Applied Thermal Engineering 112 (2017) 484–496

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Cook-off analysis of a propellant in a 7.62 mm barrel by experimental and numerical methods

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HIGHLIGHTS

- Cook-off is an involuntary self-ignition phenomenon of a propellant.
- Temperature distribution in a barrel and the cook-off time was determined.
- The outer wall temperature of the barrel was measured with a thermal imager.
- Various parametric analyses have been made that affect the cook-off time.
- The tests were conducted according to the NATO testing standards.

ARTICLE INFO

Article history:
Received 6 January 2016
Revised 26 September 2016
Accepted 16 October 2016
Available online 17 October 2016

Keywords:
Cook-off (self-ignition)
Transient heat transfer
7.62 mm barrel
ANSYS
Finite element method

ABSTRACT

Cook-off is an involuntary self-ignition phenomenon of a propellant in a cartridge often encountered in multiple sequential firings. In this study, an efficient approach has been used for cook-off analysis of a propellant by experimental and numerical methods. Various firing tests have been conducted with a 7.62 mm rifle to determine the temperature distribution in a barrel and the cook-off time. The outer surface temperature at the hottest area on the combustion chamber where the cook-off process was assumed to initiate was measured with a thermal imager as an effective method. For numerical analysis the model of the combustion chamber combined with the cartridge was created and analyzed using the ANSYS 14.5 Academic finite element solver and the temperature distribution of the inner/outer surfaces of the combustion chamber was determined. The numerical results for temperature distribution were observed to be quite close to the temperature values measured by the thermal imager. The numerical analysis was also validated by comparing the numerically determined cook-off time with the experimental measurements. At the end, various parametric analyses have been made that affect the cook-off time of a propellant.

1. Introduction

Throughout history, the issue of having more powerful and deterrent weapon systems against threats and attacks has always been among the priority areas for countries to ensure their securities. Therefore, countries have tried to take the necessary precautions in order to protect themselves against the enemy and developed more effective and powerful weapon systems. In this context, studies have led to the development of the ballistic science that examines the events occurring in a firing process of a weapon system. The studies on the development of weapon systems are particularly focused on firing a projectile with a high firing rate (number of shots per minute) as far as possible and hitting the target accurately with a highest velocity. The ability of multiple sequential firing with a high firing rate provides a significant advantage for a weapon to hit the target effectively. Although, the multiple firing ability is a very important feature for rifles it brings together some problems as well. The expansion of the barrel to high temperatures during firing process causes the combustion gas pressure in the barrel to fall down and the erosion/abrasion in the barrel to increase which have negative effects on a barrel material.

One of the major problems resulting from an overheated combustion chamber of a weapon in multiple firings is the cook-off (self-ignition) phenomenon. It is generally confined to automatic guns [1]. When the propellant in the cartridge case starts to burn, it is quickly converted into combustion gases and very high pressures and temperatures are generated inside the barrel. The heating process continues until the projectile leaves the barrel. In

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http://dx.doi.org/10.1016/j.applthermaleng.2016.10.104
1359-4311/

multiple sequential firings the time interval between two firings is about 0.1 s. This means the barrel continues to be heated nearly without having enough time to cool down. The inner surface temperature of the combustion chamber increases to high values after numerous firings. As a new cartridge is fed into the barrel and is left in place for a while, because of higher temperature the heat is transferred in a very short time from the inner surface of the combustion chamber to the new cartridge case and from the case to the propellant. If the temperature of the propellant rises above the ignition temperature, the event called cook-off starts to occur and the projectile is fired as the propellant ignites spontaneously. Generally, the firing and heating processes continue for large numbers of shots until the ignition temperature is reached which leads to cook-off. The consequences of this involuntary and spontaneously occurring event may be disastrous and the shooter can easily be injured. Therefore, the cook-off time and temperature for a certain number of rounds fired in periodic intervals should always be considered by a weapon designer.

