SIMULATIONS OF HYPERVELOCITY IMPACTS WITH SMOOTHED PARTICLE HYDRODYNAMICS

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ABSTRACT

This paper is devoted to the results of Smoothed Particle Hydrodynamics (SPH) simulations of high velocity impacts on thin aluminium plates using LS-DYNA computer code. The numerical results of the damage produced on plates are compared with experimental data. Two simulations are presented :

- An aluminium sphere impacting an aluminium plate at 6.64 km/s
- A steel sphere impacting an aluminium plate at 5.53 km/s

Experimental and numerical results are in good agreement.

INTRODUCTION

The risk of collision between spacecraft and orbital debris is more and more important. The size of the most numerous fragments ranges from 1 to 10 mm. The velocity of orbital debris can reach 15 km/s.

Today, no experimental features are available for such a velocity. Only simulations can be used to understand the events and design shields.

Few years ago, a new numerical technique emerged : Smoothed Particle Hydrodynamics. Matter is represented by particles connected with internal forces. This method is naturally adapted for large deformations.

To assess this method in the case of hypervelocity impacts, several simulations have been performed, based on publications in the open literature.

First, SPH algorithm is briefly described. Then, two simulations of hypervelocity impacts are described and compared with experiment results: the first one is an aluminium sphere on aluminium plate impact at 6.64 km/s ; the second one is a steel sphere on aluminium plate impact at 5.53 km/s.

SPH METHOD

If we consider a function f defined on a domain Ω, we can approximate with a function $\langle f \rangle$ defined by :

$$\langle f\rangle(x) = \int_\Omega f(y)\; W(x-y,h)dy$$

is a smoothing function which has the following properties :

$$\int_\Omega W(x,h)dx = 1 \qquad (4.14)$$

$$W(x,h) \xrightarrow[h\to 0]{} \delta_x$$

δ_x is the Dirac distribution h is the smoothing length.

Particle methods are based on quadrature formulas on moving particles ($\underline{x}_i(t)$, $w_i(t)$) where $\underline{x}_i(t)$ is the position of the particle and $w_i(t)$ the weight. We can approximate a function f with the following expression:

$$f(\underline{x}) \approx \sum_{j\in P} w_j(t) f(\underline{x}_j) W(\underline{x}-\underline{x}_j, h)$$

We can demonstrate the relation :

$$\nabla\langle f\rangle(\underline{x}) = \langle \nabla f\rangle(\underline{x})$$

∇f and $\nabla\langle f\rangle$ are respectively the gradient of f and the gradient of $\langle f \rangle$. We have :

$$\nabla\langle f\rangle(\underline{x}) \approx \sum_{j\in P} w_j(t) f(\underline{x}_j) \nabla W(\underline{x}-\underline{x}_j, h)$$

∇W is the gradient of W.

The most useful function used by the SPH community is the B-spline (figure 1) which has some good properties of regularity.

It is defined by :

$$\theta(y)=C\times\begin{cases}1-\frac{3}{2}y^2+\frac{3}{4}y^3 & y\le 1\\ \frac{1}{4}(2-y)^3 & 1<y\le 2\\ 0 & y>2\end{cases}$$

C is a constant and $y=\frac{\|\underline{x}-\underline{x}_j\|}{h(\underline{x}_j)}$. W, the smoothing function is then defined by :

$$W(\underline{x}-\underline{x}_j,h)=\frac{1}{h}\theta(\frac{\underline{x}-\underline{x}_i}{h})$$

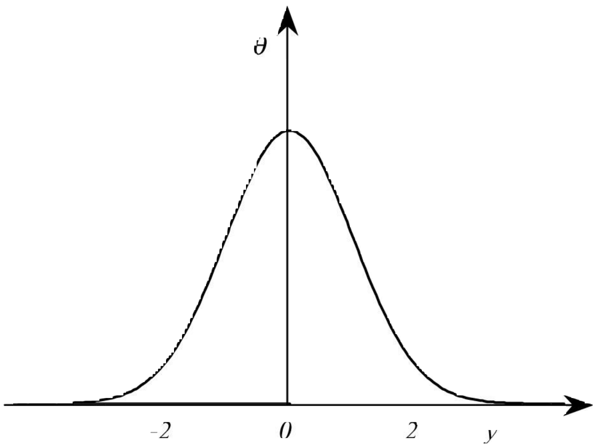


Figure 1 : B-spline function

FIRST IMPACT CONFIGURATION

The first test consists in a 9.53 mm diameter 2017-T4 aluminium sphere impacting a 2.2 mm aluminium 6061-T6 plate at 6.64 km/s. The shape of debris clouds at 6 ms and at 19.8 ms are shown in figure 2:

