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Research Article

APPLICATION OF THE GAS-DYNAMIC PRINCIPLE OF DEEP LOOSENING OF THE SUBSOIL ARZYK LAYER OF SOIL

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Tojiyev Rasuljon Jumabayevich
Fergana Polytechnic Institute, Fergana, Uzbekistan
Orchid: -https://orcid.org/0000-0001-5636-5840

ABSTRACT

The article provides information about a new method of deep loosening of the subsoil layer of soil, based on the application of the energy of a detonation wave. For this purpose, the design and justification of the parameters of a device that impacts the soil non-contact and operates based on detonation energy, intended for deep loosening of the subsoil layer of soil, were developed.

KEYWORDS

Subsoil horizon, loosening, deep loosener, detonation wave, gas-dynamic impulse, soil, detonation, pressure impulse, shock wave, stress.

INTRODUCTION

One of the directions of the ongoing reforms in Uzbekistan is to enhance the efficiency of agricultural production. There are various paths and methods to elevate agricultural production to a global level. This can be achieved through the intensification of agricultural production, primarily by applying scientifically grounded systems of agriculture, efficient use of land resources, and increasing their fertility. Enhancing the efficiency of irrigated land use is impossible without improving the fertility of the subsoil layer through deep soil processing.

At a bulk density of subsoil horizons of 1.4 g/cm^3, especially at 1.5 g/cm^3 and above, plant roots primarily develop in the plow layer, which is prone to frequent drying during hot summer periods.

M.V. Mukhamajanov [1] believed that dense subsoil horizons over vast areas of old irrigated lands contribute little to the yield of agricultural crops, effectively lying as dead capital. In his opinion, these layers can be made water- and root-permeable for cotton by loosening them without turning the layer over.

According to experiments conducted at the Institute of Experimental Biology of Plants of the Academy of Sciences of Uzbekistan, loosening the soil to a depth of 50 to 60 cm in combination with ordinary plowing to a depth of 30 cm allows for an increase in the yield of raw cotton by an average of 3 to 4 centners per hectare compared to ordinary plowing to 30 cm, due to better moisture penetration into the soil, aeration, and improved nutrient uptake by plants.

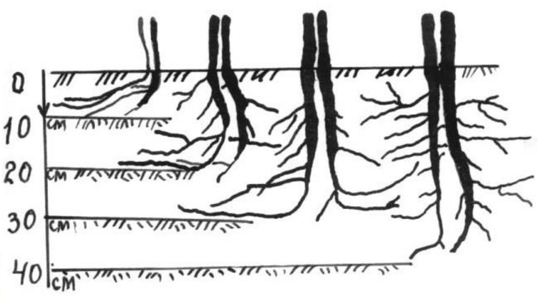
Experience from foreign cotton farming, especially in the USA, also indicates a rather widespread adoption of periodic deep soil loosening, for which special tools (subsoilers, kilifers, etc.) have been created and produced. Some practical experience in deep soil loosening (up to 50 cm) on old irrigated lands with compacted subsoil layers has been accumulated in the Bukhara, Andijan, Fergana, and Namangan regions. However, the widespread application of this method is hindered by the lack of highly efficient soil treatment tools in production.

Deep soil processing is fairly widespread in Western European countries, the USA, and Canada. In Arizona (USA), the depth of soil processing for cotton on serozem soils has reached 50 cm or more [2]. According to many farmers and researchers at experimental stations, deep processing, especially on heavy soils, improves conditions for cotton development [3]. In arid regions of the USA, deep loosening is considered the most promising method for combating salinity, resulting in at least a 10% increase in yield.

M.V. Mukhamajanov and S. Suleimanov [1] established that in compacted layers, the main and lateral roots of cotton are forced to change their growth direction toward less compacted layers.

With deep processing, the root system of cotton develops in favorable conditions, experiencing minimal deformation, less compression, and less bending (see Fig. 1), and is covered with lateral branches along its entire length. Thus, according to M.V. Mukhamajanov and S. Suleimanov [1], when plowing to a depth of 30 cm and loosening the soil to 55 cm, the number of taproots directed vertically downward with almost no deformation was four times greater than with plowing to 30 cm without loosening. The experiments of A. Juraev [1] confirmed that loosening the subsoil horizon to 50 cm allowed cotton roots to penetrate to a depth of 190 cm, which led to an increase in the yield of raw cotton.

