Computational method and experimental measurement of gun tube flow heat transfer

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Abstract

In the present study, the action of the hot and compressed propellant gas flow inside the barrel of a powder gun on heat transfer and barrel erosion has been investigated (1) theoretically using a boundary layer & ablation model developed at ISL and (2) experimentally measuring bore temperature and bore surface erosion in ISL’s 60-mm-caliber erosion-gun. For theoretical description, an in-bore boundary layer model was developed using some basic assumptions for the interior gun tube flow. Prandtl's boundary layer equations were applied to solve the unsteady, compressible and turbulent boundary layer development for discrete projectile locations. Melting erosion at the inner surface is taken into account in this interior ballistics heat transfer model. This allows the prediction of tube erosion where melting processes at the bore surface are dominant.

1 Introduction

In conventional gun tube flows generally the Reynolds number is so high that viscosity and heat conduction are important factors only in the boundary layer at the inner tube wall. Across this wall layer the normal velocity increases from zero to free stream velocity, and the gas temperature changes from the inner tube surface temperature to the higher gas temperature inside the core flow of the propellant gas. For the theoretical description of the formation of the turbulent boundary layer, usually the conservation equations for mass, momentum and energy are used. The turbulence of the flow is taken into account with a turbulence model, e.g., the k-e model. It is difficult, however, to find an analytical solution for the complex system of equations needed. Thus, the
calculation of the complete set of differential equations must be performed with extremely time and memory consuming numerical methods, e.g., [1-3].

Compared with these efforts an analytical solution has the advantage to provide easily the influence of important input parameters. Therefore an analytical solution resulting from Prandtl's boundary layer equations has been developed for predicting the formation of turbulent in-bore boundary layer.

2 Analytical boundary layer model for gun tube heating

2.1 Existing calculation schemes

If only the boundary layer formation is taken into account, then simplified conservation equations [4] can be applied. Such calculations have been carried out by May and Heinz [5] for the case of a compressible and laminar tube boundary layer. The calculations of Adams and Krier [6] involve the unsteady, compressible and turbulent boundary layer using the boundary layer equations combined with a simple turbulence model. Here again, numerical methods are required in order to solve the differential equations in references [5] and [6].

The disadvantage of all these theoretical models as mentioned above is that they are time consuming and require a great amount of computer resources. Therefore, it is desirable to have a simplified analytical solution, even if it yields to an approximate description of the realistic event.

2.2 Equations for the 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 downstream as the projectile is accelerated down the tube. In addition, a stationary bore boundary layer originates at the breech: "breech boundary layer". The entire boundary layer formation can be described, by coupling both the projectile and breech related boundary layers at the position of equal boundary layer thicknesses.

The formation of the gun tube boundary layer is treated in two dimensions which is justified when the boundary layer thickness is small compared with the bore diameter. The time-dependent and unsteady boundary layer development between breech and projectile is approximated by taking into account the actual flow pattern upstream of the projectile at successive time intervals \( \Delta t_0, \Delta t_1, \Delta t_2, \ldots, \Delta t_n \), see Seiler et al. [7]. During each of the steps \( \Delta t_0, \Delta t_1, \Delta t_2, \ldots, \Delta t_n \) the problem is treated as a stationary one, wherefore the time-dependence is eliminated from Prandtl's boundary layer equations used [4]. Then following the procedure described by Seiler et al. in [7] the solution for the projectile boundary layer heat flux is:
For the breech boundary layer heat flux the following relation is valid:

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

\[
\left(\frac{v_2 \delta^{**}}{L \delta}\right)^{n+3} \frac{n+1}{n+3} \left[\ln\left(\frac{x}{L \delta^{**}}\right)\right]^{n+3}.
\]

3 Wall temperature calculation

The heat flux \( \dot{q}_w(x) \), resp. \( \dot{q}_w(x) \), into the tube is approximately treated one-dimensional in depth (y) and therefore the one-dimensional heat-conduction equation was applied, see Seiler et al. [7]. By integration of the heat-conduction equation with the given boundary conditions, a solution for the temperature change \( \Delta T_w \) into the tube wall as a function of the heat flux \( \dot{q}_w(x) \), resp. \( \dot{q}_w(x) \) is obtained. The procedure for calculating the wall temperature variation \( \Delta T_w \) is presented in detail in [7]. With the relations given in [7] it is possible to calculate the gun tube heating \( \Delta T_w = \Delta T_w(x, y, t) \) for the whole firing cycle as a function of time t and for each location x along the gun tube, as well as inside of the tube wall in depth y.

