Defence Science Journal, Vol. 57, No. 2, March 2007. pp.

SHORT COMMUNICATION

Estimation of Heat Loss in a Closed Vessel

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ABSTRACT

Power cartridges are designed and developed for use in military aircraft in association with High Energy Materials Research Laboratory, Pune. During development, the cartridge is fired in a closed vessel to generate basic design parameters. When the cartridge is fired, the heat is lost to the walls of the vessel due to conduction, convection, radiation, and to some extent, by expansion of the vessel. An attempt has been made to estimate the heat loss from the vessel and the surrounding. The aim of this study was to lay down the technical results theoretically and their validation through experiments.

Keywords: Closed vessel, heat transfer, heat loss, heat generation

NOMENCLATURE

A	Surface area of the vessel
b	Co-volume of gas
C	Charge weight of propellant
C_v	Specific heat at constant volume
C_p	Specific heat at constant pressure
$\overline{C}$	Mean molar heat capacities of gaseous products
d	Internal dia of vessel
F	Force constant of propellant
h	Overall heat transfer coefficient
ΔH	Heat loss by propellant
K	Thermal conductivity
l	Length of closed vessel
M	Molecular weight
m	Mass of gaseous products
n	Number of moles of gas per unit mass
P	Maximum pressure obtained from P-t curve, when propellant is burned inside the closed vessel
p	Absolute pressure of gas
Q	Amount of heat generated by propellant
R	Gas constant for products of combustion
T	Temperature of propellant gas
T_a	Ambient temperature
T_e	Adiabatic flame temperature of propellant
t	Time when propellant burns
ΔT	Temperature difference

Revised 3 April 2006

V Volume of gas

v Specific volume of gas

Greek Symbols

π Constant, 3.147

γ Ratio of specific heat for propellant gases

1. INTRODUCTION

In all modern fighter aircraft, power cartridges are used to operate different systems and to save the precious life of the pilot from the endangered aircraft in an emergency in the shortest possible time. Hence, these are also known as escape-aid cartridges. The energy required for reliable functioning of aircraft systems is derived from these cartridges. To generate the required power, the main fillings in these power cartridges are the propellant along with pyrotechnic composition, depending on their end use. The propellant, when suitably initiated, burns inside the aircraft system, producing large quantity of gases at high pressure and temperature. These gases produce the power required to operate the system.

A closed vessel is a test equipment used to simulate the actual volume available in the aircraft system in which the cartridge is fitted. A closed vessel is one of the methodology/technique from which energy generated by power cartridge is measured in terms of maximum pressure (*P*) and time to maximum pressure (Tp_{max}) developed in the vessel. Design of a power cartridge is based on these two basic parameters. When the propellant burns inside the closed vessel, a large quantity of gas (in terms of moles per unit mass) is generated. The gas (combustion product of propellant) acts as a working fluid on the walls of the closed vessel. This shows that energy released by propellant undergoes several conversions. The chemical energy of the propellant is converted into internal energy/heat energy of a gas. From practical point of view, there is a rough inverse relation between the amount of heat (*Q*) and the volume of gas produced (*V*). To some extent, the balance between *Q* and *V* for a particular propellant determines its usefulness for a particular application. One reason for this is that the value of *Q* largely determines the temperature of gas (*T*), which is an important consideration for certain roles.

According to the first law of thermodynamics, energy can neither be created nor destroyed. It can be converted from one form to another. This is also known as law of conservation of energy. The amount of heat lost to the walls of the closed vessel depends on the following factors:-

- The amount of heat content in the propellant, being delivered to the vessel
- Thermal conductivity (*K*), the thermodynamic property of material of the closed vessel
- To some extent, it also depends on the surrounding temperature.

The objective of this study is to estimate the percentage of heat loss to the walls of the closed vessel during firing of a power cartridge.

2. ASSUMPTIONS

An attempt has been made to estimate the heat lost to the walls of the closed vessel when the propellant burns inside the vessel. The following assumptions are made.