Fig. 1. Development of the cotton root system with depth of processing.



The deep loosening devices currently in use do not meet modern energy efficiency requirements and have low productivity. Therefore, we have proposed a new method for deep loosening of the subsoil layer, based on the application of detonation wave energy, which has not been used anywhere before.

We conducted theoretical and experimental research on the use of detonation energy during the drilling of boreholes to improve the meliorative condition of lands and increase the yield of cotton.

First, we will provide a brief overview of the development of the theory and experiments on the detonation of gas mixtures. This is necessary primarily for the correct selection of theoretical tools in determining the main design parameters.

It should be noted that detonation is the process of flame front propagation in gas and condensed mixtures of fuel and oxidizer, consisting of a shock wave, a zone of chemical reactions, and a zone of expansion of the products of chemical reactions. This type of combustion, unlike so-called normal combustion, is characterized by high velocities. For example, for most hydrocarbon fuel mixtures (acetylene, propane, gasoline, etc.) with air, the propagation speed lies in the range of 1600-1800 m/s, while for condensed mixtures (such as TNT), it is 6000-7000 m/s.

After the arrival of the DW at the open end of the tube, a rarefaction wave forms in the direction of the closed end, since the flow speed of the DP is less than the speed of sound. The pressure at the closed end before the arrival of the rarefaction wave remains constant and is equal to P.

With a known value of M (D) of the shock wave in air, the parameters of the air behind the shock wave are determined by known dependencies [38].

1. $P_{1m} - P_0 = \frac{2\rho_0 \cdot D^2}{K+1}\left(1 - \frac{C_0^2}{D^2}\right) \rightarrow \frac{P_{1m}}{P_0} = 1 + \frac{2 \cdot \rho_0 \cdot D^2}{K \cdot \rho_0 \cdot C_0^2 (K+1)} \cdot \left(1 - \frac{C_0^2}{D^2}\right) \rightarrow P_{1m} = \frac{P_{1m}}{P_0} = 1 + \frac{2M^2}{K(K+1)} \cdot \left(\frac{M^2-1}{M^2}\right)$, at the same time $[P_0 = K \cdot \rho_0 \cdot C_0^2]$ (1)

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2. $U_{1m} = \frac{2D}{K+1}\cdot\left(1-\frac{C_0^2}{D^2}\right) \to \bar{U}_{1m} = \frac{U_{1m}}{C_0} = \frac{2M}{K+1}\cdot\left(\frac{M^2-1}{M^2}\right)$ (2)

3. $\rho_{1m} = \rho_0\left[1-\frac{2}{K+1}(1-\frac{C_0^2}{D^2})^{-1}\right] \to \bar{\rho}_{1m} = \frac{\rho_{1m}}{\rho_0} = \left[1\frac{2}{K+1}\left(\frac{M^2-1}{M^2}\right)\right]^{-1}$ (3)

At the contact discontinuity between the air and combustion products: due to the continuity of pressure **P** and speed at the contact discontinuity.

1) $P_{kp} = P_{1m}$

2) $U_{kp} = U_{1m}$

3) $\rho_{kp} \neq \rho_{1m}$

Since **ρ**, **u**, and **T** lose continuity at the contact discontinuity line; **"T"** due to the heating of the **"PS"**: and **"ρ"** already due to **"T"**. Therefore, $\rho_{\square r}$ and $T_{\square r}$ are determined as follows:

It is shown that the **"PS"** expand at the end with a variable angle **λ = f(t)**, where **t** is the time from the beginning of the outflow.

In the initial phase of the outflow, the angle is maximized:

d - diameter of the impact spot.

Assuming that the **"PS"** expand isentropically in the jet, and taking the adiabatic proof of **"PS"** as $K_{\square r} = K\_air$ /(actually $K_{\square r} = 1.29$, **K = 1.4**)/, we find:

3) $\bar{\rho}_{kp} = \frac{\rho_{kp}}{\rho_0} = \left(\frac{\rho_{1m}}{\rho_0}\right)^{\frac{1}{k}} = P_{1m}^{\frac{1}{k}} = \left(1+\frac{2M^2}{K(K+1)}\cdot\frac{M^2-1}{M^2}\right)^{\frac{1}{k}}$ (4)

4) $\bar{T}_{kp} = \frac{T_{kp}}{T_0} = \left(\frac{\rho_{1m}}{\rho_0}\right)^{\frac{k-1}{k}} = \left(\frac{\rho_{kp}}{\rho_0}\right)^{\frac{k-1}{k}} = \bar{P}_{1m}^{\frac{k-1}{k}} = \left[1+\frac{2M^2}{K(K-1)}\cdot\frac{M^2-1}{M^2}\right]^{\frac{k-1}{k}}$ (5)

These quantities are maximal for the chosen point in space; then, there is a decrease in these quantities from the moment the shock wave arrives at this point in space (**τ = 0**) until the end of the effect ($\tau_{\square a}$), where ($\tau_{\square a}$ is the time of the air compression phase).