4 Analytical ablation model

4.1 Assumptions

It is assumed that ablation occurs only by melting erosion with no evaporation. Melting erosion takes often place when hot gas flows with a high stagnation temperature are in contact with colder walls. This process is extensively treated by several authors, see Adams [8]. In the paper of Seiler et al. [9] an analytical ablation model for calculating melting processes on the sharp-nose cone of a ram-projectile is described. This model was used and transformed to predict
surface melting in gun barrels. It is assumed that the tube geometry remains approximately unchanged by heating and ablation, i.e., ablation is small. Therefore, the boundary layer formation is considered to be uninfluenced. Due to strong shear stresses it is supposed that the molten material is wiped away from the bore surface immediately as it is produced by heat input in the case that the wall temperature exceeds the melting temperature.

4.2 Ablation equations

Heating and melting ablation are decoupled during time a interval $\Delta t_n$ at each point $x$ along the gun tube barrel. Assuming that for $t < t_n$ the wall temperature $T_{w,n-1}(x,y,t) < T_{melt}$ and for $t = t_n$ the wall temperature $T_{w,n}(x,y,t)$ becomes here warmer as the melting temperature $T_{melt}$ by the heat input into the wall $\dot{q}_{w,n}(x,t) = \dot{q}_g$, see Figure 2. From here on melting occurs in the layer $\Delta y_1$ at time interval $\Delta t_n = t_{n+1} - t_n$ and the melting heat $h_{melt}$ of the wall material has to be taken into account. The total heat flux input $\dot{q}_{w,n}$ must be subdivided into one part $\dot{q}_{c,n}(x,t)$ for heat conduction and the other one for heat of melting:

$$\dot{q}_{w,n}(x) \Delta t_n = \dot{q}_{c,n}(x) \Delta t_n + \rho h_{melt} \Delta y_j, \quad j = 1, \ldots, m. \quad (3)$$

For obtaining the molten layer $\Delta y_j(j = 1, \ldots, m)$ along the time steps $n$ at each tube location $x$, equation (3) can be solved using the solution given in [7] for $\Delta T_w = \Delta T(x, y, t)$ and the additional assumption

$$T_{w,n+1}(x, y= y_{n+1}) = T_{melt}. \quad (4)$$

At the end of time interval $\Delta t_n$ the molten layer $\Delta y_j$ is wiped away by the shearing forces exerted by the strong wall shear stress $\tau_w$. The described processes of melting and shearing are continued during the whole firing cycle:

$$t < t_n : T_{w,n-1} < T_m$$

$$t = t_n : T_{w,n} > T_m \xrightarrow{\Delta y_1 = y_{n+1} - y_n} T_{w,n+1} = T_m,$$

$$t > t_n : T_{w,n+1} > T_m \xrightarrow{\Delta y_2 = y_{n+2} - y_{n+1}} T_{w,n+2} = T_m,$$

$$\vdots$$

$$T_{w,n+m} > T_m \xrightarrow{\Delta y_m = y_{n+m} - y_{n+m-1}} T_{w,n+m} = T_m.$$  

Then, the total erosion $e$ at position $x$ is:

$$e(x) = \sum_{j=1}^{m} \Delta y_j(x), j = 1, \ldots, m. \quad (6)$$
5 Erosion gun with 60 mm caliber

The 60-mm-caliber erosion gun (Figure 3) is specially designed for testing inner coatings in steel barrels. The gun barrel begins with a tube segment of 170 mm length which is used for the erosion measurements. This cylindrical insert can be removed for erosion investigations. This removable segment is equipped with bore holes for temperature and pressure gauging. Erosion data are gathered by determining the increase of the inner bore diameter. The bore temperature is measured with the thermocouples shown in Figure 4, see [7].

Pressure and temperature distributions are shown for firing no. 127, resp. 128, in Figure 5: pressure $p_1$ at measuring station M1 (combustion chamber), $p_2$ and barrel temperature $T_2$ at station M2. M2 is placed in the middle of the 170 mm long cylindrical erosion insert. The gun powder used is 1.2 kg L1 and the projectile mass is typically 1.5 kg with a nylon driving band. Therewith a muzzle velocity of about 1400 m/s was achieved. Gun firings have been done with (1) steel inserts (35 NCD 16), (2) inserts coated with 150 μm chromium and (3) inserts with 50 μm chromium coated on a thick copper layer.

6 Heating & ablation model compared to gun firings

6.1 Input parameters for the calculation code

As input parameters the thermophysical properties density, specific heat and heat conduction for the gun barrel steel as well as for chromium are used [7]. Additionally, the data for the copper layer (CuCrZr) are enclosed: density $\rho = 8930$ kg/m$^3$, specific heat $c = 391$ Ws/kg K, heat conduction $\lambda = 175$ W/m K.

