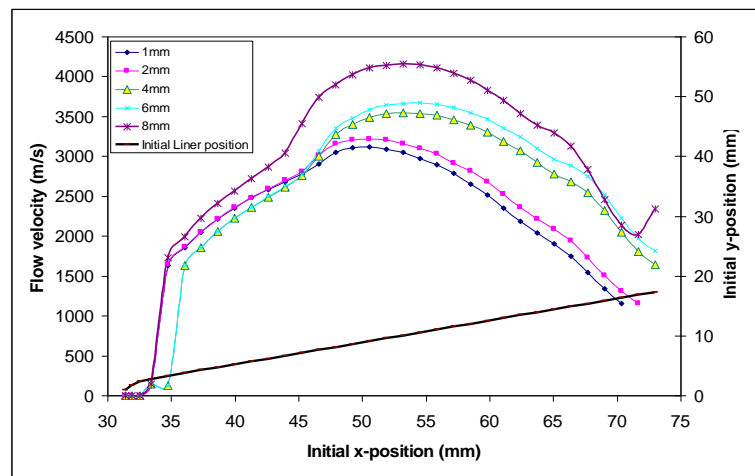**Figure11 (b)** Impulse –t history of OWP with 8mm casing thickness

Figure 12 The flow velocity of different casing thicknesses with initial x-position of the liner
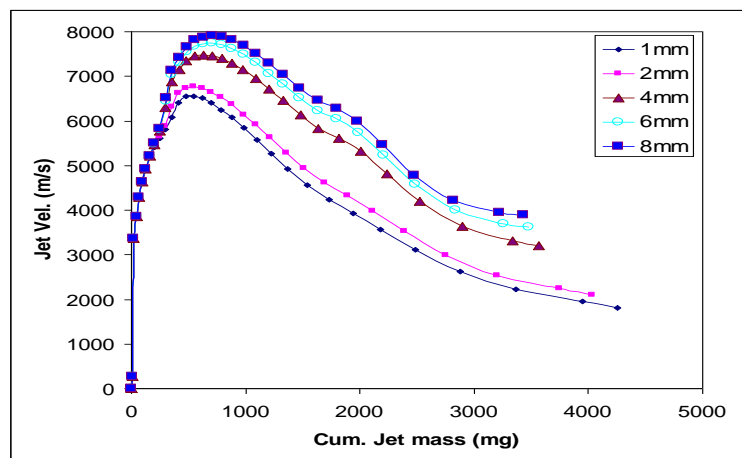

Figure 13 The jet velocity of different casing thicknesses with cumulative jet mass
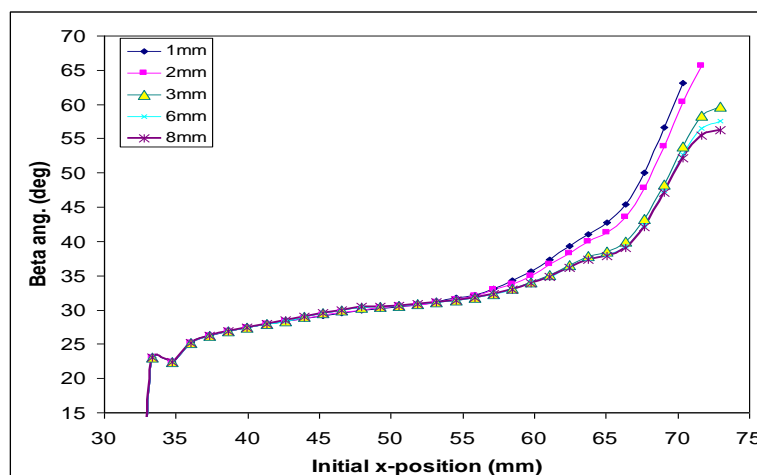

Figure 14 The collapse angle of the jet of different casing thicknesses with initial x-position of the liner

5. Conclusion

From the above work analysis including the W.S. geometry, material, and the shaped charge confinement thickness, the following conclusions have been drawn:

- The effect of the applied waver on the produced jet is not only attributed to the time delay; but also to the shape of the detonation wave where a narrower angle between the wave front normal and the liner wall will produce a faster jet, hence increasing the jet velocity.
- The casing material thickness has a significant effect on the formed jet characteristics such as jet tip velocity and its kinetic energy, therefore the predicted penetration capability of this jet with a thick confinement is predicted to be much higher than that with a thin confinement.
- The jet collapse angles for the tested casing thicknesses charges have nearly the same pattern and the same minimum collapse angle at the apex but at the region close to the liner base, a significant difference appears where the thick confinement produce narrower angles than that with thin confinement. Hence a better coherent behavior for the thick confinement shaped charge is observed.
- The W.S. effect is improved by imploding an explosive barrier such as TNT and PETN. The difference in the main charge and W.S. detonation velocity will create   a two velocity gradients jet which could be effective to open holes in rock to connect the well bore to oil reservoir when the shaped charge is used as oil well perforator.

6. References

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