Thus, the variable field of flow parameters for a pipe of length **L**, diameter **d**, filled with a stoichiometric gasoline-air mixture, can be expressed as a function of a single variable **χ**.

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$$\frac{P_{nc}}{P_0} = P_{nc} = \frac{P_{kp}(\bar{\chi})}{\tau_c{}^8(\chi)}[\tau_c(\bar{\chi}) - \tau]^8 \qquad (6)$$

$$\bar{P}_{kp}(\bar{\chi}) = P_{1m}(\bar{\chi}) = 1 + \frac{2M^2}{K(K+1)} \cdot \left(\frac{M^2-1}{M^2}\right), \quad \mathrm{M} = \frac{5}{\chi+1} + 1 \qquad (7)$$

$$\frac{\rho_{nc}}{\rho_0} = \bar{\rho}_{nc} = (P_{nc})^{\frac{1}{k}} \qquad (8)$$

$$\frac{T_{nc}}{T_0} = \bar{T}_{nc}(\bar{P}_{nc})^{\frac{k-1}{k}} \qquad (9)$$

$$\frac{U_{nc}}{C_0} = \bar{U}_{nc} = \frac{\bar{U}_{kp}}{\bar{\tau}_c^4}[\bar{\tau}_c(\bar{\chi}) - \bar{\tau}]^4 \qquad (10)$$

$$\bar{U}_{kp}(\bar{\chi}) = \bar{U}_{1m}(\bar{\chi}) = \frac{2M}{K+1}\left(\frac{M^2-1}{M^2}\right) \qquad (11)$$

$$\bar{\tau}_c = \bar{\tau}_{c_\circ} \cdot l^{-0,17\cdot\bar{\chi}} = 3{,}8 \cdot l^{-0,17\cdot\bar{\chi}}, \qquad \bar{\tau}_c = \frac{\tau_c \cdot C_0}{L} \qquad (12)$$

The calculation of the flow process between the open end of the pipe and the ground surface provides a clear representation of the characteristic flow zones, geometry, and the overall time of the process. For accuracy and convenience in determining the initial data regarding the load on the ground from the action of the detonation pipe, experiments were conducted according to the following scheme.

Description of the process:

In a pipe of length **L_{tr}** and diameter **d_{tr}**, a detonation of a fuel-air mixture occurs. From the open end of the pipe, which is at a distance **l** from the ground surface, an shock wave and a flow of detonation products exit. The wave and flow expand on their way to the surface and impact the ground in the area of the "spot" with a diameter of **d_n**.

The expansion is determined by the angle **λ**. For a given diameter **d_{tr}** and different lengths **L_{tr}**, measurements of the force exerted at various distances **l** were carried out.

The measurement was performed using a special device in which the force was perceived by a plate resting on a gas (air) cushion. From the measurements of the change in pressure in the gas cushion, the effective force was calculated.

The results were approximated by the following dependencies:

$\mathrm{F}(t) = A \cdot S \cdot l^{-\alpha t}$ — The force acting on the "spot" with a diameter of **d_n**.

$\mathrm{S} = \frac{\pi}{4} d_n^2$ — Area of the "spot" / cm²/.

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t	Time, from “0” to $t_k=3.5\ L_{тр}\backslash Spg$
t_k	Final time, outflow / process time
$C_{пg}$	Speed of sound in the products of detonation of the fuel-air mixture
A=35$\cdot(13-l)$	Dependence reflecting the decrease in impact force with increasing “l”
$0\leq l\leq 0{,}07$	Measurements were taken in these ranges of “l” for the pipe d_тр = 25 mm (the pipe used in the loosening devices).

