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# IMPROVING THE SAFTEY OF SHELTERS BY ADDING BLAST VALVE TO THE OPENING OF VENTILATION

*By*

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## ABSTRACT

The opening (inlet and outlet for ventilation, doors and windows) in the shelter represents the weakest part in the shelter. Openings for breathing air and cooling have contradictory requirement we can recognize that for protection it would be best to seal the openings, However this would eliminate the function of it and supply of air is needed for breathing thus, solutions had to be found to comply with all the requirements. Blast valves are built in the ventilating openings to stay open for ventilation and to automatically close when pressure increases due to explosion and automatically re-opens when the pressure is released.

The paper presents the performance of one type of a blast valve using a numerical approach putting in an open hole in a shelter by using: AUTODYN software to discuss the reduction of the pressure and MATLAB software to argue pressure drop / air flow rate.

It also presents the design of the blast valve, spring and how it operates.

## KEY WORDS

Blast valve, opens for ventilation and blast waves

## NOMENCLATURE

| | | | |
|---|---|---|---|
| $A$ | Cross section area | $D$ | Diameter |
| $E$ | Modulus of elasticity | $G$ | Modulus of rigidity |
| $G_m$ | Mass flow rate | $I$ | Impulse (psi-ms or mpa-ms) |
| $I^+$ | Positive impulse | $L$ | Length |
| $P$ | Pressure | $P_r$ | Reduced pressure |
| $P_1$ | Pressure at the start of pipe | $P_2$ | Pressure at the end of pipe |
| $P_o$ | Atmospheric pressure | $P_s$ | Maximum overpressure |
| $Q_{nor}$ | Volume flow rate at normal condition (p=101325 Pa, T=273.15 K) | $R$ | Gas constant of air |
| $T$ | Times (ms) | $T^+$ | The duration of positive time |
| $T_{air}$ | Air temperature | $T_r$ | Reduced temperature |
| $V$ | Poisons ratio | $Z_m$ | Average compressibility coefficient |
| $Z_1$ | Compressibility coefficient at the start of pipe | $Z_2$ | Compressibility coefficient at the end of pipe |
| $\rho_{nor}$ | Density at normal condition (p=101325 Pa, T=273.15 K) | $\delta$ | Kinematics viscosity of air at T=273.15K |
| $\lambda$ | Friction coefficient | $\xi$ | Minor losses coefficient |

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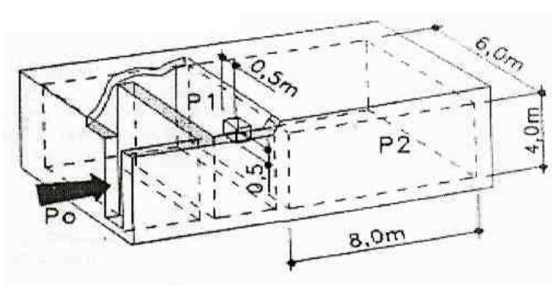
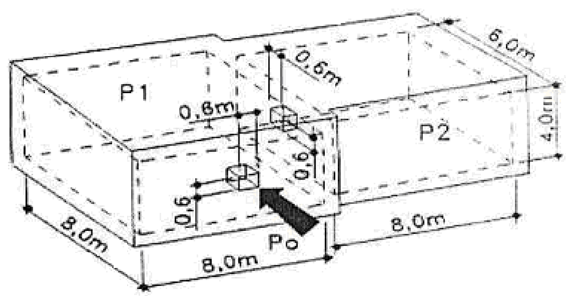
## Introduction

Shelters were already built in the world war (I) 1914-1918. During this period, breathing air was no real problem because the shelter were not overcrowded and small openings to the outside insured the necessary supply of fresh air. The pressure waves, created from bombs available at the time, were not very harmful inside the shelter after penetrating through the small ventilation openings.

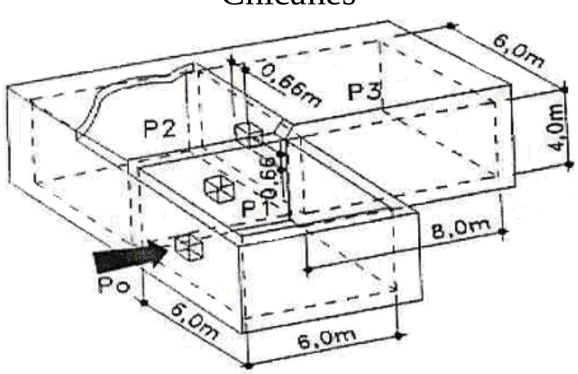
The situation dramatically changed in the World War (2) 1939-1944. New, very powerful bombs had been developed and these were dropped in very large numbers not only on the military targets but also on the civil population sought protection in bunkers. The civil shelters were mainly overcrowded and therefore required the increased amount of fresh air breath to provide acceptable survival condition in respect of smells and humidity with the increase of blast pressures, air inlets and outlets became a real problem. The openings became relatively large and mechanical ventilation had to be installed. This led to the development of blast protection for air intake. At the beginning it was quite understandable, that mechanical devices had not been considered, as there was no available knowledge about duration of positive and negative pressure phase or magnitude of impulses Solutions were then studied and very pragmatic methods found as shown in Figure 1.



