Theoretical and experimental study on heat transfer behaviour in gun tubes using aerosil additive for surface erosion protection

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Abstract

The action of additive particles on reducing heat transfer from the hot, compressed propellant gas flow into the barrel of a powder gun has been investigated by both theoretical considerations and experiments performed at the 20 mm calibre erosion gun of ISL. For this purpose a boundary layer model was developed and its theoretical results were compared with bore temperature measurements carried out at two measuring stations which are placed near the forcing cone inside the gun tube. For theoretical description, Prandtl's boundary layer equations were applied to solve the unsteady, compressible and turbulent boundary layer development for determination of the heat flux \( q(x) \) from propellant gas to barrel wall. A solution of the heat conduction equation was used to get the entire tube temperature development during firing. We assumed that the additive particles used (aerosil: \( \text{SiO}_2 \)) in this study form a thin deposit layer acting as a barrel coating on the barrel's inner surface. The thickness of this layer is determined by matching the calculated temperature distribution to that obtained by thermocouple measurements. It was found that the \( \text{SiO}_2 \) layer thickness is of the order of 1.5 \( \mu \text{m} \pm 0.5 \mu \text{m} \) per firing which is in accordance with metallographic investigations of surface sensors at ISL.

1 Aim of additive investigations

It is well-known since many centuries that small particles with some micrometer in diameter which are added into the propellant gas flow can reduce gun erosion
dramatically. Unfortunately the mechanism behind the protective action of these particles, commonly called additive particles, has not been fully understood until now. There are theories which try to explain the action of additives on erosion reduction in gun barrels. One of them deals with heat transfer reduction by forming a thin additive layer of some micrometers in thickness which may protect the gun’s steel against excessive barrel surface temperatures. In order to investigate this phenomenon we carried out some firings with an aerosil additive (SiO₂, 2.2% of charge mass) which was initially placed at the back of the projectile between powder and rear. For estimating the formation of the additive layer, calculations of the temperature development have been done using a boundary layer model. Herein the additive deposition is simulated by a coating layer and the calculated temperature results are matched to experimental ones by choosing that additive layer thickness at which both temperatures, experimental and calculated ones, are equal.

2 Calculation schemes

2.1 Equations and solvers

For the theoretical description of the gun tube flow, the conservation equations for mass, momentum and energy need to be solved together. The calculation of the complete set of differential equations is usually performed with numerical methods, e.g., [1, 2]. But, in conventional gun tube flows the Reynolds number is generally so high that viscosity and heat conduction are important factors only in the boundary layer formed at the inner tube wall. For this reason, in some cases it is reasonable to consider only the formation of the boundary layer.

2.2 Existing schemes

If only the boundary layer formation is taken into account, then simplified conservation equations [3] can be applied. Such calculations have been carried out by May and Heinz [4] and Adams and Krier [5]. Again, numerical methods are required in order to solve the differential equations in references [4] and [5]. Compared with these numerical efforts, an analytical solution of the set of conservation equations would have the advantage to easily show the influence of important input parameters, although due to some simplifications the solution is not as exact as the results obtained by solving the full set of equations. Therefore an analytical time-step procedure resulting from Prandtl’s boundary layer equations was developed for predicting the formation of the in-bore boundary layer inside the gun tube.

3 Analytical boundary layer model for gun tube heating

3.1 Equations for boundary layer development

The simplified formation of the boundary layer inside a gun tube is schematically illustrated in Figure 1. In the vicinity of the base of the projectile an unsteady
boundary layer is formed at the wall of the gun barrel called "projectile boundary layer". It develops instationary as the projectile is accelerated down the tube. A second boundary layer, the "breech boundary layer", originates at the breech. The entire boundary layer formation is described by coupling both the projectile and breech boundary layers at equal boundary layer thickness $\delta$.

The formation of the gun tube boundary layer is treated in two dimensions which is justified where the boundary layer thickness is small compared with the bore diameter. The time-dependent and unsteady boundary layer development between breech and projectile will be approximated by taking into account the actual flow pattern upstream of the projectile at successive time intervals: $\Delta t_1$, $\Delta t_2$, ..., $\Delta t_{n-1}$, with $\Delta t_n = t_n - t_{n-1}$, see Figure 2. During each of the steps, $\Delta t_1$, $\Delta t_2$, ..., $\Delta t_{n-1}$ the problem is treated as a stationary one, wherefore the time-dependence can be withdrawn of Prandtl's boundary layer equations used, eqns see Schlichting [3]. The procedure for solving the gun boundary layer problem begins with a relation for the wall shear stress $\tau_w$:

$$
\tau_w = \frac{d}{dx} \rho \left( \frac{\delta}{u_\epsilon - u} \right) + \rho \left( \frac{\delta}{u_\epsilon - u} \right) dy.
$$

