

Thermal Behavior of a High-Energy Material Immersed in a Fire

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Abstract

One of the uncertainties in the calculations of time-to-explosion for containers of high-energy materials immersed in fires is that of the thermal boundary at the container-explosive interface. Understanding this interface is critical in evaluating risks, safety issues and prevention mechanisms. In this work, the use of the Duhamel superposition method, coupled with measured internal temperatures, has shown that a 0.1m- diameter steel pipe containing PBX-9501 demonstrates similar thermal behavior when heated by either a propane fire or electricity. Similarly, the use of a transient heat transfer model has provided a great physical understanding of the system. For instance, the model predicted that a thermal contact resistance dropped the steel/explosive interface temperature by nearly 40%. The results are in agreement with an ignition model for HMX explosives.

Introduction

If an explosive device is accidentally exposed to an enveloping fire, (i.e. accidents in transportation, normal handling, terrorist or battle action, etc), it will, after certain period of time, undergo a thermally induced reaction that may cause damage to the surroundings. The violence and the time to explode depend strongly on the heat flux reaching the explosive. Since the thermal interface condition is not yet well understood, it has been proposed that pool fires be used for the simulation of accident scenarios [1]. For instance, all propellants and explosives used in munitions must pass fast and slow cook off test with no reaction more severe than burning [1]. In other words, the case must fail structurally before the propellant ignites. Therefore, the tests are very important in designing and selecting the material case, and the attachments to the case-explosive interface. However, it is very difficult to perform well-controlled fire experiments and thus the uncertainties are usually an obstacle for a good description of the interface.

The main goal of this paper is to report some similarities in the thermal behavior of a highly energetic material when heated by a fire and electricity. The paper discusses in detail the analysis of the experimental results and presents a novel treatment of the interface.

Experimental

A series of Fast cooks off experiments were carried out considering two experimental conditions. The first condition was the typical fuel fire cook off (i.e. variable heat flux). The fuel was propane and it will be referred

to in this paper as the fire test. The second condition consisted of supplying a constant heat flux on the surface of the container using an electrical heating band. This will be referred as the electrical test.

Fire test: Approximately 4.3 Kg of PBX-9501, an HMX based explosive, was contained in a 0.1 m diameter by 0.3 m long steel pipe with threaded end caps. The pipe was instrumented with 23 type-K thermocouples. Twelve thermocouples were attached to the outside of the cylinder and eleven thermocouples were placed inside, at the interface between the explosive and the cylinder wall, and at different axial and radial locations. The cylindrical container was supported by chains from a steel A-frame and six propane burners were positioned beneath the container.

Electrical test: Approximately 1.4 Kg of PBX-9501 was contained in a 0.1 m diameter by 0.1m long steel pipe. A 35 W/sq in band heater (with a resistance of 17.5 Ohms) supplied by Entherm was used to heat the container. The pipe was instrumented with 20 type-K thermocouples. Eight thermocouples were placed inside the explosive material at 1.5 mm from the interface between the explosive and the cylinder wall. The other twelve thermocouples were attached between the band heater and the steel surface. A 2-inch layer of pipe insulation was wrapped around the outside of the band heater to minimize the heat losses to the surroundings.

Transient Heat Transfer Model

The system can be treated as a semi-infinite slab because the thermal penetration (diffusion length) is much smaller than the actual thickness of the explosive. Assuming that the thermophysical properties are

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constant, the unsteady temperature distribution $T(x,t)$ in the solid for $t>0$ can be obtained as follows

For $0 < x < L_{steel}$

$$\frac{\partial T(x,t)}{\partial t} = \alpha_{steel} \cdot \frac{\partial^2 T(x,t)}{\partial x^2} \quad (1)$$

For $L_{steel} < x < \infty$

$$\frac{\partial T(x,t)}{\partial t} = \alpha_{PBX} \cdot \frac{\partial^2 T(x,t)}{\partial x^2} \quad (2)$$

The initial condition is given by

$$T(x,0) = T_0 \quad (3)$$

The boundary conditions for the electrical test case are defined as

$$-K_{steel} \frac{\partial T(0,t)}{\partial x} = \frac{V}{A \cdot R^2} = q_s \quad (4)$$

$$\frac{\partial T(\infty,t)}{\partial x} = 0 \quad (5)$$

Analyzing the experimental temperatures (see Figure 1), it is clear that the steel-explosive interface requires a special treatment. Since the steel has a very high thermal conductivity, it would be expected that the temperatures at the steel and the explosive surfaces were very similar. However the measurements indicated that there was a significant temperature drop at this interface.

In the interface between two materials, the rate of heat flow must be continuous, that is,

$$-K_{steel} \cdot \frac{\partial T(L_{steel}^-,t)}{\partial x} = -K_{PBX} \cdot \frac{\partial T(L_{steel}^+,t)}{\partial x} \quad (6)$$

However, when two unpolished surfaces are brought into contact, they actually touch only at a limited number of points, the total of which is usually only a small fraction of the apparent contact area. The remainder of the space between the surfaces may be filled with air or another fluid. When heat flows from one solid to the other, heat flow paths converge toward the actual contact spots, since the thermal conductivities of solids are generally greater than those of fluids. This creates an additional resistance to the heat flow at the interface. The gap may be filled with a gas and could

increase even more due to the thermal expansion of the materials and the generation of gas from the exothermic combustion of the explosive.

