Elimination of a Fire through Shock Wave Interference: The Numerical Model and Application Scenarios

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Abstract— The authors present a non-traditional approach to the elimination of large-scale fire events, for example road and railway tanker accidents. The proposed solution consists in utilising the interference of shock waves generated by highly explosive substances. Within the analysis, the authors introduce the results obtained via the numerical modelling of the dynamical system behaviour and include the basic verification of the solution, which is carried out by means of the related experimental model.

1. INTRODUCTION

The energy of a shock wave can be utilised to stop the propagation of a land or forest fire [1]. If the use of concentrated charges is assumed, then these charges (weighing between 6 and 12 kilograms each) are to be distributed in a row at the distance of 1 m from one another, connected via a detonating cord, and detonated simultaneously just before the arrival of the fire front to approximately 10 meters from the explosive setup (Fig. 1).

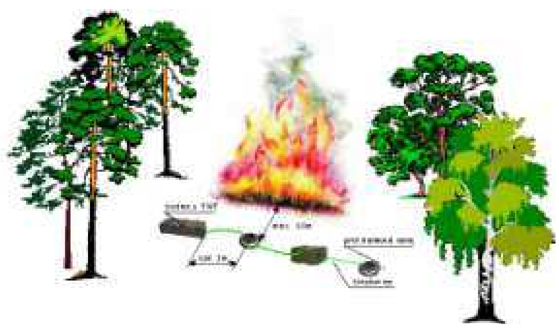

Figure 1: The use of concentrated charges arranged in a row to generate a shock wave suppressing the propagation of a surface fire.

Generally, it is possible to extinguish a fire by means of elongated charges containing suitable blasting agents [2]. The propagation of a surface fire can be effectively stopped by the initiation of charges configured in two rows or a circle; in this case, the energy released by two or more interfering shock waves constitutes a powerful fire-eliminating instrument, as indicated in source [2].

2. NUMERICAL MODEL AND ITS FORMULATION

The actual creation of the numerical model is based on the laws of hydrodynamics, or the behaviour of compressible and incompressible fluids; see references [2]. In the given instance, the exciting detonation wave travels through the air, which (in the assumed conditions) acts as a compressible fluid; the interference of the waves, however, significantly changes the superposed wave propagation speed in the air, and this environment can be interpreted in the indicated situation as an incompressible fluid. For the definition of the model, we assume the equilibrium state, and this description constitutes the basis of the numerical model design. The model of the assumed task is restricted to closed area Ω_F according to Fig. 2. We then have

$$\Omega_F = \bigcup_{i=1}^{4} \Omega_i \text{ a } \bigcup_{i=1}^{4} \Gamma_{\Omega i} = \Gamma_F. \tag{1}$$

From the state of the dynamic equilibrium of the system in the area Ω_F, it is possible to observe (in a simplified manner) at the boundary Γ_1 the conditions for the undamped process of an incompressible environment.

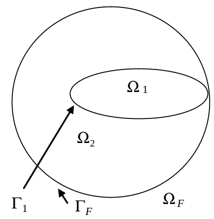

Figure 2: The general distribution of areas and boundaries in the numerical model.

To facilitate successful creation and solution of the model, a higher number of stability conditions have to be applied during the formulation of the physical model; thus, the designed mathematical model becomes more stable. For the given purpose, we can conveniently utilise the following formulas: The law of conservation of mass

$$\rho_0 U_s = \rho_1 (U_s - v_p) \quad \text{in the area } \Omega_F, \tag{2}$$

where ρ_0 is the volume density in the initial state (or in an uncompressed space), U_s is the wave speed in the uncompressed space, v_p is the shock wave speed, ρ_1 is the volume density in the compressed space. Then, for the law of conservation of momentum, we can write the equation

$$p_1 - p_0 = \rho_0 U_s v_p \quad \text{in the area } \Omega_F, \tag{3}$$

where p_1 is the instantaneous value of pressure in the compressed region, and p_0 is the instantaneous value of pressure in the uncompressed region. The law of conservation of energy is expressed as

$$\vec{e}_{Te1} - \vec{e}_{Te0} = \frac{1}{2} (p_1 + p_0) (V_0 - V_1) \quad \text{in the area } \Omega_F, \tag{4}$$

where $\vec{e}_{Te1}$, $\vec{e}_{Te0}$ are the specific deformation tensors in the compressed (index 1) and uncompressed space (index 0), V_0 is the specific volume of the uncompressed region, V_1 is the specific volume of the compressed region. The above-discussed models are formed using ANSYS tools, such as LS Dyna or Autodyn [4]. As both the burning and the pressure wave propagation are dynamical processes, it is suitable to complete the model with the parameter of the state of oxygen balance during the burning [3].

