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Thermal response of an unprotected structural steel element exposed to a solid rocket propellant fire

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ABSTRACT

The thermal response of an unprotected structural steel element exposed to a solid rocket propellant fire is investigated. A 2 kg aluminized composite propellant Butalane® is positioned onto a 5 mm steel plate and ignited with a torch in the experiments. Radiative and convection-dominated heat transfer regions are observed, with the latter dominating the heating of the plate to a maximum of 820 K. Results obtained from thermal modeling reproduce the experiments well in terms of time evolutions of the structural element temperature.

1. Introduction

More stable and easier to store than liquid-fuel rockets, solid-propellant rockets are still used for military and space purposes (e.g. air-to-air and air-to-ground missiles, model rockets, or boosters for satellite launchers). Solid Rocket Propellant (SRP) may be in solid or powder form. In the military field, solid rockets can be loaded on fighter planes, which however raises the problem of safety due to the risk of falls and possible ignition during take-off, landing, and handling. This problem is even more acute during flight deck operations on aircraft carriers. In the event of a fall, the propellant load may fragment into small pieces, increasing the specific area available for combustion and thus environment severity. The burning of SRP can generate a high-temperature (~3000 K) flame [1], which in turn can propagate the fire to remote targets and/or lead to damage of the flight deck structure. Moreover, as underlined by Hunter et al. [2], when a solid propellant burns, initial combustion is anaerobic and the most severe fire environment is located under and beside the propellant. Estimating the thermal effects generated by the combustion under atmospheric conditions of a propellant load on a structural steel element is a challenge in terms of scientific knowledge and safety assessment. In the last five decades, combustion of SRP has been widely studied (see [2–15], to name but a few). Basic phenomena (e.g. physics-chemistry, the ignition process, and additive and pressure effects on the burning rate) are generally studied on a small scale, with samples varying from a few milligrams to a few grams. Due to the hazardous nature of solid propellants and the strict rules associated with their use, only a small number of available studies are dedicated to the open burning of propellant specimens of the order of one kilogram or more [8–11]. Various measurement means have been used in order to accurately quantify the large scale effects of SRP combustion, including, inter alia, pyrometry, spectrometry and ultrasonic wave gauges. In ambient conditions, the burning regression rates were found to be approximately 1 mm/s and the ejection velocity of combustion products to be in the range of 15–30 m/s. Temperature measurements inside the propellant sample were carried out using immersed probes, but the reliability of such measurements was questionable due to aluminum oxide deposition on the gauge surface. Price [7] tested various techniques to measure the temperature and emissivity of propellant flames using a photomultiplier at three wavelengths. The best results were obtained using the assumption that the medium could be considered as a gray body in the range of 400–600 nm. Following the work of Price [7], Diaz [8] developed an experimental apparatus to estimate the effect of a propellant fire on its surroundings.

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Nomenclature

a	initial radius of the propellant sample (m)
b	radius of the top surface of the truncated-cone-shaped burning propellant sample (m)
c	specific heat at constant pressure (J/kg/K)
e	levitation height of the propellant sample (m)
h	height, measure from the upper surface of the plate (m)
h_{conv}	convective heat transfer coefficient (W/m^2/K)
H	height of the truncated-cone-shaped burning propellant sample (m)
$\dot{m}$	mass loss rate (kg/s)
n''	number of bundles emitted per unit flame area (1/m^2)
N_{ij}	number of quanta emitted from the elementary surface i of the flame that become absorbed by the elementary surface j of the plate
p	amount of radiant energy per unit time transported by each bundle (W)
P''	emissive power of the flame (W/m^2)
Pr	Prandtl number
q''	heat flux (W/m^2)
r	radial coordinate (m)
Re	Reynolds number
S	surface area (m^2)
t	time (s)
T	temperature (K or °C)
v	radial velocity (m/s)
V	sample volume (m^3)
w	axial velocity of the gas ejected from the bottom surface of the propellant sample (m/s)
x,y,z	Cartesian coordinates (m)
α	half-angle of the truncated-cone-shaped burning propellant sample (°)
ε	emissivity
λ	thermal conductivity (W/m/K)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant ($=5.67 \times 10^{-8}$ W/m^2/K^4)
μ	dynamic viscosity (kg/m/s)

Subscripts, superscripts

cond	conductive
conv	convective
l	lower surface of the plate
g	gas
i	elementary surface area of the flame
j	elementary surface area of the plate
m	Cartesian coordinate
p	plate
rad	radiative
rr	radiative loss
s	solid propellant
u	upper surface of the plate
w	plate surface
$\dot{\square}$	per unit area
$\square''$	time derivative

Acronyms

Al	aluminum
Al_2O_3	aluminum oxide
AP	ammonium perchlorate
CCD	charge-coupled devices
CFD	computational fluid dynamics
DGA Tn	Direction Générale de l'Armement Techniques navales
FDS	fire dynamics simulator
HTBP	hydroxyl-terminated poly-butadiene
IR	infrared
LES	large eddy simulation
MCM	Monte Carlo ray tracing Method
MLR	mass loss rate
NIST	National Institute of Standards and Technology
Rad	radiative heat flux gauge
SFM	solid flame model
SRP	solid rocket propellant
TC	thermocouple
Tot	total heat flux gauge
TDMA	tri-diagonal matrix algorithm

However, reported results are largely dependent on the type of propellant considered. In 2007 and 2011, Chassagne et al. [9,10] conducted different types of tests in atmospheric conditions using AP/HTPB/Al propellant samples ranging from several kilograms to two tonnes (i.e. the third stage of a ballistic missile). Most of these results are classified. The authors determined the infrared (IR) signature of the flame plume by radiative heat flux measurements, IR thermal imaging and IR spectrometry inspired by the technique developed by Eisenreich and Eckl [11]. A graphite chimney with a diameter of 47.5 cm and graphite sight tubes, capable of resisting high temperatures, were designed to support the sensors. A nitrogen purge system was also installed to eject smoke from the tubes. This technique was previously developed and used by Diaz [8]. Heat flux exchange was measured using a cone calorimeter. Measurements were performed for two propellant compositions in order to highlight the role played by aluminum particles (4% and 20% by weight) in thermal radiation to the surroundings. In-situ temperature and emissivity measurements were made by pyrometers at three standoff distances above the initial propellant surface. These data were determined in the near-IR and mid-IR spectral regions in order to provide new data on the radiative emission properties of a propellant flame. The burning rate was also measured by means of a US parametric ultrasound sensor positioned at the bottom of the sample. Infrared and ultraviolet cameras were also used. The radiative heat flux emitted from the flame was evaluated by means of heat flux gauges positioned at various heights. The top surface of the sample was ignited using Mi9 powder. A quasi-steady state was nearly achieved after 50 s of burning, with burning rates of 1.42 ± 0.04 mm/s and 1.10 ± 0.04 mm/s for the 20% and 4% aluminized propellant samples respectively. From 2002 to 2007, the Johns Hopkins University Applied Physics Laboratory conducted three series of fire tests to obtain data on the environment under a solid propellant burning on its bottom surface in the open [2,12–14]. The propellant contained 71% ammonium perchlorate oxidant and two fuels: 18% powdered aluminum and 11% of a hydroxyl-terminated polybutadiene rubber. Using blocks of propellant ranging from 3 to 91 kg, they determined burn characteristics such as the burning rate and self-levitation, total heat flux and temperatures. The blocks were placed on sand or concrete supports to simulate near-launch pad surfaces, or graphite supports to simulate low-recession surfaces. A specific device was developed to allow propellant self-