The quantities denoted with index $\epsilon$ in eqn (1) describe the core flow behaviour (see Figure 1) and those without index are related to the boundary layer region with thickness $\delta$. The experimentally determined velocity profile in turbulent boundary layers is given approximately by the power-law equation, see [3]:

$$
\frac{u}{u_\epsilon} = \left( \frac{y}{\delta} \right)^{1/n}, \quad 5 \leq n \leq 10.
$$

Introducing eqn (2) into (1) for both the breech and the projectile boundary layer two sets of differential equations are obtained which are solved with the boundary conditions present in the outer core flow. The flow velocity $u_\epsilon$ between breech and projectile is linearly approximated to theoretical results given by Krauth [6], with:

$$
u_\epsilon(x,t) = u_p(t) x/L.
$$

The projectile speed $u_p$ is a function of $x$ or $t$, with $x = x(t)$. $u_\epsilon$ depends on $x/L$, with $L$ the distance between breech and projectile. Additionally Krauth [6] shows that the propellant gas pressure and temperature distributions are practically constant along the $x$-coordinate inside the accelerator tube. Therefore we assumed $p$ and $T$ to be constant along $x$ during each of the time intervals $\Delta t_n$. However, the quantities $u_p$, $p$, and $T$ change in time with stepwise projectile displacement, given with $x_p = x_p(t)$:

$$
p = p(t), \quad T = T(t).
$$

Integration of the two differential equations yields analytical solutions for the boundary layer thickness $\delta$ and wall shear stress $\tau_w$. Using Reynolds analogy [3], the heat flux $\dot{q}_g$ from gas to tube surface was calculated, Seiler et al. [7].
3.2 Projectile boundary layer heat flux

Following the procedure described by Seiler et al. in [9] the solution for the projectile boundary layer heat flux is:

\[
\dot{q}_g(\bar{x}) = \left( \frac{n+1}{n+3} \right) \frac{2}{n+3} \left( B(n) \eta \right) \frac{n+1}{n+3} \left( \frac{c_p(T_r-T_w)}{\rho e} \right) \frac{2}{3} \rho_e \]

\[
\left( \frac{\nu_2 \delta^{**}}{L \delta} \right) \frac{2}{n+3} \frac{n+1}{n+3} \left[ -\ln \left( \frac{1}{L \delta^{**}} \right) \right] \frac{2}{n+3}.
\]

3.3 Breech boundary layer heat flux

Eqn (6) gives the solution for the breech boundary layer heat flux as:

\[
\dot{q}_g(x) = \left( \frac{n+1}{n+3} \right) \frac{2}{n+3} \left( B(n) \eta \right) \frac{n+1}{n+3} \left( \frac{c_p(T_r-T_w)}{\rho e} \right) \frac{2}{3} \rho_e \]

\[
\left( \frac{\delta^{**}}{\delta} \right) \frac{2}{n+3} \frac{n+1}{n+3} \left( \frac{\nu_e}{L} \right) \frac{2}{n+3}.
\]

4 Gun tube temperature calculation

The variation of the calculated heat flux along the coordinate \( \bar{x} \) in eqn (5), respectively along the breech \( x \)-coordinate in eqn (6) is very small. Therefore, the one-dimensional heat-conduction equation was applied along the tube coordinate \( X \) from breech to projectile. Herefore, the projectile boundary coordinate \( \bar{x} \) is transformed as \( x = L - \bar{x} \).

\[
\frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial y^2} \text{ with } k = \frac{\lambda}{\rho c}
\]

Gatau [8] obtains by integration of equation (7) with the given boundary conditions analytical solutions for the gun tube temperature change \( \Delta T_w \). These solutions are valid for a non-coated wall as well as for a coated one as a function of both heat fluxes which are denoted by the parameter \( F \), as:

\[
F = \dot{q}_w(x), \text{ resp. } F = \dot{q}_w(\bar{x}),
\]

4.1 Solution for non-coated barrel wall

\[
\Delta T_w (y,t) = \frac{F}{\sqrt{\lambda \rho c}} \left[ 2 \sqrt{\frac{\pi t}{k}} \exp \left( -\frac{y^2}{4kt} \right) \frac{y}{\sqrt{k}} \text{erfc} \left( \frac{y}{2\sqrt{kt}} \right) \right]
\]
4.2 Solution for coated barrel wall

The barrel wall temperature distribution is denoted in eqns (10) as $\Delta T_2$, and inside the coating layer as $\Delta T_1$. The parameter $a$ in eqns (10) describes the thickness of the coating layer.

