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Research paper

Numerical Modeling of Heat Transfer in Gun Barrel with Experimental Validation

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Abstract

Transient heat transfer in a gun barrel has been investigated numerically in this paper. Numerical modeling is conducted with the objective to obtain temperature history of the gun barrel. From the temperature history, the maximum number of gun shots before the cook-off temperature of the gun barrel attained can be known. Gun barrel is a part of firearm functioned to control gas flow which is aimed to propel projectiles out of the barrel with high velocity. Each propelled projectile produces very high temperature caused by projectiles explosion and friction between projectiles and bore surface. If the temperature of the gun barrel reaches the cook-off temperature, the bore surface will be damaged. Heat conduction equation in cylindrical domain is used to model heat transfer inside the gun barrel. Numerical results are obtained by implementing the finite volume method. From the numerical simulations, we found that our numerical method has very small error compared to experimental data that are 1.68% and 0.95% for total heat transfer and maximum temperature of bore surface, respectively. Moreover, the maximum number of gun shots in order not to attain the cook-off temperature is 27 times with ten seconds per shot and rest time six seconds in every six gun shots.

Keywords: *Numerical modeling, gun barrel, finite volume method, temperature history, bore surface, cook-off temperature.*

1. Introduction

Artillery is a class of military heavy equipment to fire projectiles which can not be reached by small infantry weapons such as aircraft, tank, and fortification.

There are two types of artillery, i.e. artillery with the wheels as an impeller and artillery which is installed on the ground. The fire power of artillery is influenced by the size of the caliber. Caliber is the internal diameter of the gun barrel. The larger the caliber the more power produced.

When the artillery was shot, there was some amount of heat transferred into bore surface in the gun barrel. Heat transfer in gun barrel is caused by convection from the combustion gases in the barrel. In general, after shooting, the barrel is naturally cooled by convection from the outer surface of gun barrel, but natural cooling is inefficient and only small fraction of the total heat transfer (Mishra et al., 2010a). As a result, during the continuous shooting, the temperature of gun barrel is continuously increasing until attaining a cook-off temperature. The cook-off temperature occurs when material of gun steel is broken because of over heat. The cook-off on the gun barrel may cause serious injury to the user and damage to the weapon system. Many experiments showed that the cook-off will occur in 1200 seconds if the temperature of bore surface is stable at 180°C (Dorsch et al., 2013).

Many of researchers are more interested to conduct mathematical modeling and numerical simulation than conducting an expensive direct experiment to measure the performance of gun barrel. Guo et al. (2013) conducted numerical simulation of muzzle blast overpressure in gun barrel. Their simulation showed that by using muzzle brake, it can reduce about 74% of overpressure compared to without muzzle brake. Furthermore, Ahmed et al. (2008) studied simulation of large caliber gun during the firing cycle. They used finite element method which is implemented in commercial software ANSYS. Moreover, Yin et al. (2009) modeled and simulated gun barrel’s lateral vibration using finite element method. Their results can estimate initial disturbance influence to gun firing accuracy.

This paper presents numerical modeling of gun barrel which is aimed to avoid the cook-off temperature by considering temperature history of surface bore. Mathematical model of heat transfer in gun barrel can be described by heat conduction in cylindrical domain (Mishra et al., 2010a, 2010b; Alexiades et al., 1992). Numerical solutions of heat transfer model are obtained by adopting finite volume method (FVM). Comprehensive review about finite volume discretization can be found in (LeVeque, 2002). Further, the numerical results are validated by the experimental data and also compared with finite element analysis (FEA) results which had been presented in (Mishra et al., 2010a).

2. Mathematical Model

Mathematical model of heat transfer in gun barrel can be formulated as heat conduction equation in cylindrical domain. Fig. 1 illustrates heat transfer in the gun barrel. Here, qconv and qrad are convection and radiation heat flux of gun barrel respectively, and qin is convection heat flux into the inner surface bore. Further, Rin and Rout are inner and outer radius of gun barrel respectively. We assume that the heat conduction in the axial direction is negligible compared to conduction in the radial direction (Hirvonen et al., 2005; Tarwidi & Pudjaprasetya, 2013). Heat transfer caused by friction between projectile and surface bore is ignored and the effect of gravity on convection heat transfer is also negligible. According to these assumptions, the heat transfer problem becomes one-dimensional radial direction.