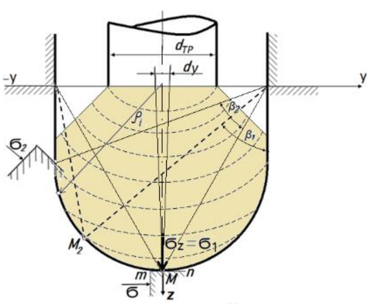
35 - a number reflecting the pressure in the shock wave and the speed of the detonation products behind the wave.

l - the number “l”

α - the exponent in the approximation dependence. It is determined from experimental functions F(t) and expresses the dependence of F(t) on the length of the pipe L_(тр).

The central idea of the research is the application of the detonation wave as a "tool" for force impact. Detonation of conventional fuels (gasoline, gas) with air produces a force impulse with the following parameters:

- Pressure in the shock wave: 35 atm;
- Velocity of detonation products: 800 m/s;
- Movement of the detonation wave through the channel at a speed of approximately 1600 to 1800 m/s.



Such a gas-dynamic impulse impacts any surface as a sharp, brief blow. The force of the blow and its direction can be regulated, allowing the impact to be directed, for example, strictly perpendicular to the surface without lateral (shear) components of force. The "tool" here is the gas-dynamic impulse, in contrast to the claws of a deep tillage tool.

According to the recommendations presented in the literature, the shape of the head part of the contact surface can be approximated as the surface of a hemisphere. The distribution of pressure on the surface of the head of the hemisphere is critical in the force impact of the soil on the contact surface. B.G. Korenyev and I.T. Rabinovich [4] suggest considering the soil as a plastically (irreversibly) compressible continuous medium that possesses internal "friction and cohesion" between the conditional particles. Therefore, the total resistance force F_{conp} of the soil applied to the contact surface of the gas-detonation pipe can be determined as follows.

$$F_{conp} = F_1 + F_2 + F_3 \qquad (13)$$

where:

F_1 – the force of dynamic resistance caused by the inertia of the particles of the medium, as well as the friction between them;

F_2– the friction force at the contact surface;

F_3– the force of static resistance, the magnitude of which depends only on the strength of the barrier.

The static (strength) resistance force is determined by the formula:

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$$F_3 = \begin{cases} P_* \dfrac{\pi d^2}{4} \quad npu \quad P(t) \succ P_* \\ P_*(t) \dfrac{\pi d^2}{4} \quad npu \quad P(t) \prec P_* \end{cases} \qquad (14)$$

where P_* - compressive strength of soil.;

P(t) – pressure impulse on the contact surface from the gas.

The force F_1 of dynamic resistance is calculated using the formula proposed by A.Ya. Sagomonian [5, 6].

$$F_1 = 0{,}285 \frac{\pi d^2}{4} \varepsilon \rho_0 v^2 \qquad (15)$$

where ε - magnitude of excess pressure.;

ρ_0 – initial soil density;

v – velocity of the contact surface..

In this case, the insertion involves not a solid hemisphere but a gas under increased pressure. Therefore, the interfacial friction force F_2 can be represented as the friction forces of the combustion products that are under higher pressure against the soil.

As is known, the friction force F_2 is determined by the formula.

$F_2 = f\,P$ (16)

where f – friction coefficient;

P – normal pressure on the soil.

The soil mass affected by the shock wave will undergo deformation at all its points. It is noteworthy that there are multiple points within this mass with identical stress values, and the geometric locus of these points must represent a certain regular curve.

Figure 2. Calculation scheme.

Under uniform or strip loading, the position of any point is most simply determined using polar coordinates, i.e., the angle formed by rays from the point to the edges of the strip. These angles are referred to as the angle of visibility and are denoted as 2β2\beta2β. The ray is inclined to the vertical at angles β1or β2 if they are measured from their verticals in the same direction, they are considered positive. If they are measured in opposite directions, one of them is given a negative sign. The algebraic sum of angles β1 and β2 equals the angle of visibility.

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In the soil mass, there can be an infinite number of points with the same angle of visibility. However, since all of them correspond to the same width of the strip, like a chord, their geometric locus forms a circle, with the angles of visibility inscribed within this circle. Therefore, one can take the most convenient specific position of points on the circle drawn through an arbitrary point M and derive a relationship for the principal stresses, normal and tangential, at any point.
It is known that the vectors of the principal stresses σ1 from the loading of the shock wave are directed along the bisectors of the angles of visibility, while the stress σ2is perpendicular to them.
The loads from the shock wave can be represented as a system of numerous concentrated elemental forces, continuous over a segment equal to the width 2d of the diameter of the detonation pipe. By utilizing the well-known formulas of Flanagan and Mitchell [7] and integrating the stresses due to these forces within the angle of visibility, we can obtain the following formulas for the principal stresses at any point in a linearly deformable soil mass:

$$\begin{cases} \sigma_1 = \dfrac{P}{\pi}(2\beta + \sin 2\beta) \\ \sigma_2 = \dfrac{P}{\pi}(2\beta - \sin 2\beta) \end{cases} \quad (17)$$

where β - angle of visibility.