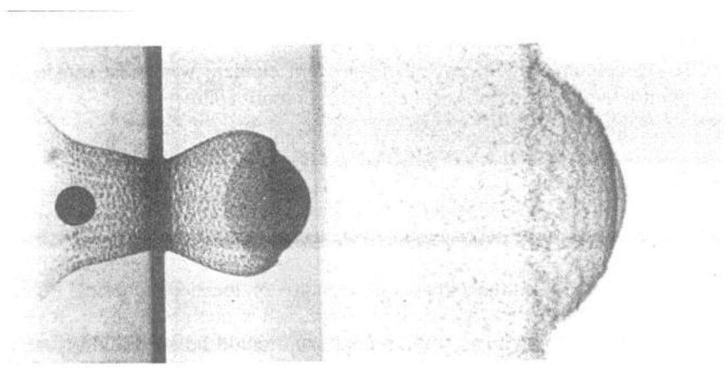


Figure 2 : debris cloud at 6 and 19.8 ms

High quality X-ray photography of the debris cloud is available. Moreover, velocities at various positions in the debris cloud have been measured.

SIMULATION WITH LS-DYNA AND SPH

Modelling procedure

To simulate the first impact, we represent (figure 3) a plate with brick elements. The central part is replaced by particles. There are 12420 bricks and 149552 particles. There are 10 particles in the thickness of the plate. The particles are "tied" to the bricks. The projectile is represented with particles.

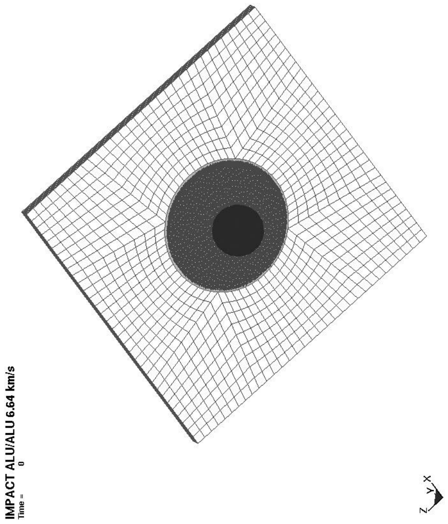


Figure 3 : target and projectile meshes

Material models

To represent the behaviour of metal during a high velocity impact, the STEINBERG-GUINAN model is used. This model is suitable for modelling materials deforming at very high strain rates. It allows to consider the melting in the material to be considered. A MIE-GRUNEISEN equation of state is used to compute the pressure.

Failure criterion

In order to simulate the failure of the material, the hydrodynamics pressure is limited to –0.02 Mbar. If the pressure is below this limit, the material spalls.

RESULTS

The results of the simulation are compared with experimental and analytical data. Several parameters are compared : impact pressure (figure 5 and table 1), axial velocity (figure 8 and table 2), dimensions of the cloud (figures 6 & 7 and table 2).

Impact pressure

A 1D calculation using the HUGONIOT relations is used to calculate the impact pressure.

In the target, the pressure is given by :

$$P_{Hc} = \rho_{0c} U_{Sc} v_1$$

ρ_{0c} is the density of the target.

v_1 is the velocity of the particules at the impact point.

U_{Sc} is the relative velocity of the shock wave in the target.

In the projectile, the pressure is given by :

$$P_{Hp}=\rho_{0p}U_{Sp}\left(v_0-v_1\right)$$

v_o is the impact velocity.