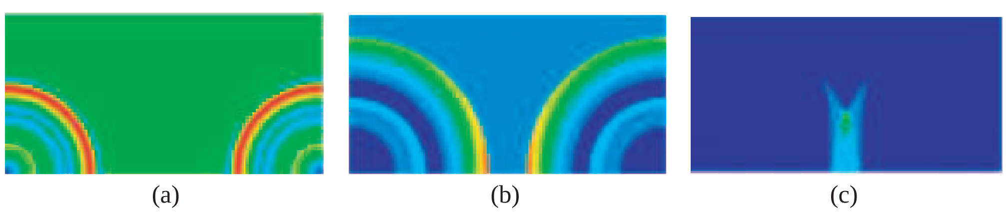

Figure 3: The distribution of the pressure state $p(t)$, (a) $t = 0.0\,\mu s$, (b) $t = 203.0\,\mu s$, (c) $t = 318.0\,\mu s$ in elongated charges.

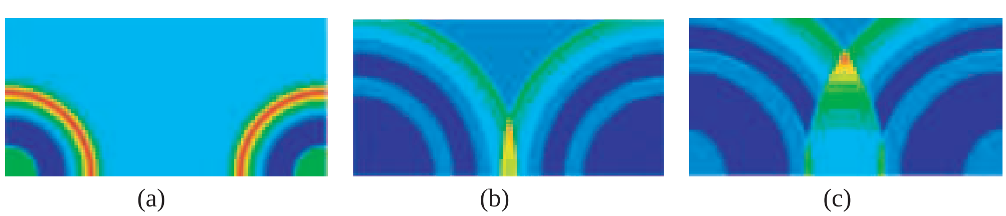

Figure 4: The initial pressure condition $p(t)$, (a) $t = 11.0\,\mu s$, (b) $t = 350.0\,\mu s$, (c) $t = 500.0\,\mu s$ in the circular configuration of elongated charges.

The distribution of the state of instantaneous oxygen balance in a fluid (or the air) can be determined according to several models [10], from which the Jones-Wilkins-Lee model appears to be the most convenient option for the purposes of the research described herein. The instantaneous oxygen distribution has to be considered during the actual creation and processing of the model. The model can be expressed by the formula

$$p(\rho, W) = A\left[1 - \frac{\omega\rho}{R_1\rho_0}\right] e^{\left(-\frac{R_1\rho_0}{\rho}\right)} + B\left[1 - \frac{\omega\rho}{R_2\rho_0}\right] e^{\left(-\frac{R_2\rho_0}{\rho}\right)} + \omega\rho(W - W_0), \tag{5}$$

where A, B, R_1, R_2, ω are the constants for the given blast, and W_0 is the reference internal energy in the uncompressed state. Examples of the representation of pressure development analysis for both the standard arrangement of elongated charges and their circular configuration are shown in Figs. 3 and 4, respectively.

3. DESIGN OF A FIRE ELIMINATION METHOD UTILISING A CONTROLLED EXPLOSION

Tanker fires on railway tracks or roads are often poorly accessible for fire-fighting trucks and other heavy equipment, and this condition constitutes a significant problem as classical fire extinguishing methods frequently have to be used. In this context, the main disadvantage of the classical techniques consists in two aspects, namely the use of high-pressure hoses and limited access to water sources. Owing to these drawbacks, it is often necessary to carry out a very demanding transfer of fire-fighters and the related bulk of technical equipment to suppress a mere local fire, which is nevertheless situated in difficult terrain [7, 8]. In such conditions, considerable damage to property may arise in addition to personal health risks. Another important factor is the actual length of the fire suppression process; with long quenching of burning liquid fuel, there is a high probability that the fire will eventually produce a detonation and spread itself in the surrounding areas, Figs. 5 and 6. The above-described drawbacks and limitations of known fire-extinguishing methods related to flammable liquids transported by road or railway tankers can be substantially reduced by the proposed novel technique of eliminating such liquid substance fires [9]; more concretely, the discussed method is a procedure utilizing the interference of shock waves induced by the explosion of blasting agent charges. The principle of the technique consists in creating a direct or concave operational line formed by a homogeneous detonating system [2] (Fig. 5) or, alternatively, by individual detonating elements; these elements are then interconnected by means of a quick match string (Fig. 8) that carries the detonation pulse. The total detonating potential of the operational line corresponds to a speed of 4200 to $6700\,\mathrm{m\cdot s^{-1}}$. If we use a new version of electronic detonators, then each detonator can be placed separately in the individual detonating elements; subsequently, the relevant programming is carried out. Thus, we may eliminate the process of interconnecting the individual charges (detonating elements) by means of the quick match string that carries the detonation pulse (the detonating fuse/cord). The exact distance between this line for centralised detonation launch and the actual burning object depends on the fire intensity. The explosion of a charge in the air or a compressible fluid is accompanied by the propagation of a shock wave from the point of detonation, and this wave then progressively loses its energy until it converts itself into an acoustic wave, whose speed is identical with the speed of sound propagation. If the shock wave collides with a solid barrier, it reflects from this barrier and acts on it with a reflective pressure (whose value may reach as high as thirty six times the pressure on the shock wave front). These characteristics determine the eventual destructive force of the shock wave. However, the reflective pressure value in acoustic waves constitutes merely a double of the pressure on the shock wave front. It is possible to prevent the propagation of fire by means of exploding charges arranged in two rows (or in a circle); this arrangement enables us to utilise the interference energy of the impact and the reflection related to two (or several) shock waves. The interference of two circular (or spherical) waves occurs, for example, during the explosion of two charges which are placed within a sufficient distance from each other (Fig. 4). Thus, undulations are generated that propagate simultaneously against one another from the direction of both sources. If two charges of the same explosive having an identical weight are blasted at the same moment of t_0, they oscillate in identical phases. The resulting interfered wave is then given by the superposition of both travelling waves. If both the charges are blasted at the same moment of t_0, the wave fronts travel against each other and, after colliding at the speed of v_0, they induce a backward wave; this wave, however, has a speed of v_0 that may be up to 64-fold higher, which constitutes a double (the sum) of both reflective pressures. If we allow simultaneous induction of waves from two elongated charges arranged in a parallel way, with the fire area located between the charges, we obtain a situation when both the blast waves collide and reflect at a multiple speed in the middle of the fire area. The effect is multiply more intensive in comparison with the application of only one detonating wave, and the advantage of the