"Formula (27) describes the mechanism of stress distribution in the soil layer at the open end of the detonation pipe."

If you need the translation for the specific formula (28) as well, please provide the formula or its content!

$$P = \frac{\sigma_1 \pi}{2\beta + \sin 2\beta} \quad (18)$$

Considering (29), the interfacial friction force can be written as follows: $F_2 = f\dfrac{\sigma_1 \pi}{2\beta + \sin 2\beta}$ (19)

"To determine the total soil resistance force Fsop applied to the contact of the detonation pipe, the values of F1, F2, and F3 are used.

$$F_{\text{сопр}} = \frac{0{,}285\pi d^2 \varepsilon \rho_0 v^2}{4} + \frac{P_* \pi d^2}{4} + \frac{f\sigma_1 \pi}{2\beta + \sin\beta} \quad (20)$$

When the contact surface moves, the force acting on it from the gas equals the resistance force of the soil. This condition, taking into account formulas (6, 7), can be expressed as follows.

$$\frac{\pi d^2}{4} P(t) = \frac{\pi d^2}{4} \cdot 0{,}285 \varepsilon \rho \cdot v^2 + P_* \frac{\pi d^2}{4} \quad (21)$$

, $P(t) = \beta \varepsilon^{-\lambda t}$

From this, the relationship for determining the penetration speed can be derived.

$$v = 1{,}875\sqrt{\frac{P(t) - P_*}{\varepsilon \cdot \rho_0}} \qquad (22)$$

to zero over time. $t_1 = \frac{1}{\lambda}\ell n\frac{\beta}{P_*}$

The penetration depth XXX is determined from the expression.

$$X = 1{,}875\sqrt{\frac{\beta}{\varepsilon\rho_0}}\int_0^{t_1}\sqrt{e^{-\lambda t} - \frac{P_*}{\beta}}dt$$

After integration, we will obtain.

$$X = \frac{3{,}752}{\lambda}\sqrt{\frac{P_*}{\varepsilon\rho_o}}\left(\sqrt{\frac{\beta}{P_*} - 1} - arctd\sqrt{\frac{\beta}{P_*} - 1}\right) \qquad (23)$$

is "Multiplying X by the pulse frequency f will give us the drilling speed $V_{бур}$.

$$V_{бур} = X\,f \qquad (24)$$

The mechanized method is based on the principle of detonation of fuel-air mixtures in pipes, as described earlier. The force of the micro-explosions can be regulated both by the magnitude of each individual explosion and by the frequency of their occurrence. The created and tested explosion generators are capable of producing up to 20 micro-explosions per second.

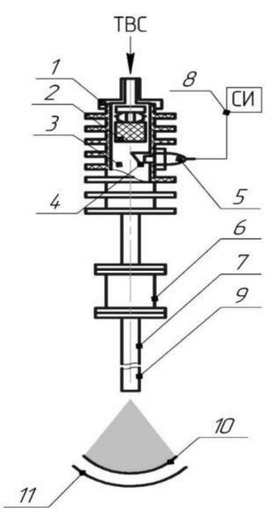

Fig. 3. Diagram of the detonation wave generator. 1 - device for supplying fuel-air mixture (TVC); 2 - flame barrier valve; 3 - ignition chamber; 4 - spark plug; 5 - tube accelerator; 6 - pipe; 7 - signal sensor; 8 - nozzles; 9 - combustion products (PS); 10 - shock wave."

The detonation wave formed in the combustion chamber, upon exiting the open end of the pipe, breaks down into a shock wave that propagates through the air and is followed by a flow of combustion products (Fig. 9).

The use of the detonation pipe as a tool for creating boreholes in the compacted sublayer of irrigated soils, typical for cotton-growing regions and leading to waterlogging, salinization, and loss of fertility in large areas of soil, is discussed.

