A survey on automatic measuring the density of High Explosives

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Abstract. The high explosives are used to give the initial power to drive the nuclear weapons to bomb. They are solid and vulnerable to force, electricity, and fire. And they are also expected to be stable in density, geometry, and compositions. This paper focuses on the automatic density measuring methods of the high explosives in modern science and technology, detailed methods are summarized and comparisons are made. The components, connections and accuracy for one of the direct way based on the Boyle’s and Marriot’s law are discussed as one potential automatic measuring method for high explosives.

1. Introduction
The nuclear weapons are mass destructive and long-time effect on the target area once they were bombed. Therefore, they are under strict control for both the owner and other nations [1], and they are maintained by skilled experts and traditional technologies. Every new technology, measurement, or instrument would be tested thoroughly before its application. However, meeting the modern industry, there is also a strong need to maintain the nuclear warheads automatically and intelligently.

High explosives are the basic components of the nuclear warheads [2]. They have high energy density, and they are vulnerable to electricity, force and fire, furthermore, they are thermal-decomposing. All of these properties show that they are quite difficult to be maintained and kept stable. The modern technologies are also doubtable for the governors to be applied considering the impact of the particles, force and energy [3]. Researchers and engineers are also wandering to evaluate the influence [4]. Causing the thermal decomposition of high explosives, the density parameter was paid great attention to and it was also easily measured in reality. Thus, lots of job were done to update the measuring methods.

In this paper, we sum up the density measuring methods of the high explosives at first, and look forward to find some automatic measuring methods for the high explosives.

2. TRADITIONAL MEASUREMENTS
The density measuring methods could be classified in two groups: the direct methods and indirect methods based on the density calculation formula:

\[ \rho = \frac{m}{V} \]  \hspace{1cm} (1)

In the above equation, \( \rho \) represents the density of a solid, \( m \) is the mass of the solid, and \( V \) is the body volume.
If a density is calculated with equation (1) which means the mass and the body volume is measured at first, we call this method the direct way. Otherwise, with the indirect methods, the density is calculated with other equations based on the specific physical mechanical or chemical rules.

2.1. The direct measuring methods of the density
The direct measuring methods calculate the density of the solid with equation (1) by measuring the mass and the bulk volume. However, the solid could be irregular in most cases and it is difficult to measure both the mass and the volume. In engineering, these methods are often combined with other methods for simplicity, such as the Archimedes’ Law, and the Boyle’s and Mariotte’s law.

2.1.1. The Archimedes’ Law
This law tells the buoyant of a mass in liquid:

$$F_b = \rho_l \cdot g \cdot V_m \quad (2)$$

Where $F_b$ represents the buoyant of the bulk in liquid, $g$ represents the acceleration of the gravity, and $V_m$ represents the bulk volume.

We can also get the measured value of the bulk’s mass or volume with specific devices.

**Mass measuring methods.** We can measure the mass in liquid if the bulk’s density is larger than that of the liquid. The measured mass $M_{te}$:

$$M_{te} \cdot g = M_{th} \cdot g - F_b \quad (3)$$

Where $M_{th}$ represents the real mass, we often use the measured mass in air instead in engineering.

And then, the density could be calculated as follows:

$$\rho = \frac{m_{th}}{m_{th}-m_{te}} \cdot \rho_t \quad (4)$$

**Volume measuring methods.** In some cases, the mass could not be easily measured whereas the volume is more suitable to be measured. This often occurs during the test for liquids’ density. The famous test is to measure the milk’s density. However, it is not suitable for solids.

2.1.2. the Boyle's and Mariotte's law
This law tells the relationship between the pressure, the volume and the temperature of the gas:

$$\frac{PV}{T} = \text{const.} \quad (5)$$

Therefore, if the temperature $T$ is ignored or atoned in some way, then the volume measurements could be switched to the pressure measurements. The pressure of the gas could be obtained with the Archimedes’ Law or the pressure sensors.

The bulks’ volume of the solids could be calculated with the following equations $^{[5]}$:

$$V = V_0 - \frac{p_0}{p-p_0} V_f \quad (6)$$

Where $V$ represents the bulks’ volume; $V_0$ represents the gas volume at the beginning; $V_f$ represents the loading volume of the gas, $p_0$ and $p$ are the pressure of the gas at the beginning and the end stage of the measurements.

The density of the solids could be then calculated as follows $^{[6]}$:

$$\rho = \frac{(p-p_0)(m_1-m_0)}{pV_0-p_0(V_0+V_f)} \quad (7)$$

Where $m_1$ and $m_0$ are the mass measured in the platform.