- The propellant gases follow real gas behaviour
- The propellant burns under constant volume conditions
- The temperature of propellant gases (*T*) is equal to adiabatic flame temperature (T_e) of the propellant during the entire period of burning. In reality, due to heat loss during the burning period, *T* never reaches the adiabatic T_e, but comes quite close to it.

The chemical energy of the propellant is converted to thermal energy, i.e., heat, which is lost to the walls of the closed vessel due to conduction and convection. Heat lost due to radiation is neglected since it takes place at elevated temperature.

3. THERMODYNAMIC PROPERTIES OF THE PROPELLANT

Thermodynamic properties of propellant can be determined in following ways:

3.1 Gas Volume

The gas volume generated by the propellant can be found out using state equation for ideal gas[1].

$$pv = \text{RT},\ v = \frac{V}{m},\ pV = mRT,\ pV = nMRT$$

where $m = nM$

But for real gases, volume of gas generated is calculated by applying correction factor for volume as follows:

$$p(v\text{-}b) = nMRT \tag{1}$$

where b is co-volume of the gas and depends upon the type of gas under consideration.

These equations are based on assumption of complete reaction to yield maximum volume. The volume of the gases is generally calculated at 1 bar and 0 °C and generally lies between 700 cm^3 to 1000 cm^3 for military explosives.

3.2 Gas Temperature

Equation (1) can be written as

$$T = \frac{p\ (v-b)}{n\ MR} \tag{2}$$

When all the variables on RHS are known, the gas temperature can be determined.

3.3 Adiabetic Flame Temperature

The maximum temperature, which the gaseous products of propellant can reach if no heat is lost to the surroundings, is called the adiabatic flame temperature. It is often used when calculating the ability of the propellant to do work. T_e is found to lie between 2500 °C and 5000 °C for military high explosives. It can be calculated if the quantities and nature of gaseous products and heat generated are known[2]:

$$T_e = T_a + \frac{Q}{\sum \overline{C}} \tag{3}$$

3.4 Force Constant

The main performance parameter is the force constant for the propellant ie, the maximum amount of energy, which can be generated by burning unit mass of the propellant. In more practical terms as applied to internal ballistics, it is the measure of the pressure. It gives the energy by burning unit mass of propellant in a given fixed volume[2] as

$$F = nRT_e \tag{4}$$

Alternatively, force constant is also determined by burning known weight (C) of the propellant in a closed vessel.

$$F = \frac{P\ (v\text{-}\ b)}{C} \tag{5}$$

3.5 Heat Generation

Amount of heat generated by burning propellant in a closed vessals at constant volume can be determined as[3]

$$Q = \frac{F\,C}{(\gamma - 1)} \tag{6}$$

4. MATERIALS AND METHODS

4.1 Propellant Composition

The method for determination of heat transfer from closed vessel consists of burning of the given mass of propellant in a closed vessel whose volume is known. The basic chemical composition and physical properties of double base propellant, i.e., MEX-VU(M) which was used for closed vessel firings is given below:

Chemical composition of the propellant:

NC (2R)	59.5 %
NG	32.5 %
Carbamite	3.0 %

DEP	5.0 %
Monobasic lead salicylate	1 part
Monobasic copper salicylate	1 part
KNO_3	1 part
Carbon black	1 part

The dimensions of propellant grains are:

Outer dia (OD)	16.30 mm
Inner dia (ID)	10.54 mm
Web	2.85 mm

4.2 Closed Vessel

A closed vessel consists of a cylindrical body, closing plug at one end and cartridge holder at the other end. A suitable gauge adapter is screwed in the closed vessel body into which a pressure transducer is fitted. The photograph of a typical closed vessel is shown in Fig. 1.

