Available online at www.sciencedirect.com
ScienceDirect
Applied Thermal Engineering 28 (2008) 881–888
APPLIED THERMAL ENGINEERING
www.elsevier.com/locate/apthermeng

Heat transfer in a 155 mm compound gun barrel with full length integral midwall cooling channels

Bin Wu [a,*], Gang Chen [a], Wei Xia [b]

[a] Department of Military Engineering, Artillery Academy, Hefei 230031, China
[b] School of Mechanical Engineering, South China University of Technology, Guangzhou 510640, China

Received 4 July 2006; accepted 7 July 2007
Available online 20 July 2007

Abstract

When firing, large amounts of heat flow into the gun bore surfaces and result in wear and erosion of the gun bore. Moreover, the chamber surface temperature will reach the cook-off temperature of propellant during long sustained firing, which will impact on user safety and facilities. For large-caliber gun, a serious limitation on the weapon's availability for action is imposed with high-energy propellants used and firing rates increasing. An effective method for solving this problem is to adopt barrel liquid-cooling technique. In this paper, heat transfer in a 155 mm midwall cooled compound gun barrel was analyzed theoretically. For the reference, heat transfer in a naturally cooled monobloc gun barrel was also discussed. Finite element analysis (FEA) method was employed to validate the results obtained by theoretical analyses. The present study showed: (1) natural air cooling is ineffective for transferring the heat out of the barrel because the combined convection and radiation heat transfer coefficient is relatively small; (2) forced midwall cooling has great heat extraction capability and is able to keep the chamber temperature below the cook-off temperature by increasing the heat transfer coefficient; (3) an optimal flow rate should be selected to balance the cooling efficiency and the pressure loss.

Keywords: Heat transfer; Gun barrel; Midwall cooling

1. Introduction

Gun bore surfaces receive large amounts of heat resulting from the combustion of ammunition propellants and from the friction between the projectile driving band and the gun bore when firing. Before another round is fired the barrel has some time to cool down, but only a small amount of heat is transferred to the environment by means of convection and radiation, which leads the temperature of the barrel to increase. During long-burst firing, heat accumulates and causes the barrel to reach a high temperature, limited by the cook-off temperature. Once the cook-off temperature is reached, propellant from a new round will self-ignite. In rapid-fire small-calibre weapon, such as machine guns and machine cannons, the barrel can become red-hot under long-burst firing condition, and subsequently the firing must be stopped immediately to allow barrel cooling. In addition to cook-off, gun bore erosion has a close relation to this intense thermal condition. In general, the major contributors to erosion damage are thermal effects, chemical attack of propellant gases, mechanical wear of projectile passage, and mechanical loading from gas pressurization [1]. No matter what the specific mechanism of erosion, it is a function of the rate of heat transferred to the gun bore surface. Wear and erosion of the gun barrel reduces the accuracy of the projectile and ultimately diminishes the life of the gun.

The mission requirements of future war fighting require the development of new generations of large-calibre guns capable of providing increased range, rate, accuracy, and energy on target. High-energy propellants with flame temperature up to 3700 K are used for improving gun

* Corresponding author.
E-mail address: mewubin@tom.com (B. Wu).

1359-4311/$ - see front matter
doi:10.1016/j.applthermaleng.2007.07.010

Nomenclature

A	area
A_{bo}	the heat exchange area of cooling channels
A_{jo}	the heat exchange area of the outside surface of the jacket
A_C	the cross-section area of the cooling channels
r	radius
r_{bi}	inner side radius of barrel
r_{bo}	outer side radius of barrel
r_{ji}	inner side radius of jacket
r_{jo}	outer side radius of jacket
c_p	specific heat at constant pressure
ρ	density
λ	thermal conductivity
a	thermal diffusivity
E	Young's modulus
ε	Poisson's ratio
δ	barrel wall thickness
l	length of barrel
V	the volume of gun barrel
n	round per minute
T	temperature
T_f	the reference temperature of the coolant
T_0	the initial temperature of gun bore surface before first round
T_∞	the ambient temperature
$T_{bi,j}$	the initial temperature of gun bore surface before round $(j+1)$th
T_c	the cook-off temperature
T_{bo}	the outside surface temperature of gun barrel
T_{jo}	the outside surface temperature of the jacket
T_{max}	the maximum bore temperature
$\Delta T_{bi,j}$	the temperature increment resulted from fired round jth
$(\Delta T_j)_V$	the temperature increment of $\mathrm{d}V$
$\overline{\Delta T_j}$	the average bulk temperature increment
h	heat transfer coefficient
h_∞	the combined convective heat transfer coefficient
h_c	the natural convection heat transfer coefficient
h_r	the radiation heat transfer coefficient
Q_{in}	the thermal energy transferred into the gun bore
Q_{out}	the thermal energy transferred out of the gun barrel
Q'_{out}	heat exchange between cooling channels and coolant
Q''_{out}	heat exchange between the outside surface of jacket and the environment
t	time
t_h	the heating period
τ	time-constant
H_∞	the total heat transfer per unit area per round
u_m	the average coolant velocity
q_V	the volume flow
j	integer

performance. However, unacceptable erosion occurs due to the large thermal energy exchange between the combustion of the ammunition propellant and the gun bore. Additionally, firing at sustained high rates will quickly make the gun too hot to load or fire and impact on user safety and facilities as a result of the possibility of cook-off. A Thermal Warning Device (TWD) is used to indicate to the gun crew when it is safe to shoot. It does not work for modern large caliber gun that are capable of firing at rates of 8–10 rounds per minute. Generally, it takes more than 12 h for the barrel to cool down from the cook-off temperature to ambient temperature under natural air cooling condition. So, other methods of cooling barrel are needed to retain barrel life and enable artillery weapons to increase individual mission durations and reduce their recovery time between missions.

Wu [2] briefly reviewed cooling technologies for gun barrels, which are either passive or active. Passive cooling technologies, such as chromium/tantalum plating and wear-reducing additives, are adopted to reduce the thermal energy input by setting up a thermal barrier between the hot propellant gas and the steel of the barrel. Lesquois et al. [3] studied thermal effects induced by mechanical friction in condition of high speed tribology and found that the hard chromium coating was a good thermal barrier and mechanical protector for the substrate steel. Matson and co-workers [4] have demonstrated the effectiveness of tantalum as protection against high temperature wear and erosion. Franco and Peter [5] showed that using silicon dioxide as an additive can lead to a reduction of the steel temperature by approximately 150 °C. Boisson et al. [6] showed that in the cross-section near the end of the barrel additives reduce the inner wall maximum temperature value to about 250 °C, and about 150 °C in the section near the forcing cone. Lawton [7] showed that the wear-reducing additive gradually reduced the surface temperature fluctuation from about 950 °C to about 600 °C, and reduced heat transfer per round from about 950 kJ/m^2 to about 600 kJ/m^2 over a period of 50 rounds, which is expected to increase the number of rounds to cook-off from about 53 to 90 at 3 rounds/min.

It is well known that chromium plating and wear-reducing additives reduce wear and erosion of the gun bore and consequently extend barrel life. However, it has a minor effect on the heat entering into the gun bore surface; the majority of the heat is still transferred into the gun bore surface and accumulates with the number of rounds. Active cooling technologies, such as finned-barrel cooling and