6.2 Steel tube

A comparison between temperature measuring results gathered with the thermocouple sensor and a calculation is given in Figure 6 for shot no. 128. As shown in [7], the thermocouples could practically be used without temperature transformation to determine the temperature in barrels of steel guns. Therefore, the calculations are done for a steel gun tube. The calculated profile begins as steep as the experimental one does. Also the maximum temperature is in good agreement as well as the shape of the whole temperature development.

6.3 Ablation

Using the procedure of equations (5) and (6), the total melting erosion $e$ was estimated at two positions: 6 cm and 9 cm upstream of measuring station M2. It can be seen in Figure 7 that the calculated melting erosion increases towards the erosion tube inlet (upstream) and decreases downstream. The calculated melting ablation is in good agreement within the limits given from the experiment. At the inlet to the erosion tube $e = 30$ μm, and the outlet erosion $e = 10$ μm per shot.
were measured and also calculated. This result confirms the model assumptions of steel melting followed by wiping. Furthermore it shows the good applicability of the model describing gun tube heating and ablation.

6.4 Steel tube with chromium coating

A chromium coating reduces the surface bore temperature compared with the case of an uncoated steel tube, see Figure 8 for 150 μm chromium layer on steel tube. Figure 9 shows that in depth of 150 μm (contact layer chromium/steel) the bore temperature is slightly higher in a chromium/steel tube compared with the simple steel case. An important result is the fact that with chromium coating the steel barrel is protected against the high maximum temperatures of about \( T = 1800 \, \text{K} \), seen in Figure 8.

It is also important to optimize the chromium layer thickness to protect in an optimal way the steel barrel against too high temperatures. Therefore calculations have been done with chromium layer thicknesses of 50/150/250 μm on steel barrels. The results are depicted in Figures 10 and 11. At the inner surface a chromium layer thickness of 50 μm can be tolerated. More than 150 μm is not necessary, see Figure 10. In order to reduce the temperature of the steel tube, e.g., below \( T = 800 \, \text{K} \) a chromium layer of a minimum of 150 μm or more is desirable.

6.5 Steel tube with chromium coating on a copper layer

To reduce drastically the bore temperature, a good heat conducting coating material should be used. Calculations with a CuCrZ-layer show that the bore temperature can be dropped strongly. Newest calculations for a duplex coating with a 50 μm chromium layer to protect the copper layer underline this effect. The surface temperature at the chromium layer is quite high (Figures. 12 and 13), but in depth the steel tube temperature remains nearly unchanged, see Figure 13. Future efforts will have to be undertaken to optimize the chromium and copper layer thicknesses or to exchange these materials by other coatings.

7 Conclusion

In the present study the boundary layer formation has been investigated theoretically and experimentally. For the theoretical description an analytical approximation beginning with Prandtl's boundary layer equations has been used. The calculation results yield informations on parameters such as boundary layer thickness and heat flux into the tube wall. Surface erosion by melting processes was considered within an ablation model. The heat flux results are used to find an analytical solution of the heat conduction equation for calculating the bore temperature at the inner surface and in depth. These outcomes are compared with bore temperature measurements gathered in the ISL 60-mm-caliber test-gun using special ISL nickel/steel thermocouples.
References


9. Seiler, F., *Boundary layer model for calculating the heat transfer into a ram projectile fired in a ram accelerator*, Second Int. Workshop on Ram Accelerator, RAMAC II, University of Washington, Seattle, USA, 1985

![Figure 1: Schematic of boundary layer formation](image-url)
Figure 2: Temperature $T_{w,1}$...$T_{w,n+m}$ and ablation $\Delta y_1$...$\Delta y_m$

Figure 3: 60-mm-caliber erosion gun

Figure 4: Thermocouple

Figure 5: Pressure and temperature distributions at stations M1 and M2
Figure 6: Measured and calculated bore temperature in a depth of 10 μm

Figure 7: Experimental and calculated bore melting erosion

Figure 8: Surface temperature for steel tubes and 150 μm chromium coating

Figure 9: Temperature in depth of 150 μm for steel, 150 μm chromium on steel
Figure 10: Surface temperature for steel tubes with 50/150/250 µm chromium

Figure 11: Temperature distribution at the contact surface between Cr and steel

Figure 12: Temperature at surface, Cr/CuCrZr-layer, CuCrZr/steel tube

Figure 13: Temperature in depth at station M2 for Cr/CuCrZr on steel