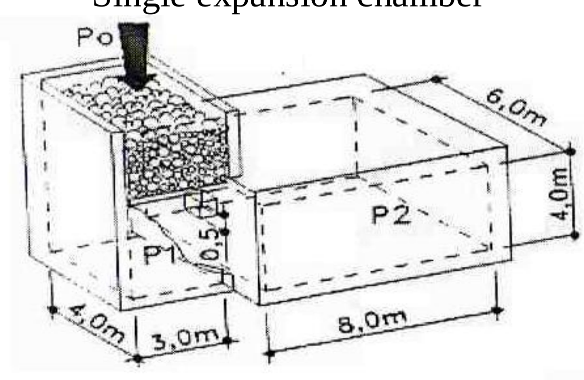

Chicanes




Single expansion chamber




Double expansion chamber




Stone bed

**Figure (1):** Some of the tradational ways to reduce blast pressure (1)

Now a day after knowing the properties of shock waves blast valves are made to reduce the pressure to a level that avoiding the threshold of the human being as shown in Figure 2.

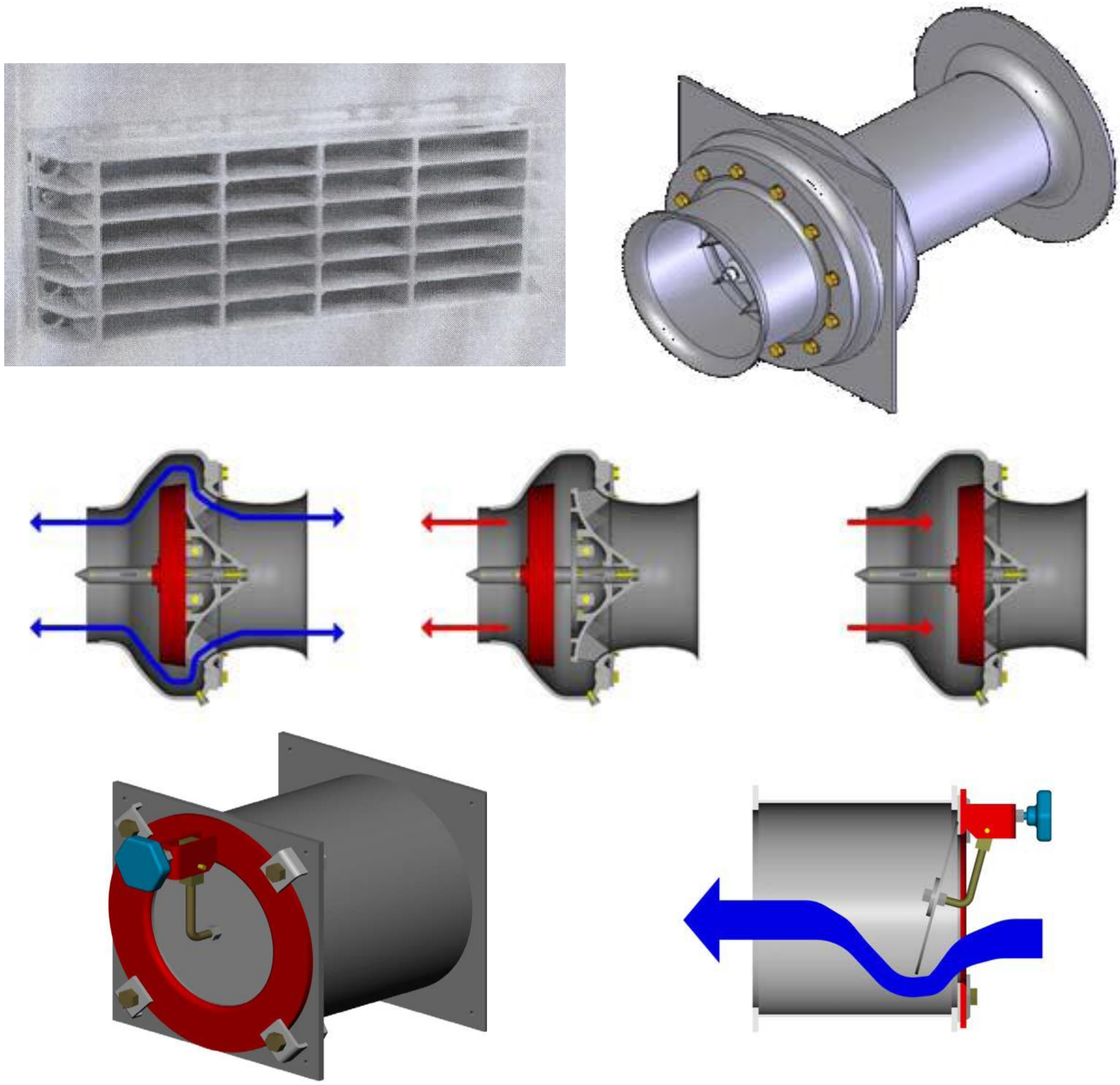


**Figure (2):** Some of the mechanical devices to reduce blast pressure (9),(10)

The main objective of this paper is to introduce the details of one of the blast valve latest model and study the reduction happened before and after putting the blast valve.