Therefore, the interface equations must contain a contact resistance that can be represented as an additional layer or air gap. The energy balance gives the condition at the interface as

$$-K_{steel} \cdot \frac{\partial T(L_{steel}^-,t)}{\partial x} = K_{air} \cdot \frac{(T_{steel} - T_{PBX})}{L_{air}} \quad (7)$$

and

$$K_{air} \cdot \frac{(T_{steel} - T_{PBX})}{L_{air}} = -K_{PBX} \cdot \frac{\partial T(L_{steel}^+,t)}{\partial x} \quad (8)$$

Where the interface consists of both the steel/air interface and the air/explosive interface. The width of can be described by expressions for the thermal expansion of both the steel and the PBX.

$$L_{air} = L_{steel}[\alpha_1 \cdot T_{steel} + \alpha_2 \cdot T_{steel}^2] + L_{PBX}[\beta_1 \cdot T_{PBX}] \quad (9)$$

Duhamel Superposition and Inverse Heat Conduction

Duhamel's superposition technique was used to obtain the heat flux from the measured interface temperature. Inverse heat conduction (IHC) equations were used to predict the interface temperature and heat flux given the measured temperature inside the explosive. The solution to the IHC equations however, is extremely sensitive to measurement errors. Duhamel and the IHC equations are well described elsewhere [2].

Results and Discussion

The flame disturbance due to wind fluctuations (speed ~5-12mph) resulted in non-uniform heating (i.e. by flame partially engulfing the pipe). The heating was more effective in the lower half of the pipe during the fire tests cylinder. The temperature at the PBX surface reached a value of 410 K at the explosion time (133 seconds).

The electrical test has the advantage of being unaffected by the wind. The voltage applied was 220 Volts corresponding to a constant applied heat flux of 76 kW/m². The temperature PBX surface reached a value of 490 K at the explosion time (189 seconds).

The model predictions and the experimental values for the temperature of the steel (T_{steel}) and the explosive surface (T_{pbx}) are presented in Figure 1. The good agreement confirms the effectiveness of the contact resistance model for the container/explosive interface. As was discussed in the model analysis, the

air gap is responsible for the drop in temperature between the steel and the PBX. For instance, at the conditions of the electrical test, an air gap thickness of 0.9 mm was enough to drop the temperature by nearly 40 % (from 800 K to 490 K at the time to explosion).

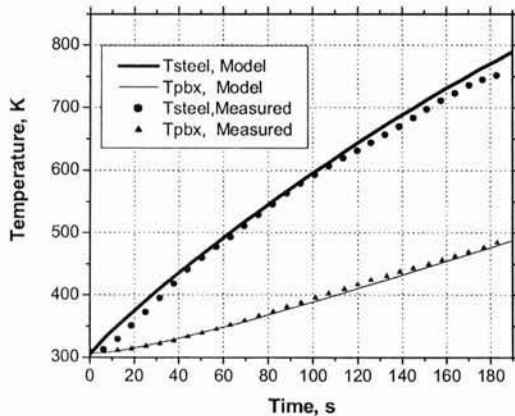


Figure 1. Temperatures for the electrical test.

The heat flux corresponding to the electrical test was calculated using three different methods: the transient model, which includes the contact resistance description; and the Inverse Heat Conduction (IHC) and the Duhamel superposition methods. The results are presented in Figure 2.

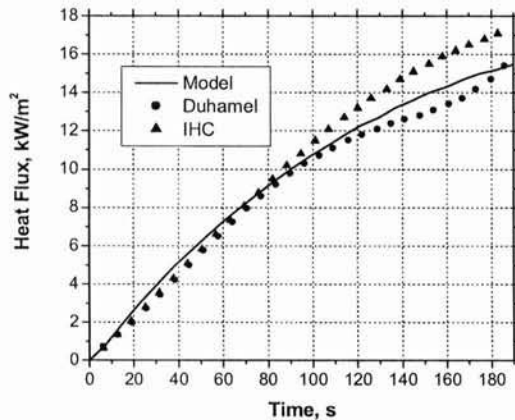


Figure 2. Heat flux for the electrical test.

The IHC and the Duhamel methods are based on the experimental temperatures and therefore, it is expected that the calculated heat flux is as accurate as the directly measured values. It is important to note that the transient model is validated by agreeing not only with the experimental surface and interface temperatures, but

also with the heat flux given by the other methods. An average of 9.4 kW/m^2 was obtained for the heat flux at the PBX surface. This value represents only 12 % of the total heat flux supplied by the electrical heater. In other words, the contact resistance is very efficient in reducing the amount of heat flux reaching to the explosive and thus causes a significant delay in the explosion time.