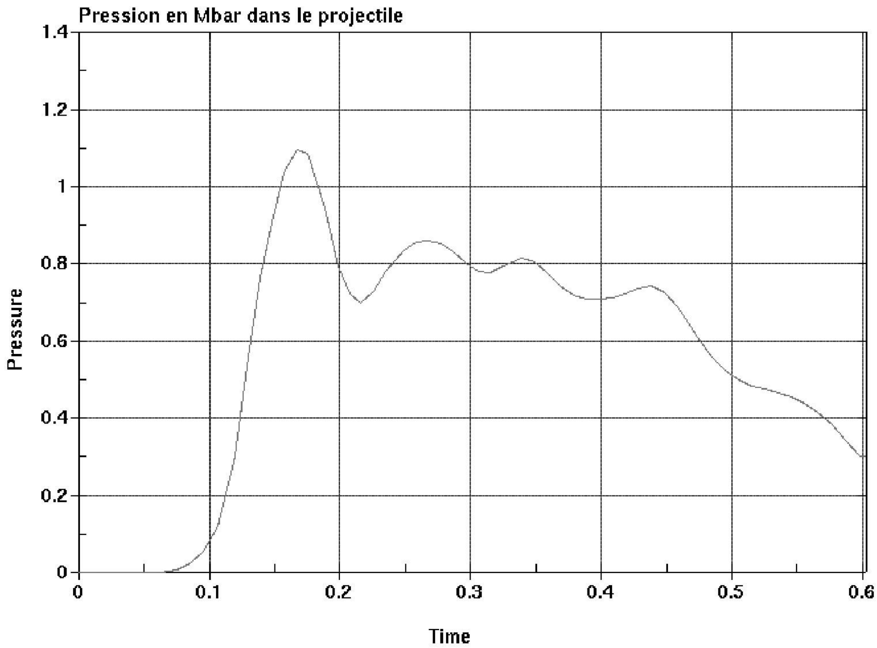
These two pressures are equal. We have a supplementary relation :

$$U_S=C_0+S\,v$$

C_o is the sound speed in the material.

S s a coefficient depending on the material.

We have enough equations to find the impact pressure. This pressure is compared with the one given by the simulation (figure 5 and table 1).



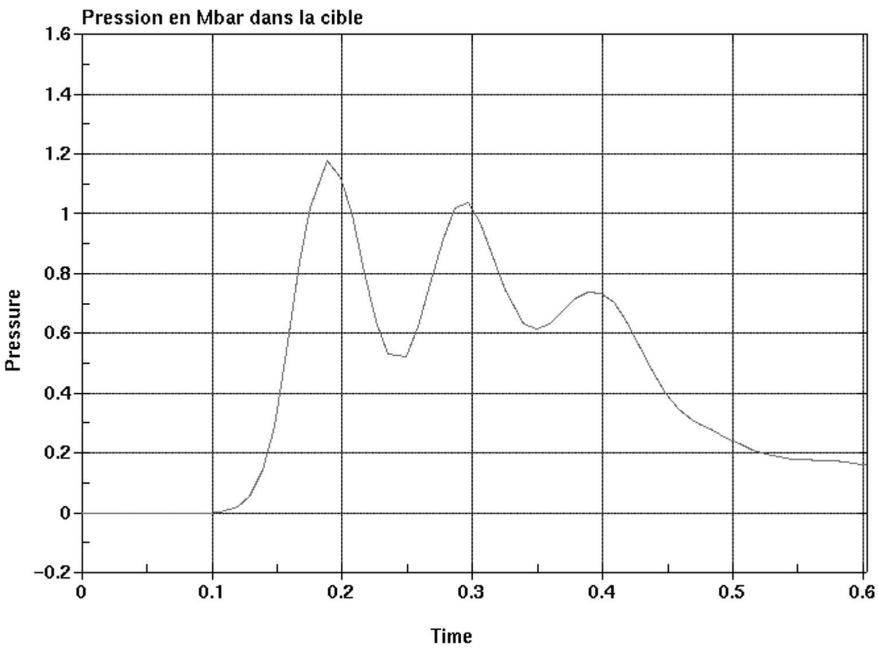


Figure 5 : pressure in the target and the projectile calculated by LS-DYNA

	target	projectile
Simulation	1.2 Mbar	1.1 Mbar
1D calculation	0.9 Mbar	0.9 Mbar

Table 1 : impact pressure calculated with LS-DYNA and 1D calculation

The pressure in the target is higher than in the projectile. We notice some oscillations in the pressure signal. The values given by the 1D theory are lower.

The shape of the debris cloud is well predicted (figures 6 & 7). The mass distribution is similar in the X- ray photography and in the simulation. The velocities (table 2) in the cloud are higher in the front of the cloud but lower in the back. However, the difference between experiment and simulation is only around 10%.