## Blast waves

An ideal blast wave is one in which the pressure rises suddenly to a peak value after which it decreases gradually to the ambient pressure, thereby forming the positive phase. The pressure diminishes below the ambient pressure and then it rises again to ambient pressure, forming the negative phase. Reflecting surfaces such as building walls will cause an impinging blast wave to reflect back and traverse shocked air thereby augmenting its magnitude from 2 to 8 time that of the incident pressure, depending on the strength of the original shock wave.

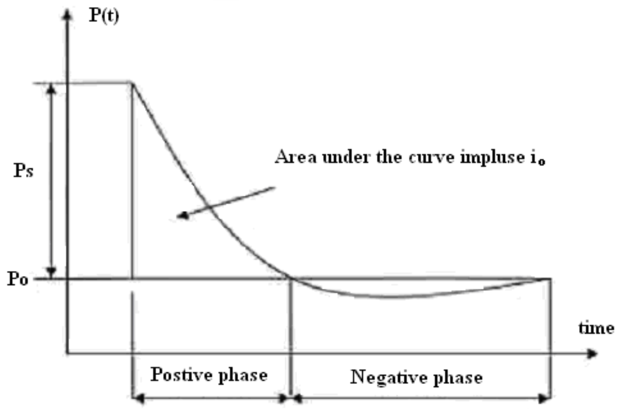



**Figure (3):** Ideal free-field blast wave profile (5)

The explosive TNT (trinitrotoluene), derived for military application, is widely used and referenced as the standard due to the large amount of data available of it properties and behavior. This and other data were used in the library of a well –known computer software program, ConWep (8). ADOS version of ConWep was released in 1992 by the U.S Army engineer waterways experiment station. The value of ConWep is that it makes use of a large amount of true field data for different types of explosives thus. Experimental and analytical tests results can be compared to those predicted by ConWep.

## Numerical investigation

The specialized finite element analysis program called AUTODYN has various capabilities to model different parts of the blast process and the effect of the explosion on the structure and the valve. The shelter was represented as a concrete wall (height 1180mm, width 1400mm and thickness 120mm) with open hole (height 180mm, width 400mm and thickness 120mm). However, the air domain outside the shelter had a flow-out boundary condition to allow the transmission of the shock waves. The dimensions (height 118cm and width 140cm).

**Table (1):** The boundary conditions of the model

| | Fix-x | Fix-y | Fix-z | Rot-x | Rot-y | Rot-z |
|---|---|---|---|---|---|---|
| Concrete wall | Yes | Yes | Yes | Yes | Yes | Yes |

Euler-FCT processors: (single material, ideal gas but more accurate) for modeling air blast. These processors include first –order and second order accurate schemes. In the Euler processor, the numerical mesh is fixed in space and physical material flows through the mesh as shown in Figure (4).

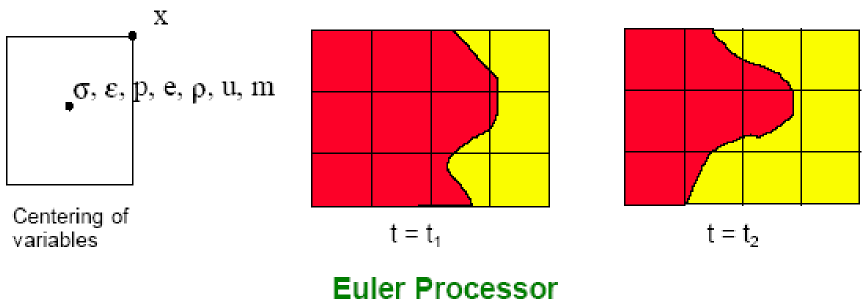



**Figure (4):** Euler processors (Manual of Autodyn software)

Lagrange processor: for the description of solid material (modeling solid continua and structures) was used in this study to model the concrete, air and valves. In the Lagrange processor, the numerical mesh moves and distorts wish the physical material as shown in the Figure (5).

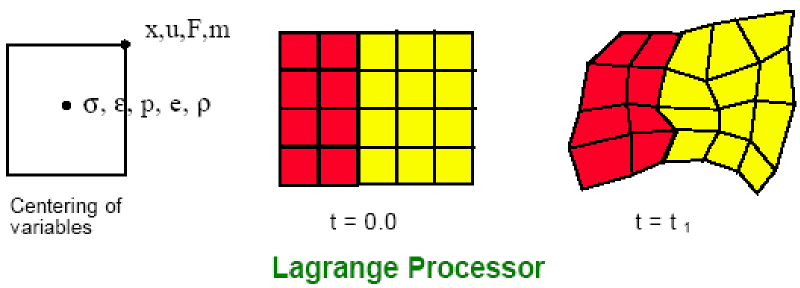



**Figure (5):** Lagrange processor (Manual of Autodyn software)

Beam element was used to model the spring (see Figure 6). The response of the beam element to an applied load includes, by default, the effect of bending moments. This option lets to reduce the beam formulation to that of a stress, in which only axial and torsion effects are considered.