The heat conduction equation of gun barrel in cylindrical domain may be formulated as (Mishra et al., 2010a, 2010b; Alexiades et al., 1992)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)=\rho c_p\frac{\partial T}{\partial t} \tag{1}$$

where T = T(r,t) is the temperature of gun barrel at radius r and time t and k (W/m•K), ρ (kg/m3), cp (J/kg•K) are thermal conductivity, density, and specific heat of gun barrel respectively. If we assume that thermal conductivity is constant, then (1) becomes

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{2}$$

where α = k /(ρcp) is thermal diffusivity of gun barrel.

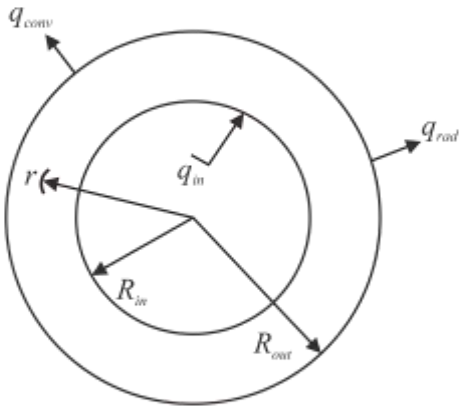

Fig. 1: Schematic diagram of a gun barrel with the illustration of heat transfer from inner to outer of bore surface.

Boundary conditions on the inner and outer surface bore can be formulated as (Mishra et al., 2010a):

$$-k\frac{\partial T}{\partial r}=h_g\left(T_g-T\right)=q_{in},\ \ t>0,\ \ r=R_{in} \tag{3}$$

$$-k\frac{\partial T}{\partial r}=h_\infty\left(T-T_\infty\right)+e\sigma(T^4-T_\infty^4)=q_{conv}+q_{rad},\ \ t>0,\ \ r=R_{out} \tag{4}$$

where hg is coefficient of convection heat transfer between bore surface and hot gas propellant, Tg is the average cross sectional temperature of the gas, and T∞ is ambient temperature surrounding gun barrel.

In this case, initial temperature of barrel is 307.6 K and thermal conductivity of gun steel is 35 (W/m•K). Here, heat transfer due to radiation is very small to the outer bore surface so that it may be ignored. Further, h∞ is the heat transfer coefficient between the outer barrel surface and the surrounding environment which has value 6.5 (W/m2K). Moreover, e = 0.782 and σ = 5.5669•10-8 (W/m2•K4) are the emissivity of the gun steel and the Stefan-Boltzmann constant, respectively (Mishra et al., 2010a). Further study and experiment results regarding to gun barrel can be found in the literature (Jaramaz, Micković, & Elek, 2011).

3. Numerical Solution

In this section, we discuss numerical approximation of (1) using finite volume method. According to conservation of energy law, (1) can be written as:

$$\frac{\partial E}{\partial t}+\frac{1}{r}\frac{\partial\left(rq\right)}{\partial r}=0 \tag{5}$$

where E(r,t) is thermal energy density per unit volume. Furthermore, q (kJ/s/m2) is heat flux which is derived from Fourier law for heat conduction: q = -kTr.

Finite volume discretization for solving (5) can be described as follows. At first, the computational domain [rin, rout] is divided into M subintervals where the length of each subinterval is Δr. Suppose rj-1/2 is node between node rj-1 and node rj. We define [rj-1/2, rj+1/2] as control volume. More detail about finite volume discretization can be found in (Tarwidi, 2015).

In order to obtain numerical scheme, it is convenient to write energy conservation in (5) into integral form. Hence, by integrating equation (5) over control volume [rj-1/2, rj+1/2] and time [tn, tn+1], it yields

$$\int_{t_n}^{t_{n+1}} \frac{\partial}{\partial t}\left(\int_{r_{j-1/2}}^{r_{j+1/2}} E(r,t)dr \right) \mathrm{d}t = q^n_{j-1/2}\ r_{j-1/2} - q^n_{j+1/2}\ r_{j+1/2} \tag{6}$$

Here, E(r,t) = ρcpT(r,t) and α is thermal diffusivity of gun steel (m2/s). Further, qj-1/2 = k (Tj – Tj-1)/Δr which is discretization form of Fourier law.

For the explicit scheme, equation (6) can be written as

$$T_j^{n+1} = T_j^n + \frac{\alpha\ \Delta t}{r_j(\Delta r)^2}\left[r_{j-1/2}\ T_{j-1}^n - \left(r_{j-1/2} + r_{j+1/2}\right)T_j^n + r_{j+1/2}\ T_{j+1}^n \right] \tag{7}$$

where rj = rin + (j-1/2)Δr and rj-1/2 = rin + (j-1)Δr. Here, the term T_j^n is the average temperature inside control volume [rj-1/2, rj+1/2].