Debris cloud

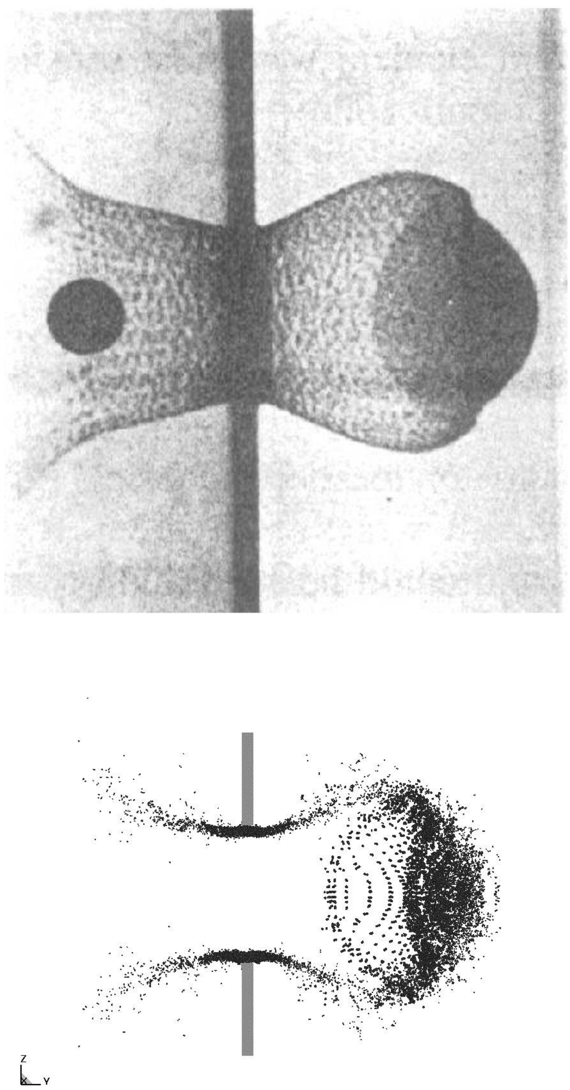


Figure 6 : 2D view of debris cloud with SPH

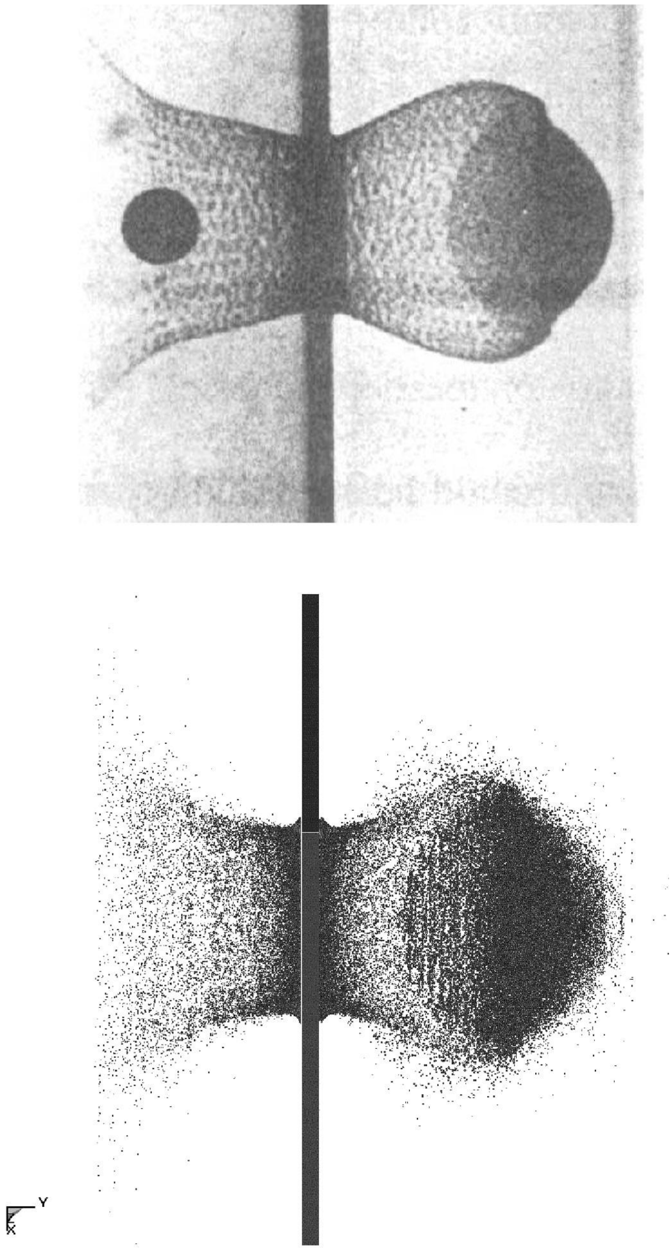


Figure 7 : 3D view of debris cloud with SPH

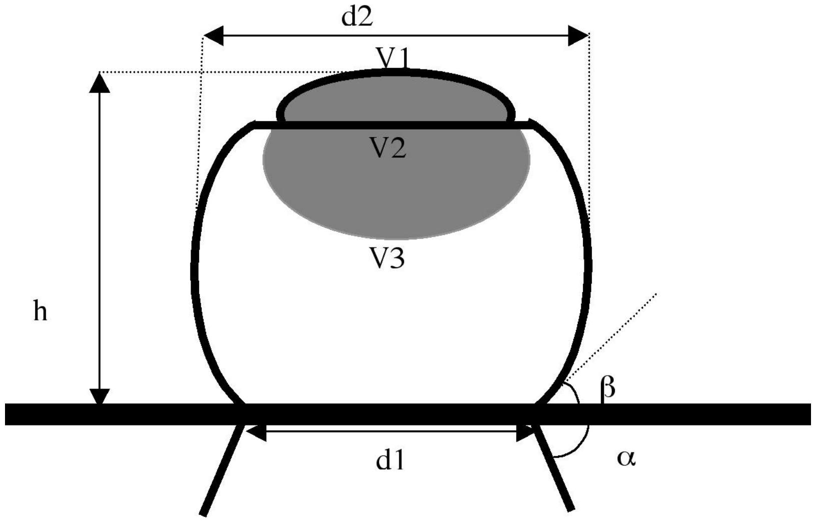


Figure 8 : correlated parameters

	Axial velocity V1	Axial velocity V2	Axial velocity V3
Simulation	6.5 km/s	5.8 km/s	3.3 km/s
Experiment	6.1 km/s	5.9 km/s	3.5 km/s

	α	β	d1	d2	h
Simulation	79°	67°	2.6 cm	3.8 cm	3.7 cm
Experiment	77°	67°	2.3 cm	3.4 cm	3.6 cm

Table 2 : comparison between experiment and simulation

SECOND IMPACT CONFIGURATION

The second test consists in a 5 mm diameter 304 L steel sphere impacting a 2.85 mm aluminium 6061-T6 plate at 5.53 km/s. The resulting debris cloud at 10.4 ms is shown in figure 1.

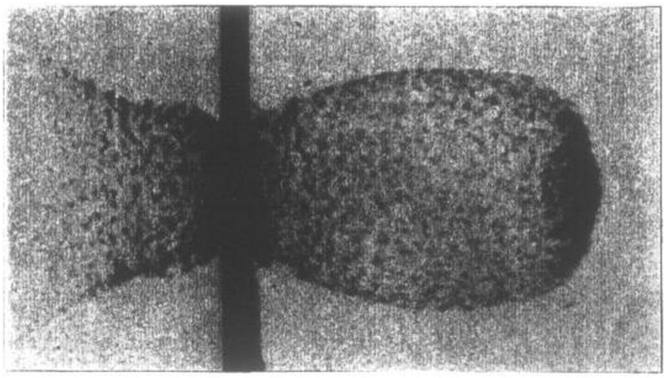