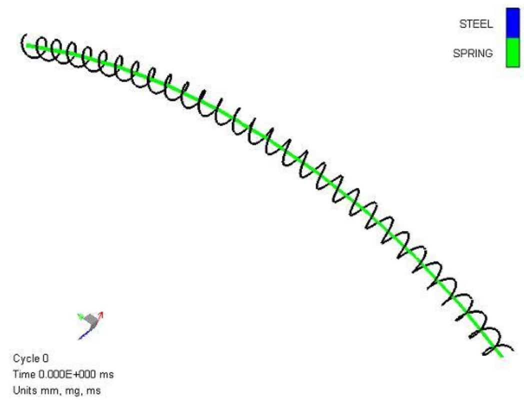



**Figure (6):** Beam element (Manual of Autodyn software)

Table 2 shows the material properties of different elements used in the numerical investigation, they are selected directly from AUTODYN library.

**Table (2):** Material data

| Air | | | |
|---|---|---|---|
| Equation of state | Ideal gas | Reference energy (Uj/mg) | 2.068E+5 |
| Reference density (g/cm3) | 1.22E-3 | Pressure shift (kpa) | 0.0 |
| steel | | | |
| Equation of state | Linear | Hardening constant (kpa) | 2.00 E+06 |
| Reference density (g/cm3) | 7.80E+0 | Hardening Exponent | 3.5 E-01 |
| Bulk Modulus (Kpa) | 1.45 E+08 | Strain Rate constant | 1.345 E+0 |
| Reference Temperature(k) | 0.0 E+00 | Thermal Softening Exponent | 0.00 E+00 |
| Specific Heat(c.v)(J/kgk) | 0.0 E+00 | Melting Temperature(k) | 1.811 E+03 |
| Strength model | Johnson-Cook | Failure model | Eff. Plastic Stn. |
| Shear Modulus (kpa) | 7.87 E+7 | Ultimate Strain | 5.00 E+00 |
| Yield stress (kpa) | 2.10 E+5 | Erosion model | None |

**Proposed blast valve**

In this study, blast valve designed to close using spring action without any additional energy like compressed air or electricity.  Blast valve designed to operate during both positive and negative phase.

using the wall with blast valve as shown in Figure 7, consisting of 6 cylindrical tubes with Ø=23mm, thickness of  5mm and length equals to 384mm, moving in specific path to close during the positive and negative phase and re-opens again after releasing the pressure. The movability of each cylindrical tube is controlled by 2 springs so 2 cases are used:

- A blast valve without springs is used where it acts as attenuaotor with fixed cylinderical tubes as shown in Figure 9.
- A blast valve with springs as shown in Figure 10.

**Table (3):** section of blast valve

| Section | Height (mm) | Width (mm) | Depth (mm) |
|---|---|---|---|
| Blast valve | 400 | 180 | 120 |

