Experimental and numerical estimation of gun barrel heating for rapid fire

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Abstract

During machine gun or machine cannon firing the gun barrel can warm up to very high temperatures. Depending on the firing cycle, especially for small calibres, the barrel can be fired red-hot. In this case, the machine gun firing must be immediately stopped for cooling. A theoretical calculation to predict the heating of the gun barrel would be desirable to design the weapon according to its future mission demands. For this purpose an interior ballistics model was developed using Prandtl's boundary layer equations to solve the unsteady, compressible and turbulent boundary layer development inside of a gun barrel from the breech to the projectile. The solution for the wall shear stress uses the Reynolds analogy to determine the heat flux into the barrel wall produced by the temperature gradient, which is directed from the hot propellant gases to the colder tube wall. To get the barrel’s temperature distribution during firing, the heat conduction equation must be solved inside of the gun tube wall. The rapid fire calculation must take into account the unsteadiness of two completely different flow conditions which appear during the repetitively firing: a) one is present during the projectile acceleration inside of the gun tube, and b) the other develops after the projectile leaves the muzzle up to the next firing. A numerically based time step procedure models the rapid fire behaviour. The numerical results are compared with bore temperature measurements in a 20-mm-caliber machine cannon at several measuring ports placed along the cannon’s barrel.

1 Introduction

In the present study the action of the hot and highly compressed propellant gas flow on the heat transfer to the inner barrel surface of a powder gun for rapid fire
was theoretically and experimentally investigated. Figure 1 presents a principle sketch of a gun set-up, showing the powder chamber, the gun barrel and the projectile beginning to accelerate as a result of the gas pressure increase due to the propellant charge combustion.

For calculating the barrel heating a theoretical model based on the boundary layer equations was already developed by the author. The theoretical results have been compared in the past to experimental data obtained with bore temperature measurements at several measuring stations in the ISL 20 or 60-mm-caliber erosion-guns. Investigations of gun barrel heating for these single shot firings have been discussed extensively by Heiser et al. [1, 2], and Seiler et al. [3-5]. The boundary layer model, described in these publications, was extended to several successive firings due to the requirement to obtain information about the heating of a gun barrel in the rapid fire case. The rapid firing cadence is given by the number of firings per minute, i.e., by the time intervals $\Delta t_1$, $\Delta t_2$, ..., $\Delta t_{n-1}$ describing the sequence from one shot to the following.

2 Theoretical background for rapid fire modelling

2.1 Model assumptions

In order to calculate the gun tube wall temperature history during the firing of a projectile, a computational model was developed to solve the unsteady, compressible and turbulent boundary layer development at discrete projectile locations. A detailed description of this work is given by Seiler et al. [5]. Figure 2 shows schematically a snapshot of the projectile displacement inside of the barrel of the gun. The entire tube wall boundary layer is modelled by two boundary layer parts with different origins: one at the barrel’s breech and the other at the base of the projectile. Both boundary layers are merged together at equal boundary layer thicknesses. Analytical solutions of Prandtl's boundary layer equations were found for both the boundary layer thickness and the heat transfer along the inner tube wall between breech and projectile.

2.2 Gun barrel temperature determination

With an analytical solution of the one-dimensional heat conduction equation the heat flux, given by the boundary layer equation solution, is used to determine the temperature distribution at the inner bore surface and inside of the gun barrel, see Seiler et al. [5]. In order to predict the temperature distribution for rapid fire the calculation procedure starts with the first shot of the firing series (time point $t_1$) and consists of n firings up to $t_{15}$ performed one after the other with time intervals $\Delta t_1$, $\Delta t_2$, ..., $\Delta t_{n-1} = t_n - t_{n-1}$.

After calculating the barrel temperature for the first shot ($n = 1$), the time scale continues and the second firing ($n = 2$) follows after the first interval $\Delta t_1$. In the calculation scheme one shot is arranged after the other up to the last one (firing n). The heat transferred to the gun barrel is being stored from firing to
firing resulting in a pulsating increase of the gun barrel temperature due to the repetitively firing of the machine cannon.