4. Results and Discussion

The purpose of this simulation is to assess error of FVM which is validated by experimental data. Moreover, we are interested to determine the maximum shot that the gun can do while the cook-off temperature of bore surface is not achieved. In this simulation, we set the time interval 10 seconds in each gun shot with rest time six seconds in every six gun shots. The artillery that used in this simulation is caliber 155 mm.

The error of the model which is solved by FVM is then calculated by comparing to experimental results (Mishra, 2010a). Mean absolute percentage error (MAPE) is used to assess the accuracy. The error is given by

$$MAPE = \frac{100}{n}\sum_{k=1}^{n}\left| \frac{T_{\exp} - T_{FVM}}{T_{\exp}} \right|$$

where n is the number of data, Texp and TFVM are the experiment and simulation results, respectively.

At first, the simulation is aimed to test FVM to solve heat transfer model and validated with the experimental data. For this purpose, the simulation is conducted with the appropriate experimental data, so that we set interval time five minutes in each shot and without rest time between two shots. Temperature history of bore surface for the first shot using FVM is depicted in Fig. 2 while the experimental results of bore surface temperature can be seen in (Mishra et al., 2010a, 2010b). It can be shown that FVM simulation has good agreement with the experimental data. The figure also reveals that FVM result has the maximum temperature of bore surface 955.68 oC whenever experimental result has 964.85 oC and it is reached at t = 2.9 ms. Moreover, total heat transfer and maximum temperature of bore surface with mean absolute percentage error (MAPE) are summarized in Table 1. We can see that FVM simulation has very small error that are 1.68% for total heat transfer and 0.95% for maximum temperature of bore surface.

Table 1: FVM simulation against experimental data for the first shot.

	experiment (Mishra et al, 2010a)	FVM	MAPE
Heat transfer total (KJ/m^2)	963.2	946.98	1.68%
Maximum temperature of bore surface (ºC)	964.85	955.68	0.95%

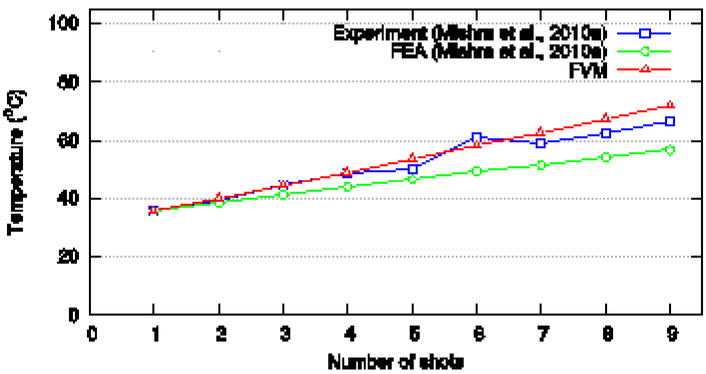

Fig. 2: Temperature history of bore surface for the first shot using FVM. simulation.

Fig. 3 displays initial temperature of bore surface in each shot using FVM against experimental data and FEA simulation. From that figure, we can compare MAPE of our numerical simulation using FVM and FEA simulation which is presented in (Mishra et al., 2010a, 2010b). MAPE of FEA simulation is 9.74% while MAPE from our numerical result is 4.02%. It is obvious that for the initial temperature of bore surface, FVM has better accuracy than FEA simulation.

Maximum temperature of bore surface in each shot using FVM against experimental data and FEA simulation is presented in Fig. 4. This figure reveals that for maximum temperature of bore surface, FEA simulation has MAPE of 1.70% while for FVM simulation has MAPE of 1.41%. Overall, it can be said that FVM results are better than FEA simulation results.

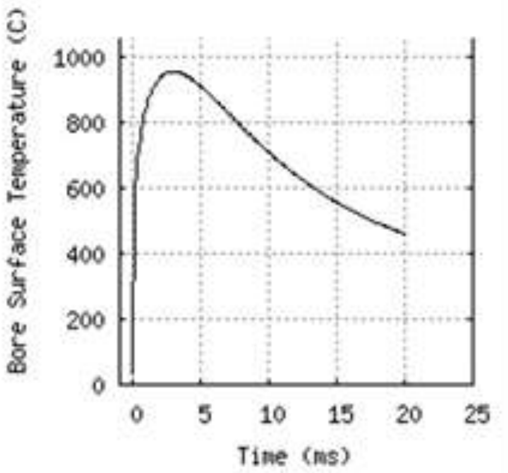

Fig. 3: Initial temperature of bore surface for each shot (with interval 5 minutes per shot) using FVM against experimental data and FEA.