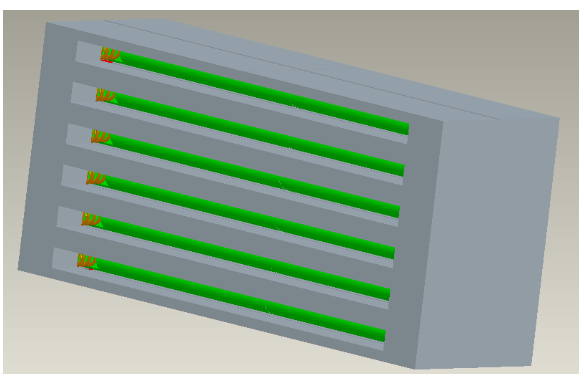


**Figure (7):** Scheme of the blast valve

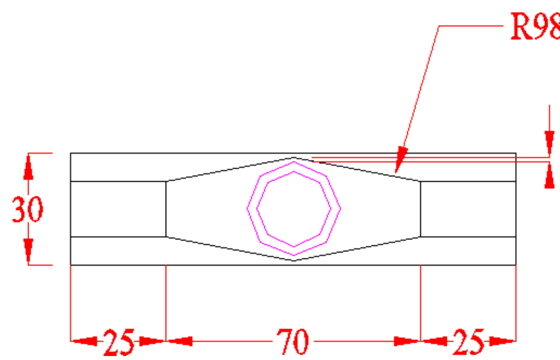



**Figure (8):** One unit of the valve without springs

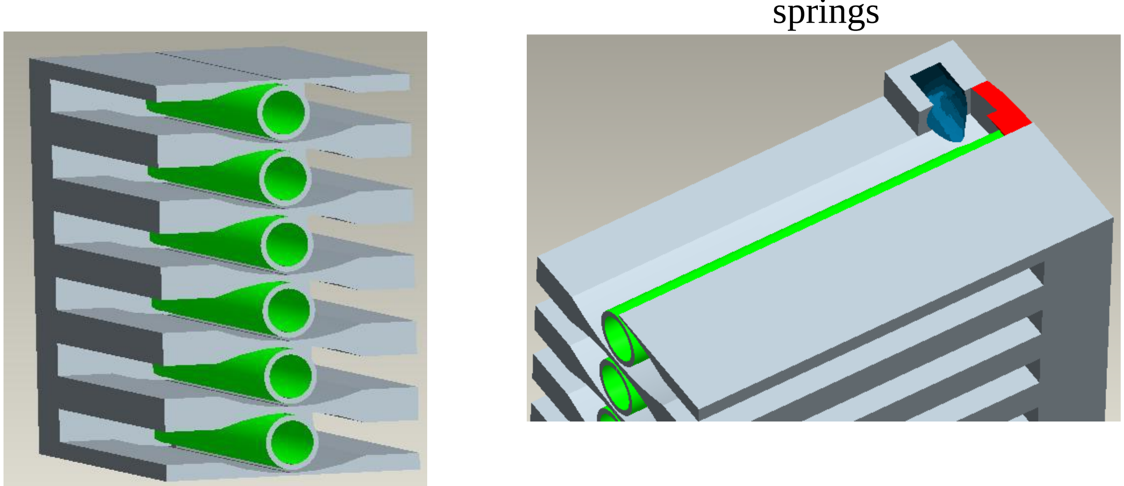


**Figure (9):** Scheme of the blast valve without using springs

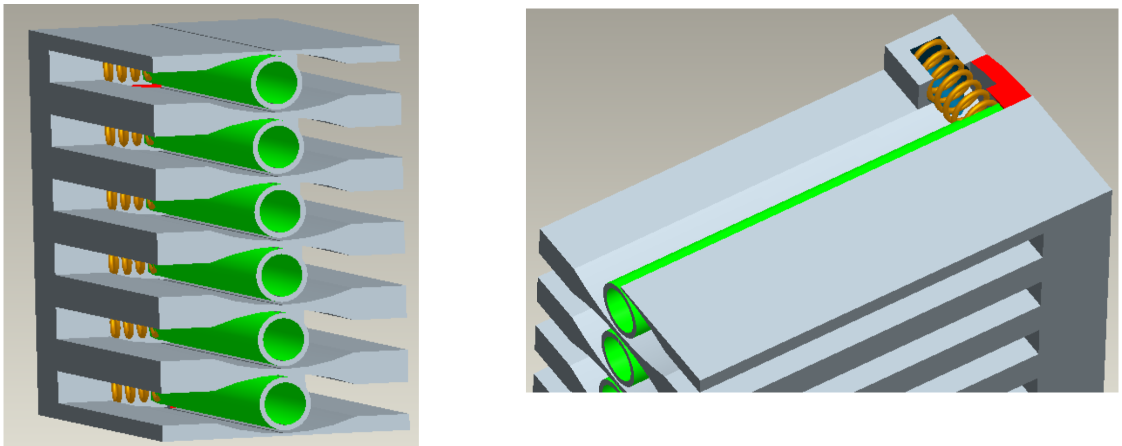


**Figure (10):** Scheme of the blast valve using springs

Figure 11 shows the blast pressure for 1 kg explosive charge mass at various gauge locations where, the distance of the explosive charge is 1m away from the wall. Gauge 2 is located just before the wall while gauge 7 is just after the wall. In this model, a wall with open hole without valve has been used.

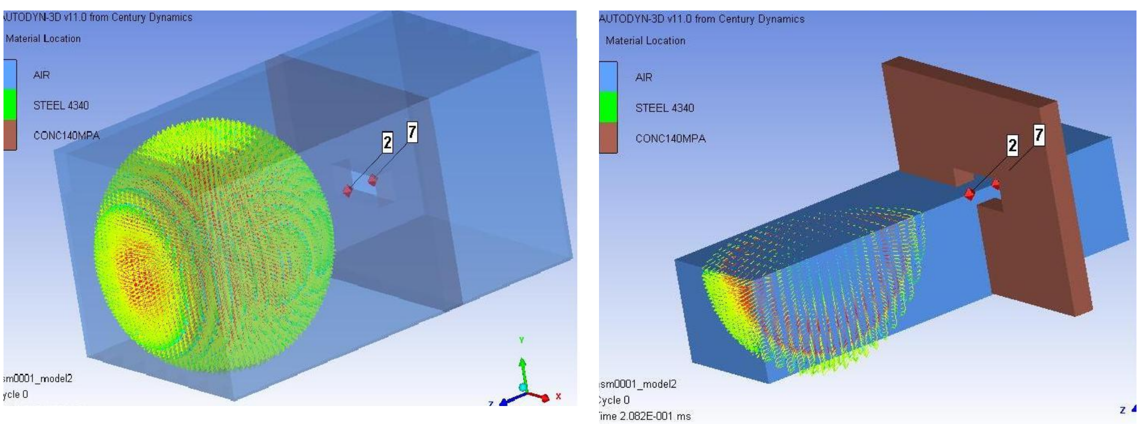



**Figure (11):** Contour air compress, t=2.082 ms

## Spring

Due to the requirements of very fast response and complete close of the vent, then:

- The spring stifness has to be very low.
- The spring dimention must be small as possible.
- Under normal ventilation mode, the closing springs are in their open middle position letting the airflow pass freely. After the explosion and pressure release, the springs return immediately to its normal position.
- Taking into consideration the length of spring when it is fully compressed will not oppose the angles/cylinders movement to reach the end of their path, getting a complete shut down for the valve.