Figure 9 : debris cloud at 10.4 μs

SIMULATION WITH LS-DYNA AND SPH

The modelling procedure is similar to the first case. The number of particles is 196520. The diameter of the particles is similar to the first case.

The material model, the failure criterion and the equation of state are the same than in the first case.

RESULTS

Several parameters are compared : impact pressure (table 3), axial velocity (figure 11 and table 4), dimensions of the cloud (figures 10 and table 4).

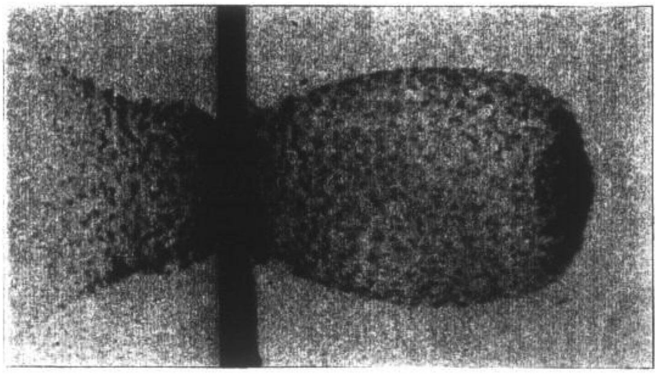
Impact pressure

The impact pressure is calculated with the HUGONIOT relations and compared with the simulation values. The results are reported in the table :

	target	projectile
Simulation	1.2 Mbar	1.1 Mbar
1D calculation	1.05 Mbar	1.05 Mbar