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The technological scheme for using the generator to create drainage holes (boreholes) is shown in Figs. 6 and 7. The detonation pipe, aimed with its open end toward the soil and moved vertically, produces a cylindrical borehole. According to experimental data, the drilling speed is 1.5 m/min.
The process of borehole formation occurs as follows: In the 1st phase, the pipe is filled with a fuel-air mixture; in the 2nd phase, ignition occurs, and the detonation wave travels to the open end of the pipe; in the 3rd phase, the detonation wave and combustion products flow into the borehole, breaking the soil into small fragments. The flow of combustion products carries the broken soil out of the borehole. If an explosion occurs in the borehole during the 1st phase, pressure increases at the bottom, leading to the cracking of the borehole's side walls.
After the combustion products are released into the atmosphere, the pipe is filled with the mixture again, and the cycle repeats.
The size of the side cracks (their length) is about 30 cm. According to specialists' recommendations, the density of boreholes (boreholes) in saline areas should be 50 holes per hectare.

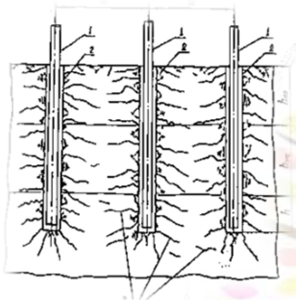

Fig. 4. Scheme of the mutual arrangement of detonation generators buried in the soil.
h_{nch}- arable layer;
h_{ych} - compacted layer;
h - buried under the compacted layer;
1 - detonation pipes;
2 - walls of the borehole;
3 - cracks in the soil from the walls of the borehole.

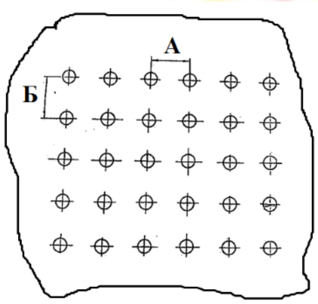

Fig. 5. Scheme of the mutual arrangement of boreholes (plan view).
A - distance between two neighboring boreholes along the front;
B - distance between two neighboring boreholes in depth.

The GDRP-3 attachment allows for drilling 8 boreholes with a depth of 2 meters in 3 minutes of machine time. To adapt the GDRP-3 equipment for the drilling task, additional nozzles for the detonation pipes and a lifting mechanism need to be manufactured. The approximate drilling time for one hectare is:

$$t = \frac{n(3+\Delta t)}{8 \cdot 60} \quad (25)$$

where, Δt is the additional time to machine time;
n is the number of boreholes per hectare.
With Δt = 2 minutes, t = 30 minutes."

After processing with the installation based on the use of the impulse of the detonation force, there was a noticeable increase in bicarbonates.
The increase in the content of bicarbonates in the soil layer, in our opinion, is related to the increase in CO_2 concentration directly in this layer, which occurs due to the injection of the fuel-air mixture into the gas-dynamic pipes. After the introduction of CO_2 into relatively moist soils, the following reaction occurs:"

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$$H_2O + CO_2 = H_2CO_3 \quad (26)$$

It is known that carbonic acid is weak, but it can quickly react with soil carbonates:

$$CaCO_2 + H_2CO_3 = Ca(HCO_3)2 \quad (27)$$

The formed H_2, CO_2, and HCO_3 maintain a weak alkaline reaction temporarily, thus enriching the soil solution with calcium and magnesium from their carbonates. As a result, the nitrification process is intensified, leading to improved nutrition of cotton due to nitrates.

To organize the cyclic operation of the detonation tool (DT), the following design will be developed, consisting of the following main components (see Fig. 3):

1. The device for supplying the mixture (I) consists of a nipple with three slots on the flange and a coupling nut with corresponding projections, allowing for quick disconnection of the TVS supply line for maintenance and repair work.
2. The flame barrier valve (2) is located at the entrance of a self-contained unit mounted in the ignition chamber. It performs the following functions: it ensures the filling of the DT with fresh mixture during the intake phase, prevents the flow of combustion products (CP) upstream during the working phase of the cycle, and cools the CP entering the valve grid during the working phase of the cycle, thereby reducing thermal and mechanical stress on the valve.

Additionally, the cooled portion of the CP serves as an intermediate layer between the fresh mixture and the CP during the exhaust phase. This prevents the spontaneous ignition of the fresh mixture from the CP of the previous cycle."

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