We have taken some assumptions as follows:

- Min. pressure required to close the system = 0.35 bar after balance.
- The used material of the spring is steel with the following Specifications:
  - G: modulus of rigidity = 79.3e9
  - E: modulus of elasticity = 196.5e9
  - V: poisons ratio = 0.28

**Results of the pressure-time history for previously described models**

Figure 12 shows the comparison of pressure versus time to gauge 2 and gauge 7, where gauge 2 reads 1082.9 kpa that means that the change of pressure equals 981.575 kpa. Gauge 7 reads 635.84 kpa, $t_s$ equals 1.05 ms that and $I_s$ equals 254.8 pa.s, which means that the change in pressure is equal to 534.515 kpa. The reduction due to the open hole (40×18 cm) is equal to 45.5%.

Figures 13 and 14 shows the comparison of pressure versus time to gauge 2 and gauge 7, where the reading of gauge 2 is constant and equals to 1082.9 kpa, meaning that the change in pressure is equal to 981.575 kpa. Gauge 7 reads 369.72 kpa, $t_s$ equals 0.38ms and $I_s$ equals 49.29pa.s when using the blast valve consisting of 6 cylinders without springs as shown in figure 9, the change in pressure will be 268.395 kpa giving a reduction factor equals to 72.56%. While it reads 181.41 kpa, $t_s$ equals 0.35ms and $I_s$ equals 13.96pa.s when using the blast valve consisting of 6 cylinders with springs as shown in Figure 10, the change in pressure will be 80.085 kpa giving a reduction factor of 91.7%.

We notice that, using springs will reduce the change in pressure from 268.395 kpa to 80.085 kpa by 30.18%. Causing, it to close during the positive and negative phase.

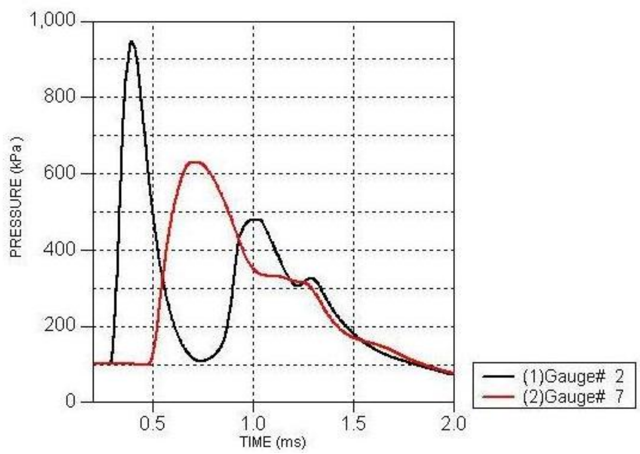



**Figure (12):** Pressue-time curve for open hole

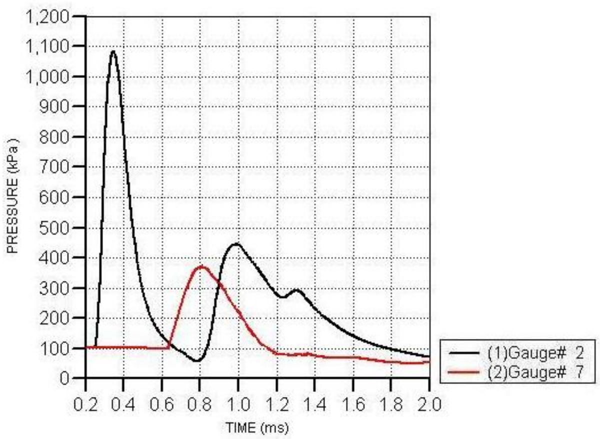



**Figure (13):** Pressue-time curve for using the valve without spring

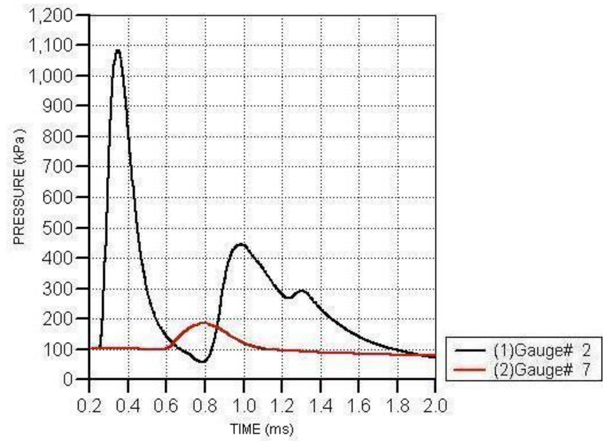



**Figure (14):** Pressue-time curve for using the valve

## Air flow rate for the blast valve

In this study, a software package (MATLAB) is used to investigate the relation between air flow rate and the change in pressure the curves indicates the actual flow characteristics of the valves without the effect of pipe system used for the flow measurements.