3 Machine cannon firing

3.1 Test gun specifications

The calculated temperature distribution is compared with measurements carried out at the ISL in a 20-mm-caliber machine cannon (German type 693) for a series of 15 successive firings done by Zimmermann et al. [6]. These data are the sole temperature measurements for machine gun firing found in the literature. The investigations were done in 1978 and the only temperature records available are those shown on the right hand side of Figs. 8 and 9 for the measuring stations M2, M3, M6 and M7 stored on a Polaroid film.

A photography of the test device can be seen in Fig. 3a. The 20-mm-caliber projectiles are successively loaded one after the other from the side into the firing chamber of the machine cannon. The time interval from firing to firing was 86 µs and equal for all \( \Delta t_1, \Delta t_2, \ldots, \Delta t_{13}, \Delta t_{14} \). The machine gun used was equipped with 7 measuring stations, M1, M2, \ldots, M6, M7, for wall temperature measurement and one station for recording the gas pressure history. The gun set-up is shown in principle in Fig. 4. There, the measuring ports along the gun barrel and the projectile placed in front of the forcing cone are shown as well as information about the scale from which the locations of the thermocouples and the tube length can be determined. A detailed description of the machine gun is given by Zimmermann et al. [6].

3.2 Thermocouple application

To measure the inner surface temperature special thermocouples developed at ISL for gun barrel purposes are used, see Seiler et al. [3]. A schematically sketch of the set-up of the thermocouples can be seen in Fig. 3b.

3.3 Machine cannon operation

For machine cannon operation for firing 20 mm calibre projectiles, having a mass of 93 g, the powder B7T100 was used. At the muzzle, the mean velocity obtained by averaging the cadence of 15 firings was determined to about 1300 m/s. Due to the use of a smooth bore the projectiles had no rotation. As shown in Fig. 5 for the computations the cannon geometry was modified with \( x = 0 \) located at the cannon’s breech. The acceleration of the projectile inside the bore was theoretically reconstructed in order to fit the muzzle velocity given. The resulting plot showing the velocity versus distance \( x \) along the gun tube is given in Fig. 6. Furthermore, the value of the base pressure is necessary as an input data for the calculation scheme performed for the repetitive firings. The
estimation for the base pressure distribution, also as a function of the projectile travel, is plotted in the diagram of Fig. 7.

4 Theoretical results

4.1 Comparison with temperature measurements

The calculations have been carried out using a time step procedure in which the time increases stepwise from \( t = 0 \) (beginning of the firing cycles) and ends at the 15\(^{th}\) time point (projectile leaves the muzzle). The heating of the barrel was estimated along the whole length of the gun tube (x-coordinate) and in depth (y-coordinate). The theoretically obtained results at measuring port M2 are compared in Fig. 8 with the temperature data measured. The calculations have been carried out for a 35 NCD 16 gun steel using the following data: density \( \rho = 7828 \) kg/m\(^3\), specific heat \( c = 460 \) Ws/kg K, heat conduction \( \lambda = 36 \) W/m K.

The data measured have been recorded with an oscilloscope and stored on photography. The signals for port M2 and M3 are given on the right side of Fig. 8. The temperature distribution at M2 was determined with the thermocouple calibration factor and some digitalized data compared with calculated results are presented on the left side diagram of Fig. 8. The scaling on the oscilloscope recordings is: 292 K per vertical division and 200 ms per horizontal division. The measured surface temperature (triangles) fits well with the theoretical temperature evolution within the given error bars ranging about ±7\% of the measured temperature values.

The calculated and measured temperature data comparison for M6 is shown in the left side of Fig. 9. The oscilloscope recording of station M6 used for the temperature determination is included at the right side of Fig. 9. M7 is also depicted on the oscilloscope record, but was not used herein.

Figure 10 shows the calculated surface temperature distributions at locations \( x = 0.3 \) (M1), 0.44 (M2), 0.76 (M3), 0.98 (M4), 1.22 (M5) and 1.54 (M6). The temperature signals shown in Fig. 10 for all different measuring locations are fitted together for comparison purposes. Notice that they are shifted in time as the projectile pass the different locations \( x \). The highest temperatures appear at location M1 which is placed near the forcing cone of the machine cannon. Downstream, towards the muzzle along M2, M3, M4, M5 and M6 the heating develops smaller, i.e., the surface temperatures decrease.