The studies on heat transfer from the barrel and cook-off process are as follows. Lee et al. [2] determined the unknown time-dependent heat flux at the inner surface of a chrome-coated gun barrel, in which the interlayer thermal contact resistance between the steel cylinder and the coating was taken into account. They estimated the heat flux and the thermal stresses by using the temperature values obtained from the solver and confirmed the results by analytical solutions. Hill and Conner [3] have developed a solver by using Mathematica software to determine the barrel temperature after multiple firings. They determined the internal ballistic boundary conditions by using the PRODAS software. It was possible to calculate the one-dimensional temperature distribution through the barrel thickness by using this solver. Chen et al. [4] used inverse and input estimation methods to recursively estimate the transient heat flux and the inner surface temperature of the combustion chamber. Conroy [5] has developed an interior ballistic code to calculate the one-dimensional two-phase heat transfer in a barrel. Akçay and Yükselen [6] have solved the unsteady temperature distribution of a machine gun barrel numerically. Chung et al. [7] derived an empirical equation to get the wear rate for a 40 mm gun barrel as a function of heat input. They compared the experimental data with the results obtained from empirical equations. Şentürk et al. [8] investigated interior ballistics of a 7.62 mm gun barrel using experimental, numerical and analytical methods with a thermo-mechanical approach. Huang et al. [9] studied the thermal effects during the firing process with 5.56 mm ceramic gun barrel by using finite element method to test the usability of ceramics on various weapons. They compared the experimental data with the simulation results. Fuller [10] tried to determine the temperature values on a small-caliber barrel by using a thermal imager. Bin et al. [11] studied cooling of a 155 mm heavy weapon barrel theoretically by opening channels to solve the self-ignition problem. They confirmed the theoretically calculated values by finite element method. Hameed et al. [12] developed an experimental test setup to determine the self-ignition time for 7.62 mm double base propellant. Mishra et al. [13] performed numerical transient thermal analyses of midwall-cooled and externally cooled gun barrels. By using the results they tried to find the self-ignition temperature and time. Riel et al. [14] identified the self-ignition time of the propellant for XW-7 rocket by determining the temperature distribution resulting from combustion of the propellant. Hasenbein [15] studied the thermal effects in determining time-temperature relationships for cook-off of XMl23EI Zone 8 propelling charges in the 155 mm XM199 Cannon. Then, he generated a curve which depicted time to cook-off as a function of maximum chamber temperature. Jacobs [16] developed a graph showing the temperature vs. self-ignition time for the fuel of a ship. Witherell and Pflegl [17] conducted an analytical and numerical thermal study of the 30 mm MK44 barrel to determine the relationship between the number of rounds fired and the time to initiate propellant and explosive cook-off in the barrel.

The previous studies in determining cook-off time of a propellant for certain amounts of sequential firings were done mostly by using experimental methods. This is a costly, dangerous and unsafe way which also requires special test setups. The aim of this study was to develop an effective method for cook-off analysis of a propellant by using numerical method. For validation of the numerical analyses experimentally, various firing tests have been conducted with a 7.62 mm rifle to determine the temperature distribution in a barrel and the cook-off time. First of all firing tests of single shot, 5 shots in 5 s intervals and multiple sequential firing of 20 shots were conducted with a 7.62 mm rifle. At the end of each firing test the temperature values on the outer wall of the combustion chamber were measured by using a thermal imager. This was also a new practical and sensitive measurement method compared to the traditional methods that use thermo-couples. Later, a constant heat flux value determined iteratively was used in the numerical analyses as boundary condition instead of gas temperature and convection coefficient which are more difficult to determine. Then, the cook-off times were measured experimentally by conducting multiple sequential firing tests with a 7.62 mm rifle for 180, 200 and 220 shots. The numerical results obtained from ANSYS finite element solver were compared with the experimental ones. It was observed that the experimental and numerical results were confirming each other. Finally, various parametric analyses were made to determine the self-ignition time for various number of shots by changing the firing time interval between two magazines, the number of cartridges in each magazine, the thicknesses of the combustion chamber and the cartridge case.

2. Theoretical formulation

In a firing process quite complex events occur in a barrel. All these events are concerned with interior ballistics of weapons which is the science of converting the chemical energy of a propellant into heat and kinetic energy. After initiating the combustion process of the propellant in the cartridge case by the impact of the firing pin on the cartridge cap, the propellant starts to burn quickly and it is converted into combustion gases which generate very high pressures and temperatures. Then, the gases push the projectile forward and as the heat transfer continues from the

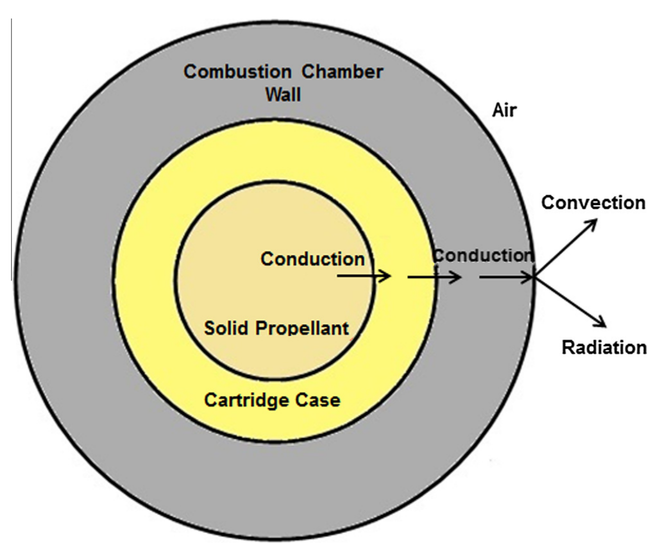

Fig. 1. Heat transfer in the first step.