The transient model cannot be applied directly to the fire test because of the uncertainties in the fireside boundary conditions (mainly due to the difficulties in measuring surface temperature). However, the Duhamel method and the measured interface temperature can be used to obtain the heat flux reaching the explosive. As shown in Figure 3, the heat flux at the time to explosion was nearly 12 kW/m^2 . The Figure 3 also reveals that the explosive shows a similar thermal behavior when heated up by either propane burners or electricity.

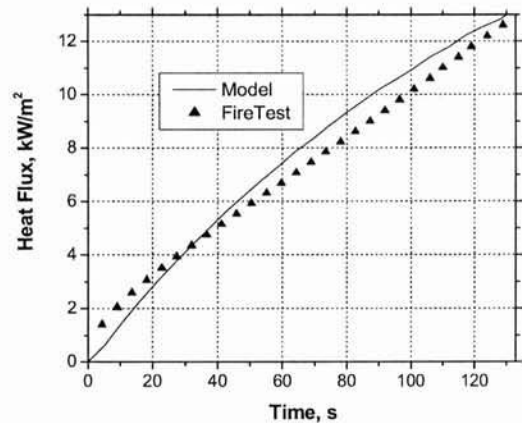


Figure 3. Experimental heat flux at the interface.

The transient heat transfer model with an input of constant heat flux of 76 kW/m^2 (identical to the electrical conditions described above) was able to reproduce the interface temperature corresponding to the fire test as shown in Figure 4. This suggests that electrical tests can be designed to represent an immersed fire scenario in which the thermal response of an explosive needs to be known. In addition, if enough information is available, the transient heat transfer model can be used to design and carry out numerical experiments. This would not only provide economical benefits but also improve the use of computer models for the evaluation of risks, prevention mechanisms and safety issues associated with explosive devices in fires.

The average heat flux and experimental time to explosion are plotted in Figure 5, along with an ignition model for HMX explosives proposed by Beckstead [3]. Even though the ignition model utilizes constant heat

flux as an input, a reasonable agreement between the experimental and the predicted time to explosion was found. Also, it is important to note the lack of experimental data in the range of the experiments reported in this paper.

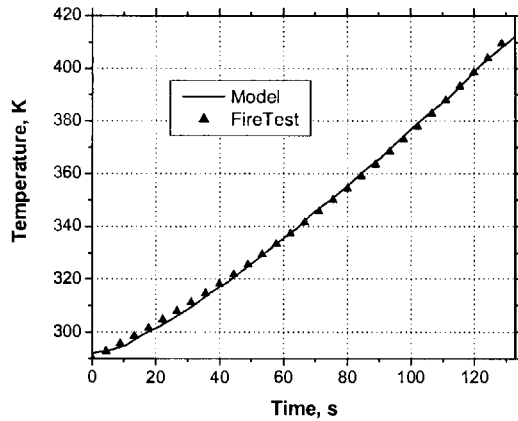


Figure 4. Interface temperature for the fire test.

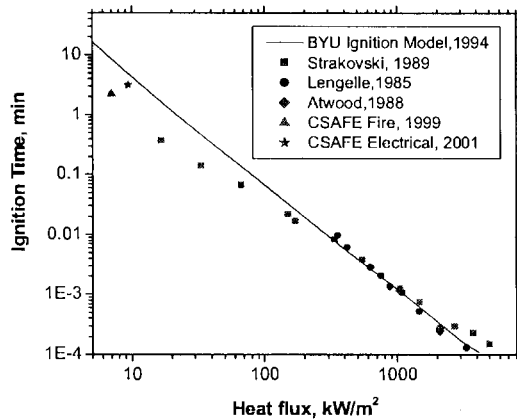


Figure 5. Ignition Model for HMX explosives.

Conclusions

A detailed heat transfer analysis has shown that a 0.1m- diameter steel pipe containing PBX-9501 demonstrates similar thermal behavior when heated by either a propane fire or a suitable power input using an electrical heating band.

Based on comparisons with measured temperatures, the model predicted that there was a significant thermal

contact resistance that reduced the temperature across the metal/explosive interface by nearly 40%. The resistance has been treated as an air gap whose length is proportional to the differential thermal expansion of the metal and the explosive. The transient model can be used in the design of electrically heated experiments to represent a fire scenario case.

The experimental time-to-explosion and the calculated heat flux showed good agreement with an ignition model for HMX-based explosives.

Nomenclature

- A: Area of the cylinder in m^2
- K: Thermal conductivity of the materials in W/m K.
- Lsteel: Wall thickness of the steel pipe, m.
- Lpbx: Thickness of the explosive, m.
- Lair: Thickness of the air gap, m.
- T: Temperature in K.
- T₀: Initial temperature, K
- t: Time, s.
- q_s: Heat flux at the surface, W/m²
- R: Resistance of the heater, Ohms,
- V: Voltage, Volts.

Greek symbols

- α_{steel} : Thermal diffusivity for steel, m^2/s
- α_{pbx} : Thermal diffusivity for PBX-9501, m^2/s
- α_1 : Thermal expansion coefficients for steel, 1/K.
- α_2 : Thermal expansion coefficients for steel, 1/K².
- β_1 : Thermal expansion coefficient for PBX-9501, 1/K.

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