$$\Delta T_1(y,t) = \frac{F}{\sqrt{\lambda_1 \rho_1 c_1}} \sum_{n=1}^{\infty} \sigma^n \left[ 2 \sqrt{\frac{t}{\pi}} \exp \left( -\frac{y^2}{4k_1 t} \right) - \frac{y}{\sqrt{k_1}} \text{erfc} \left( \frac{y}{2\sqrt{k_1 t}} \right) \right]$$

$$\Delta T_2(y,t) = \frac{F_i + \sigma}{\sqrt{\lambda_1 \rho_1 c_1}} \sum_{n=0}^{\infty} \sigma^n \left[ 2 \sqrt{\frac{t}{\pi}} \exp \left( -\frac{(2n+1)a + y - a}{2\sqrt{k_1 t} + 2\sqrt{k_2 t}} \right) \right. - \left( \frac{2n+1)a + y - a}{\sqrt{k_1} + \sqrt{k_2}} \right) \text{erfc} \left( \frac{(2n+1)a + y - a}{2\sqrt{k_1 t} + 2\sqrt{k_2 t}} \right)$$

$$\sigma = \left( \frac{\rho_1 c_1 \lambda_1}{\rho_2 c_2 \lambda_2} - 1 \right) \left( \frac{\rho_1 c_1 \lambda_1}{\rho_2 c_2 \lambda_2} + 1 \right).$$

Introducing the heat fluxes of eqn (5), and (6) in (10a, b) by assuming that the heat flux at the surface $y = 0$ is equal on both, the gas side and the wall side, with stepwise constant $F = \dot{q}_g(x,t) = \dot{q}_w(x,y=0,t)$ during time interval $\Delta t_n$, the temperature distribution inside the gun barrel and inside the coating layer becomes additionally a function of the coordinate $x$: $T_w(x,y,t)$.

The procedure is carried out for each of the $n$ time step intervals $\Delta t_1, \Delta t_2, \ldots, \Delta t_n$, at the locations $x_1, x_2, x_3, \ldots, x_n$ between breech ($x = 0$) and projectile ($x = x_p$), with $0 \leq x_n \leq x_p$, as explained in detail by Seiler et al. in [9]. To obtain the whole temperature history $T_w(x,y,t)$ inside the gun tube wall at $x_1, x_2, x_3, \ldots, x_n$ as a function of time $t$, the wall temperatures, stepwise calculated for $x_1, x_2, x_3, \ldots, x_n$, are added at each location $0 \leq x_k \leq x_p$ over $t$, i.e., the $n$ time steps. For each $x_1, x_2, x_3, \ldots, x_n$, the total bore temperature increase $\Delta T_w$ is given as:

$$\Delta T_w = \Delta T_{w,1} + \Delta T_{w,2} + \Delta T_{w,3} + \ldots + \Delta T_{w,n} = \sum_{k=1}^{n} \Delta T_{w,k}. \quad (11)$$
5 Erosion-gun facility with 20-mm-caliber

5.1 Test gun with 20 mm caliber

For bore temperature determination single-shot experiments have been performed in a test gun device of 20 mm caliber, described by Seiler et al [9]. The set-up consists mainly of the combustion chamber and the gun tube containing a cylinder inset, see Figure 3. This removable cylinder is equipped with bore holes in two measuring cross-sections A and B with measuring ports M3 and M4 which can be instrumented with thermocouples for temperature gauging. The barrel is smooth and the projectile starts from the forcing cone. A bag is used for propellant loading and the combustion is released electrically.

5.2 Thermocouple measurements

For bore temperature gauging nickel-steel thermocouples have been developed at ISL as shown schematically in Figure 4. They consist of a steel housing and a centered nickel wire. The front side of the thermocouple is coated with a galvanic nickel layer of 10 μm thickness. Therefore, the temperature is measured at the nickel-steel contact layer in a depth of 10 μm and not at the inner bore surface directly, see Seiler et al [7].