A steel pipe made of angles (30×3mm) and sheets of steel of thickness 3mm are made as a emulator of Ø= 1m and length= 2.5m as shown in Figure 15. The above-mentioned steel pipe used, as it is difficult to calculate the change in the airflow with respect to pressure drop in an open area. Moreover, to be able to make a comparison of the results with the (LUWA shelter and security technology) and (Temet shelter and protective structures) products of attenuator and blast valves.

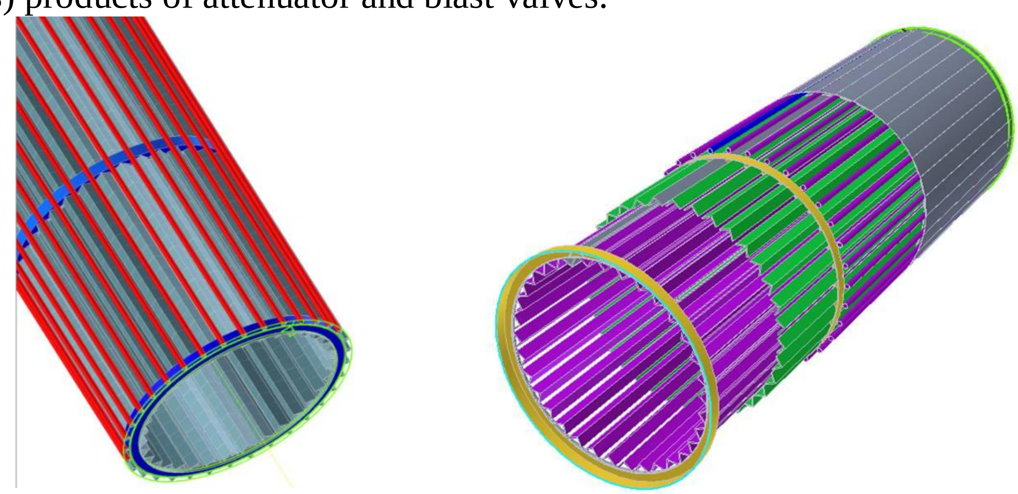


**Figure (15):** Scheme of the emulator

**Figure (16):** The pipe made by Temet Company

## Calculations of air flow rate

Pressure drop calculation when flow rate known as compressible flow with constant temperature, which can calculated as follows:

$$p_1^2 - p_2^2 = Z_m RT\left(\frac{G}{A}\right)^2\left(\lambda\frac{L}{D} + \sum\xi + 2\ln\frac{p_1}{p_2}\right) \qquad (1.1)$$

Where:

- $P_1$: pressure at the start of pipe
- $P_2$: pressure at the end of pipe
- $Z_m$: average compressibility coefficient
- R=287 J/kgK: gas constant of air
- $T_{air}$: air temperature
- $G_m$: mass flow rate
- A: cross section area
- $\lambda$: friction coefficient
- L: pipe length
- D: pipe diameter
- sum $\xi$: the sum of minor losses coefficient

Average compressibility coefficient calculated as:

$$Z_m = \frac{1}{2}(Z_1 + Z_2) \qquad (1.2)$$

Where:

- $Z_1$: compressibility coefficient at the start of pipe
- $Z_2$: compressibility coefficient at the end of pipe

Compressibility coefficient for given pressure and temperature calculated using:

$$Z = 1 + \frac{9}{128}\frac{P_r}{T_r}\left(1 - 6T_r^{-2}\right) \tag{1.3}$$

Where:
- $P_r$: reduced pressure
- $T_r$: reduced temperature

Which are calculated as follows:

$$P_r = \frac{p_i}{p_c} \tag{1.4}$$

$$T_r = \frac{T}{T_c} \tag{1.5}$$

Density of air at given pressure and temperature calculated using:

$$\rho = \frac{p}{Z_m RT} \tag{1.6}$$

Relation between mass and volumetric flow rate calculated using:

$$G = \rho_{nor} \cdot Q_{nor} \tag{1.7}$$

Where:
- $\rho_{nor}$: density at normal condition (p=101325 Pa, T=273.15 K)
- $Q_{nor}$: volume flow rate at normal condition (p=101325 Pa, T=273.15 K)

Velocity of air calculated using:

$$V = \frac{\rho_{nor}}{\rho}\frac{4Q_{nor}}{\pi \cdot D^2} \tag{1.8}$$

Where the cross section of round pipe is:

$$A = \frac{\pi \cdot D^2}{4} \tag{1.9}$$

To find out if the flow is laminar or turbulent, Reynolds number must calculate:

$$\mathrm{Re} = \frac{V \cdot D}{\delta} \qquad (1.10)$$

Where:

- $\delta$ = 13.4*10-6mm$^2$/s: kinematics viscosity of air at $T_{air}$=273.15K

Const Friction coefficient for laminar flow (Re<2320) is:

$$\lambda = \frac{64}{\mathrm{Re}} \qquad (1.11)$$

For flow in hydraulically smooth pipe (Blasius equation):

$$\lambda = \frac{0.3164}{\sqrt[4]{\mathrm{Re}}} \qquad (1.12)$$

For turbulent flow with Re<100 000 (Prandtl equation):

$$\frac{1}{\sqrt{\lambda}} = 2\log\left(\frac{\mathrm{Re}\sqrt{\lambda}}{2.51}\right) \qquad (1.13)$$