2.1.3. Proportional calculations
To measure the density of dislocations or porous solids, the density could be calculated with the density of porosity or compositions, detailed work should be done according to the specific materials, such as the porosity’s affection $^{[7]}$ and the proportions of the compositions $^{[8]}$. There might need less accuracy in such conditions comparing with others.
2.2. The indirect measuring methods of the density

Density of the solids is a physical parameter which is related to most of the other physical, chemical, and mechanical properties. For high explosives, it balances the decomposing procedure, the detonation energy, and the piezoelectric morph, even the absorption ratio of the nuclear particles. Therefore, the density value of the high explosives could also be obtained with other methods despite the equation (1).

2.2.1. The Computed Tomography (CT) method

In nuclear physics, the intensity of the beams when penetrating the materials meets the Lambert-Beer law [9], which means that the particles are absorbed, collided, or annihilated during they are interacting with the atoms in the materials, and the intensity is described as follows:

\[ I = I_0 e^{-\mu x} \]

\[ \mu = \frac{1}{\Delta x} \ln \frac{I_0}{I} \]

(8)

In the above equation (8), \( I_0 \) is the intensity of the beams, \( x \) is the penetrating distance of the beams in the materials, \( \mu \) is the linear attenuation coefficients of the material, \( \mu \) is changed along with the energy of the particles, the chemistry components, and the density of the materials.

Therefore, if we obtained the sketches of the particles penetrating through the materials, then the density of the materials could be told if the sketches were thoroughly separated and evaluated with reference substances with known densities. This method was known as the computer tomography (CT) methods used frequently in sensing the density of the bones in human body [10].

2.2.2. The acoustic impedance method

According to [11], the characteristic impedance with respect to the free-air wave impedance \( W \) and the propagation constant \( \gamma \) could be used to formulate the density of the snow \( d \). Experiments shown that there is a good relationship between \( \log |W| \) and \( d \):

\[ \log |W| = 0.06 - 1.55 \log (1 - d) \]

(9)

The coefficient of determination \( R^2=0.918 \) shows that the density of the snow is strong related to the acoustic impedance.

The centrifugal sedimentation and flotation of nano-particles

Caterina Minelli et.al. proposed a new method to measure the size and density of nanoparticles by centrifugal sedimentation and flotation [12]. The calculation equation was obtained from the Stokes’ law:

\[ \rho_n = \rho_f + \frac{t}{t_c} \left( \frac{D_p}{D_n} \right)^2 \left( \rho_c - \rho_f \right) \]

(10)

Where \( \rho_f \) is the fluid density, \( t \) is the sedimentation time, \( t_c, D_c, \) and \( \rho_c \) are the sedimentation time, diameter, density of a sample, \( \rho_n \) and \( D_p \) are the density and the diameter of the desired nanoparticles. So if \( D_p \) is obtained, then the density of the nanoparticles could be calculated with the above equation.

2.2.3. The magnetic levitation method

The density of diamagnetic particles could be derived from the magnetic levitation [13]. An integrated analytical system was developed to acquire the high-throughput density with the following equation:

\[ \rho_s \approx \frac{\chi m}{\mu_0 g} \left( B_s \frac{dB_z}{dz} \right) + \rho_m \]

(11)

Where \( \rho_s \) and \( \chi_s \) are the density and the magnetic susceptibility of the suspended sample; \( \rho_m \) and \( \chi_m \) are the density and the magnetic susceptibility of the paramagnetic medium; \( B_s \frac{dB_z}{dz} \) is the strength and gradient of the magnetic field.

2.2.4. Other methods

Statistical analysis of the snow penetration experiments also gives another way to obtain the snow density [14]. With the SnowMicroPen penetration experiments, the density of the snow could be formulated as follows:

\[ \rho_{\text{Snow}} = \rho_l \left( \frac{1}{g \sigma f_{sl}} \right)^\frac{1}{3} \left( \sigma_s \right)^\frac{1}{3} \]

(12)
Where \( \sigma_{s,1} \) is stress on ice bonds at particular strain rate, \( \sigma_s \) represents maximum penetration resistance in case of snow, \( g \) and \( h \) are constants and \( \rho_i = 0.917 \text{Kg/m}^3 \) is the ice density.

3. **Automatic density devices for high explosives**

Considering the impaction of the force, electricity and energy, it is very suspicious for the indirect density measuring methods to be applied in high explosives. Thus, the traditional direct measuring methods should be paid more attention to during the foreseeing procedure for automatic devices.