6 Comparison of experiment and model calculation

6.1 Input parameters

The propellant considered for gun firing is the gun propellant GB-Pa 125 with an adiabatic flame temperature of 3750 K. A 50 g charge is used for the firings presented. The computations take account of the geometry and the interior ballistics of the 20-mm-caliber test device, see Seiler et al. [7]. In the calculation the diameter of the combustion chamber is reduced to gun tube diameter at equal volume, i.e., the length of the combustion chamber is increased in our boundary layer model. The projectile back starts at \( x_p = 0.33 \) m and the breech is located at \( x = 0 \). Projectile displacement is \( \Delta x = 0.01 \) m per time step \( n \). The input data for the analytical solution are based on gas pressure and muzzle velocity as they are given by the experiments done. Therewith the gas temperature, projectile and flow velocity distributions are determined. In eqns (5) and (6) the Prandtl number is \( \text{Pr} = 0.81 \), and the exponent \( n \) in eqns (2), (5) and (6) is set to \( n = 7 \). The thermophysical properties, as they are introduced in the solution of the heat conduction eqn (7) for gun steel and aerosil additive, are listed in the following: Gun steel of type 35 NCD 16: density \( \rho = 7828 \) kg/m\(^3\), specific heat \( c = 460 \) Ws/kg K, heat conduction \( \lambda = 36 \) W/m K. For the aerosil additive the density is assumed to \( \rho = 220 \) kg/m\(^3\). The specific heat \( c \) as well as heat conduction \( \lambda \) depend on gas temperature \( T \), varying from \( c = 745 \) Ws/kg K, \( \lambda = 1.38 \) W/m K at \( T = 300 \) K up to \( c = 1195 \) Ws/kg K, and \( \lambda = 4.0 \) W/m K at \( T = 1200 \) K. Herein, data for aerosil additive particles in polycrystalline form are used.
6.2 Discussion of thermocouple measurement

To compare more realistically theory and thermocouple measurements, the nickel layer exposed to the gas flow has to be taken into account in the calculation scheme. Calculations by Seiler et al. [7] for the temperature distribution in a non-coated barrel and in a nickel coated barrel show no big difference between the results with and without nickel layer. The difference between the two cases is of the order of the measuring error of about 6%. This result shows that the nickel-steel thermocouples are most adequate for temperature gauging in steel tubes.

6.3 Gun tube firing without aerosil additive

Figure 5 presents a typical temperature history with no additive inside the combustion chamber and shows the temperature distributions at $x/m = 0.36$ (M3), $0.42$ (M4), 1, 1.5, and 2, for the gun firing no. 3010. The agreement between the measured wall temperature of this “reference firing”, bold curves in Figure 5, and the calculated ones is very good and shows the excellent applicability of our interior ballistics boundary layer scheme for predicting the gun tube heating during firing.

6.4 Gun tube firing with aerosil additive

For the nine firings ($9^{th}$ firing is no. 3031) with the addition of 1.1 g ($2.2\%$) aerosil additive placed at the back side of the projectile, the temperature distribution after these nine cycles is shown in Figures 6 and 7. The thermocouples were not cleaned between firing and so far the aerosil additive layer increased by additive deposition from firing to firing. The barrel temperatures at M3 and M4 (bold curves) drop significantly as compared to Figure 5. This temperature drop is a consequence of the additive layer formation in front of the thermocouple. At both measuring stations, M3 and M4, the temperature reduction by the action of the additive seems similar. There is an agreement between calculation and experiment, taking into account the measuring error (see error bars) of about 6%, for a layer thickness ranging between 10 and 20 μm for nine firings, i.e., the aerosil layer thickness, denoted by parameter $a$, is estimated as $1 \leq a/\mu m \leq 2$ per firing. From this outcome, the averaged deposit layer thickness per cycle is, as also found by metallographic investigation described by Licht et al. [10], in the range of:

$$a = 1.5 \mu m \pm 0.5 \mu m$$

7 Concluding remarks

Temperature information on gun tube heating is very important in erosion research. Therefore, in the present study the gun tube wall boundary layer heat flux formation has been investigated theoretically and experimentally. For a theoretical description an analytical approximation scheme using Prandtl's
boundary layer equations as well as the heat conduction equation has been developed. Solutions are given for the barrel wall temperature distribution for firings with no additive as well as for firings with aerosil additive (2.2% of charge mass). This was done assuming the formation of a thin additive layer which is comparable to a coating layer at the inner steel surface of the gun barrel. Calculations with different additive coating layer thickness have been carried out and the calculated temperature distributions are compared with measured temperature data. The additive layer thickness which best agrees with the theoretical and experimental temperature evolution, gives an indication of the additive layer thickness required to reach the barrel temperature as measured in a "firing with additive". The additive layer thickness necessary to match calculation and experiment is in the range of $1.5 \pm 0.5 \text{ pm}$ per firing.

8 References


Figure 1: Schematic of boundary layer formation in a gun tube
Figure 2: Projectile speed approximation by time-step procedure

Figure 3: Gun tube set-up of 20-mm-caliber test-gun

Figure 4: Thermocouple
bore temperature $T_w / K$
(measuring station M4)

bore temperature $T_w / K$
(measuring station M3)

bore temperature $T_w / K$