For turbulent flow with Re>100 000 (Karman equation):

$$\lambda = \left(2\log\frac{d}{k_r} + 1.14\right)^{-2} \qquad (1.14)$$

The boundary layer thickness (delta) can calculated based on the Prandtl equation as:

$$\delta = 62.7\frac{D}{\mathrm{Re}^{\frac{7}{8}}} \qquad (1.15)$$

When the boundary layer thickness is bigger than the pipe roughness and if the flow is turbulent, then it can be considered as flow in hydraulically smooth pipe and Blasius equation is used.

We have taken some assumptions as follows:

- Air temperature = 20 oC
- Air density = 1.2 kg/m3

Using a blast valve with a dimension of (40×18cm) which is the same dimension of the blast valve produced by LUWA shelter and security technology where the blast valve produced by Temet shelter and protective structures has a dimension of (41×22.5cm) will give the following results:

**Table(4):** Pressure drop – airflow rate for different models

| Model | Airflow at pressure drop 100 Pa ($m^3$/h) | Airflow at pressure drop 200 Pa ($m^3$/h) | Airflow at pressure drop 300 Pa ($m^3$/h) |
|---|---|---|---|
| Blast valve produced by LUWA | 500 | 690 | 825 |
| Blast valve produced by TEMET | 500 | 720 | 900 |

Figure 17 shows the Pressure drop – airflow rate when using the open hole in the wall, which will give the following results:
When pressure drop = 100 Pa it will give an airflow rate = 4650 m3/h, while at pressure drop = 200 Pa it will give an airflow rate = 6820 m3/h, while at pressure drop = 300 Pa it will give an airflow rate = 8350 m3/h

Figure 18 shows the Pressure drop – airflow rate when using the open hole in the wall, which will give the following results:
When pressure drop = 100 Pa it will give an airflow rate = 387 m3/h, while at pressure drop = 200 pa it will give an airflow rate = 545 m3/h, while at pressure drop = 300 pa it will give an airflow rate = 672 m3/h.

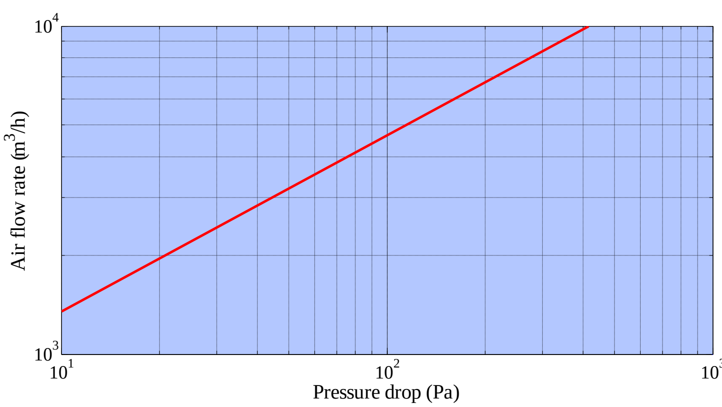



**Figure (17):** pressue drop ⁄ air flow rate for open hole

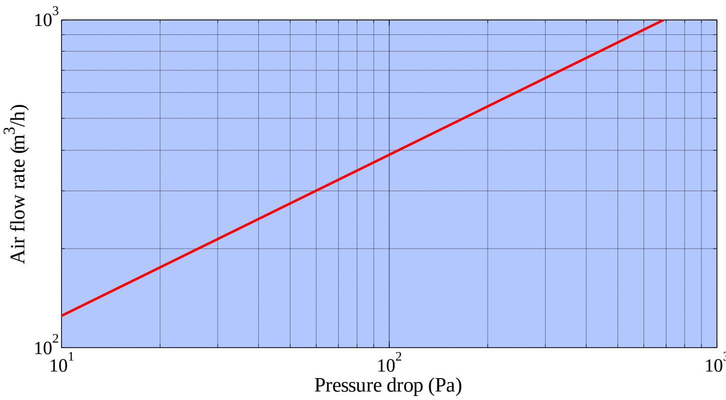



**Figure (18):** pressue drop/ air flow rate for using the valve

## DISCUSSION

The maximum average attenuation of 91.7% was achieved when a valve has been used, followed by a 72.5% using a valve without springs then 45.5% with just open hole. Thus, attenuations correlate with the opening vent area ratio.

References consider that maximum effective pressure values as defined in TM5-1300 are 0.4 MPa for 75% eardrum rupture, 0.56 MPa for 50% lung damage and 1.72 MPa for 100% lethality. The results with the valve demonstrate that they attenuated pressure to safe levels, lower than the pressure that causes threshold of human injuries.

The Pressure drop – airflow rate when using the blast valve approximatly equals 77.5% compared with the valves produced by the international companies. and approximatly equals 9% compared with open hole.

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