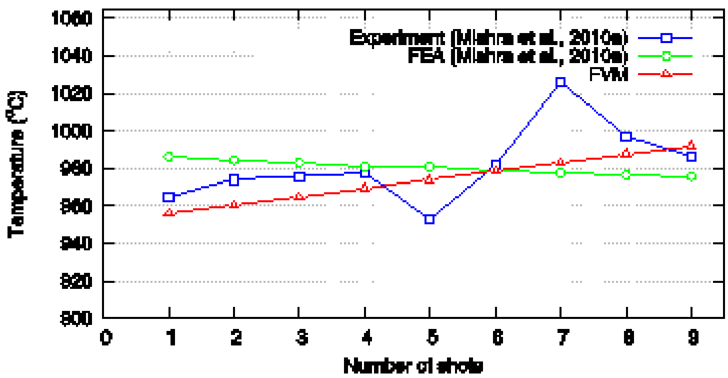

Fig. 4: Maximum temperature of bore surface in each shot (with interval 5 minutes per shot) using FVM against experimental data and FEA.

The following simulation is to test the effect of time interval per shot. Here, we set the time interval 10 seconds per shot with rest time six seconds in every six shots as simulated in (Vikas et al., 2015). Initial temperature of bore surface with interval 10 seconds per shot and rest time six seconds in every six gun shots is described in Fig. 5. At the first shooting the initial temperature of bore surface is 35.45 oC while after the 27-th of shooting the initial temperature achieves 180 oC which is the cook-off temperature. Temperature history of bore surface until 294 seconds is presented in Fig. 6. From this figure, it can be seen that maximum temperature and initial temperature in each gun shoot are increasing. Therefore, 27 times is the maximum shooting that gun barrel can do. It means that if the gun shots more than 27 times, the gun barrel will be damaged.

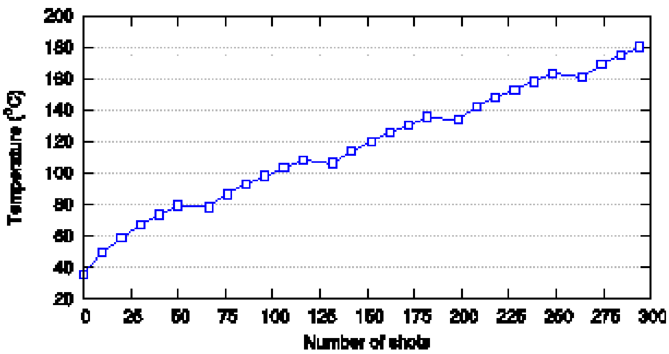

Fig. 5: Initial temperature of bore surface in each shot with interval 10 seconds per shot and rest time 6 seconds every 6 gun shots.

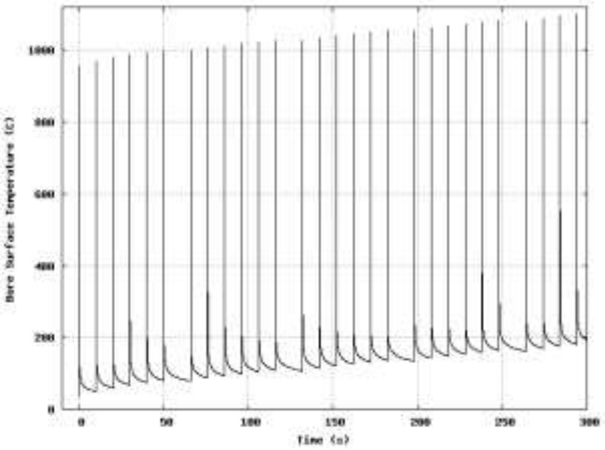

Fig. 6: Temperature history of bore surface with interval 10 seconds per shoot.

5. Conclusion

Numerical modeling of heat transfer in gun barrel has been successfully conducted. It has been shown that the numerical results using finite volume method confirm the experimental data with mean absolute percentage error for total heat transfer and maximum temperature of bore surface are 1.68% and 0.95%, respectively. It has been shown that our numerical approximation has higher accuracy than the previous study. From the numerical simulations, we can conclude that the precise time interval to have the maximum shot is about 10 seconds with the rest time six seconds in every six gun shots. By this technique, the gun barrel can shoot 27 times before it reaches the cook-off temperature with total time 294 seconds. Suggestion for the future works is conducting the numerical simulation using different time interval in each shot.

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