### 3.1. Brief prospective reviews

Detailed description of the three methods summarized in section two is shown in Table 1. We can draw a conclusion that the devices based on the Archimedes’ law are difficult to design and integrated because of the liquid medium. However, the way to calculate the density values proportionally lacks the accuracy. Consequently, for designing modern automatic density measuring devices, the Boyle’s and Marriott’s law might be the only way to deal with.

| Items          | Archimedes’ | Boyle’s | Proportionally |
|----------------|-------------|---------|----------------|
| Medium         | Liquid      | Air     | Solid          |
| Target Mass    | Volume      | Density |
| Time           | Long        | Short   | Short          |
| Accuracy       | \( \leq 0.1\% \) | \( \leq 0.1\% \) | \( >1\% \) |
| Scope          | Unlimited   | \( \rho \leq 2.55 \text{g/cm}^3 \) | Unlimited |
| Automation     | Low         | High    | High           |

### 3.2. Compositions of the modern automatic devices

Nowadays, the mass of a volume is easy to be obtained with various kinds of sensors such as the Piezoelectric sensors\(^{[15]}\), MEMS sensors\(^{[16]}\). And the pressure is also easy to be measured with pressure sensors. Therefore, we can construct the automatic devices for measuring density of the bulks if some initial volumes could be obtained, referring to equation (7).

The sketch is drawn as shown in Figure 1. A container with initial inner empty volume \( V_0 \) is equipped with two kinds of sensors, the pressure sensor and the mass sensor (piezoelectric or MEMA sensors). When a bulk with unknown volume \( V \) is involved, the mass sensor would output the mass and then, another reference volume \( V_1 \) is pushed to the container through the tunnel. The pressure sensors would tell the pressure changes before and after the action. And therefore, the total density of the bulk could be calculated with equation (7).

To automatically calculate the real density in time of the bulk, an embedded microcontroller should be introduced to acquire the signals of sensors, dispose them and calculate the density values.

The connections between different components of such devices might be appeared as the sketch shown in Figure 2. The microcontroller connects with the load device which is used to propel \( V_1 \) air into the container. The pressure sensor and the mass sensor sense and calculate the pressure of the container, the mass of the bulk. And then, the final results would be output to the printer, screen or other external devices.
Figure 1 Sketches for the new device. Figure 2 Connections between the components

3.3. Accuracy analysis

Full derivation of equation (7) and we could obtain the errors relationship between the parameters:

\[
(\Delta p)^2 = \frac{(p - p_0)^2(\Delta m_0)^2}{[pV_0 - p_0(V_0 + V_1)]^2} + \frac{(m_1 - m_3)(V_0 + V_1)(m_1 - m_2)(p - p_0)}{[pV_0 - p_0(V_0 + V_1)]^2} \frac{(\Delta m_1)^2}{(p - p_0)^2} + \frac{m_1 - m_3}{[pV_0 - p_0(V_0 + V_1)]^2} (\Delta p_0)^2 + \frac{V_0(m_1 - m_2)(p - p_0)}{[pV_0 - p_0(V_0 + V_1)]^2} (\Delta p)^2 + \frac{(m_1 - m_3)^2(p - p_0)^2(\Delta V_0)^2}{[pV_0 - p_0(V_0 + V_1)]^2} + \frac{p_2(m_1 - m_3)^2(p - p_0)^2(\Delta V_1)^2}{[pV_0 - p_0(V_0 + V_1)]^2} \tag{13}
\]

Therefore, for a standard devices composed with the mass absolute error 1g, 0.01% Gruck DPS/RPS 8000 pressure sensor, and relative error 2.5×10⁻⁴, and then we can draw the relationship curve as shown in Figure 3 and Figure 4.

Figure 3 Influence of \(V/V_0\) to \(\Delta \rho\) when \(m=100\text{Kg}\)

Figure 4 Influence of \(V/V_0\) to \(\Delta \rho\) when \(m=50\text{Kg}\)

Consequently, if we design the automatic density measuring instrument, the propelled volume of air is relevant to the container’s volume in order to achieve the better accuracy. Furthermore, to maintain the non-fluctuated temperature of the system as equation (7) required, there should be a need for the tunnel to be large in diameter and for the load to be quick and steady.

4. Discussions and conclusions

In this paper, we briefly summarized the density measurement technologies. To meet the need for automatically measuring the density of high explosives, we compared the direct and indirect methods, and drew the conclusion that one of the direct way based on Boyle’s and Marriott’s law might be easy to be achieved. Finally, we discussed about the components, connections and the accuracy and their relationship. Efforts could be helpful for the military modernizations.

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