Figure 5: The photo documentation of a tanker railway collision.

Figure 6: The photo documentation of a tanker highway collision.

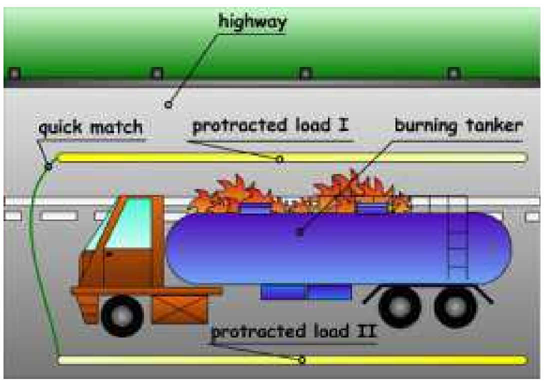

Figure 7: Elongated charges positioned to extinguish a burning tanker.

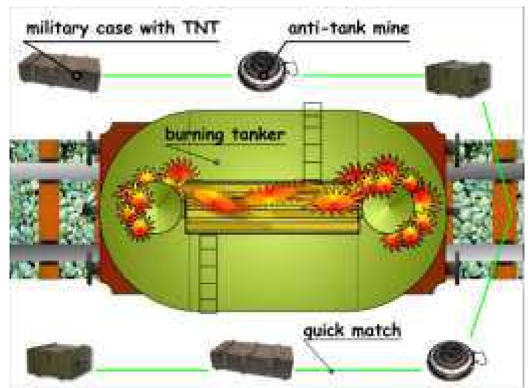

Figure 8: The arrangement of concentrated charges extinguishing the fire of a railway tanker.

solution consists in the fact that elongated charges can be located at a greater distance from the fire.

A homogeneous detonating system can be formed advantageously using a continuous elongated charge. A heterogeneous fire-quenching (operational) line usually consists of individual detonating elements; these elements can be set up by the help of concentrated charges (Fig. 8), partial elongated charges, anti-tank or anti-personnel mines, and explosive boxes (containers). In order to transfer the related detonation pulse, we can utilise instruments such as a detonating fuse or a new electronic detonator specially developed for the discussed purpose [2]. Depending on the applied initiators and detonation pulse transfer instruments [3], the detonation process is then started by means of fire initiation, electric ignition, or remote control.

4. CONCLUSION

The main advantages of the proposed method for local surface (ground) fire elimination using blasting technics consist in its simplicity, effectivity, and application characteristics. The last of these points primarily refers to possible utilisation of the method in emergencies where only a small number of people (rescuers) are involved or where water is available only with considerable difficulty. These aspects of the discussed method are further demonstrated on the reduced experimental models. Significantly, this fire extinguishing technique does not require the use of heavy or special machines, and it obviates the problems connected with the transportation of such machines or related fire-fighting persons. Thus, we may control and progressively extinguish even very complicated fires, which are often difficult to eliminate by means of currently available technologies. Above all, however, the proposed quenching method provides a higher degree of protection regarding the engaged fire-fighters and their costly equipment.

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