Table 3 : impact pressure calculated by LS-DYNA and 1D calculation

Debris cloud



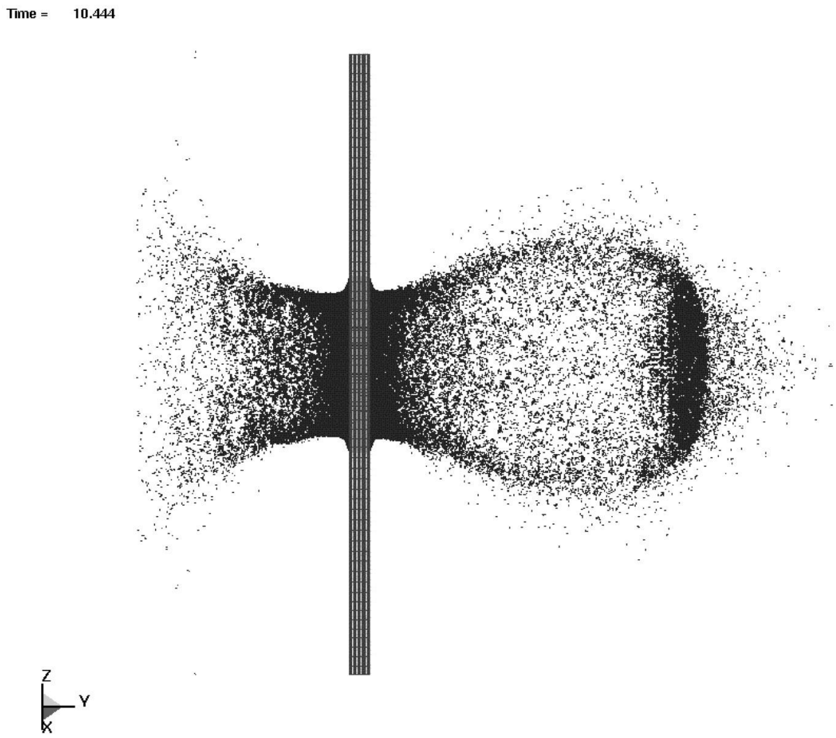


Figure 10 : 3D view of debris cloud with SPH

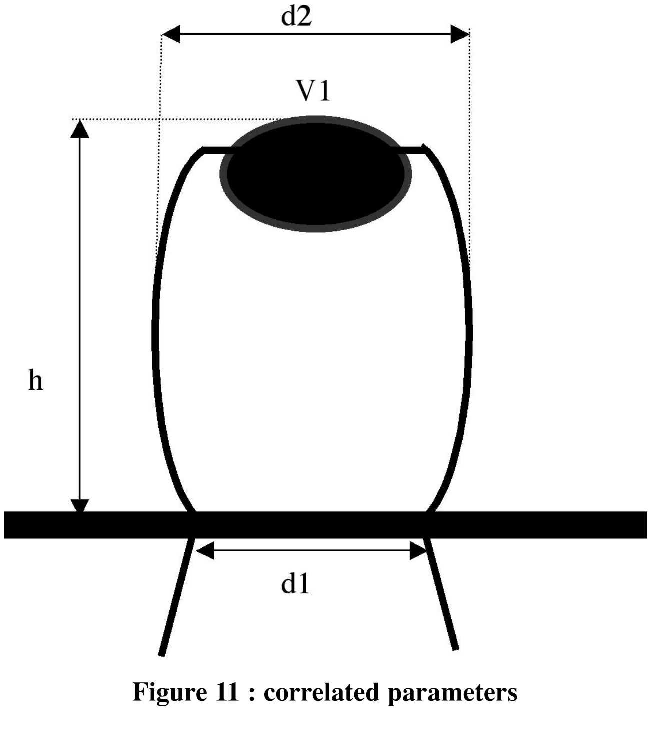


Figure 11 : correlated parameters

	V1	d1	d2	h
Simulation	5.2 km/s	2 cm	3.3 cm	4.5 cm
Experiment	4.7 km/s	1.8 cm	3.1 cm	4.6 cm

Table 4 : comparison between experiment and simulation

CONCLUSION

Experimental and numerical results are in good agreement. The difference between results is around 10%.

SPH method is able to reproduce the global shape of the debris cloud and to predict the resultant velocity. The results could be improved with more particles using a 2D axi-symmetric model.

The method is valid for velocities lower than 7 km/s. Near these velocities, others equations of state are necessary to consider solid gas transition in material.

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