The predicted temperature development inside of the barrel wall, e.g., in a depth of \( y = 150 \) \( \mu \)m are shown for measuring location M2 in Fig. 11 and for location M6 in Fig. 12. The development of the temperature in depth is lower compared with the development of the surface temperature at M2 (Fig. 8) and M6 (Fig. 9). The reason is due to the fact that the heat must be transferred into the tube wall by heat conduction and this is a time-dependent mechanism. For location M2 a temperature gradient develops in y-direction as shown in Fig. 13. The depth profiles are given for the 1\(^{st}\) shot at \( t = 1.5 \) ms, 2.5 ms and 6 ms.
Additionally, the result for the 15th shot is also included. The time points are relative to the 15th firing the same as for the 1st one: t = 1.5 ms, 2.5 ms and 6 ms, but the overall time for the 15th firing is: t = 1205.5 ms, 1206.5 ms and 1210 ms. In Fig. 14 the temperature profiles are given for M6. It can be withdrawn from both diagrams that after the first round the heat input influences only a wall layer of less than 1 mm. With ongoing time, e.g., after the 15th firing the wall even in deeper wall layers is heated up to no more than 500 K.

The above discussed temperature behaviour is also demonstrated in Figs. 15 (M2) and 16 (M6). There, the temperature versus depth y is given for the shot numbers n = 1, 2, 4, 7, 10 and 15. The time point shown is t = t_y + 2 ms. The time point t_y is the time at which the successive firings are released to fire. Because the repetition rate is 86 ms the t_y are as follows: t_1 = 0 ms, t_2 = 86 ms, t_3 = 172 ms, ..., t_13 = 1032 ms, t_14 = 1118 ms, t_15 = 1204 ms. The y-T diagram in Fig. 15 (M2) proves that the temperature increase during each of the successive firings, is restricted to a thin layer located near the inner tube surface of less than 0.5 mm. Herein, the temperature gradient becomes very steep and at the surface the temperature grows after the 15th round up to about 1300 K. In deeper wall layers the temperature increase develops slower. The maximum temperature inside of the barrel wall is less than about 700 K at a depth y between 0.5 mm and 2 mm. For M6 (Fig. 16), after the 15th shot, the surface temperature is about 900 K and quite lower than for M2. In depth the temperature is slightly lower than at the tube location M2.

4 Conclusions

The single firing heat transfer procedure developed at ISL was here extended to rapid fire. A theoretical model to predict the heating of a machine gun barrel using a 2 MHz Personal Computer with a computing time of some hours was established worldwide for the first time. The calculation scheme applies stepwise solutions of Prandtl’s boundary equations and of the heat conduction equation to model the heat input into a machine cannon during rapid fire. The available experimental temperature evolutions for two of the 7 measuring locations along a 20-mm-caliber machine cannon gun tube have been compared with the theoretical predictions.

The agreement between theoretically and experimentally determined surface temperatures proves the very good applicability of the theoretical procedure developed for calculating the heating of a machine gun under rapid fire.

From the results presented it can be deduced that the wall temperature in each of the successive firing cycles is strongly influenced only in a thin layer near the tube inner surface. For the 20-mm-caliber gun weapon firings, this layer is restricted to less than 0.5 mm. In this layer steep temperature gradient appear in y-direction towards the tube surface. In deeper wall layers the temperature increase moderately during the firing series performed.
References


Figure 1: Principle sketch of gun tube arrangement

Figure 2: Boundary layer formation from breech to projectile in a gun tube
Figure 3a: Machine cannon of ISL type 693, 20-mm-caliber

Figure 3b: ISL gun thermocouple

Figure 4: Measuring ports along the barrel of the machine cannon

Figure 5: Model geometry for the 20-mm-caliber machine cannon of ISL
Figure 6: Projectile speed vs. travel

Figure 7: Pressure at the projectile base vs. travel

Figure 8: Surface temperature evolution vs. repetition time range (M2)

Figure 9: Surface temperature evolution vs. repetition time range (M6)
Figure 10: Surface temperature evolution vs. repetition time range (M2 - M6)

Figure 11: Temperature evolution in 150 μm depth vs. repetition time range (M2)

Figure 12: Temperature evolution in 150 μm depth vs. repetition time range (M6)

Figure 13: Temperature profiles vs. depth (M2)
Figure 14: Temperature profiles vs. depth (M6)

Figure 15: Temperature profiles vs. depth (M2)

Figure 16: Temperature profiles vs. depth (M6)