An extension of closed vessel method to determine the burn rate of propellants in the intermediate pressure region 9.8 MPa to 75 MPa was introduced in 1975[4]. The method consists of burning of a known charge weight and web size of the test propellant along with a known charge weight of standard propellant whose burning rate is very fast compared to the test propellant. Subsequently, the equations are given in succeeding paras to estimate percentage heat lost.

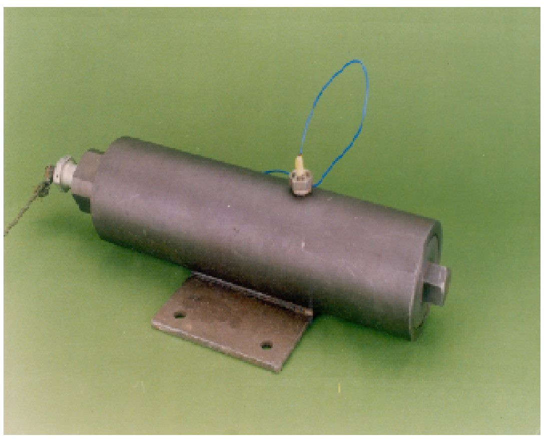

Figure 1. Photograph of atypical closed vessel.

4.3 Method of Closed Vessel Firing

The power cartridge is loaded in the cartridge holder and the firing mechanism is screwed in. The firing mechanism consists of body, firing pin and sear. The firing pin is held in position with the spring. When the sear is pulled by lanyard, the firing pin strikes percussion cap, thereby creating flash and initiates explosive train. The resultant flash passes through flash holes and initiates the booster. Booster augments the flash and pass to the main charge, i.e., propellant. When the propellant burns inside the closed vessel, intense pressure is generated which is transmitted to the transducer. The transducer converts this pressure into volt, which gets amplified by an amplifier. The result is recorded in the form of pressure-time (*P*-*t*) curve. A typical *P*-*t* curve obtained during closed vessel firing is shown in Fig. 2.

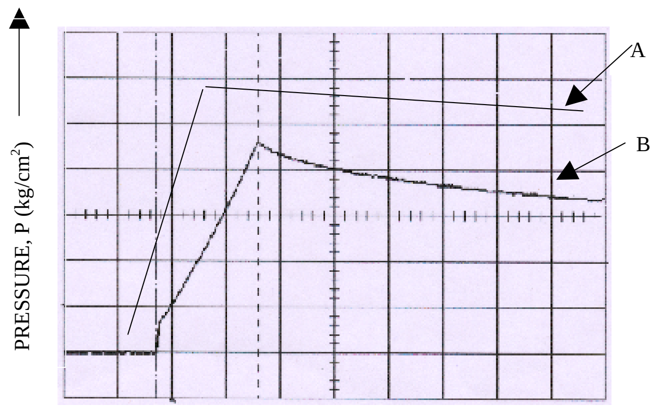

Figure 2. Pressure-time (P-t) curves obtained during closed vessel firing.

When the propellant charge burns inside the closed vessel under constant volume conditions, the pressure rises smoothly and continuously to maximum pressure and, time to maximum pressure i.e. $T_{P\max}$ corresponds to pressure when reaches to maximum value inside the closed vesel when the whole charge is burnt. Under the ideal conditions, when there is no loss of pressure due to leaks, heat loss, etc., the maximum pressure remains steady until the gases are evacuated by opening of the closing plug. The pressure-time record under these ideal conditions looks like curve A in Fig. 2. Amount of heat generated or the energy released by the propellant (Q) is lost to the walls of the closed vessel and from vessel to the surrounding by conduction and convection respectively. Heat lost by radiation is neglected since it takes place at elevated temperature over a period of time. However in this case, the closed vessel is subjected to elevated temperature for a short duration, i.e., order of ms. The pressure record at any instant is less than that which should have been produced under ideal conditions. The recorded maximum pressure P (curve B) is less than what it should have been under ideal conditions (curve A). It reaches earlier on time at curve A than that of curve B. This is due to the fact that, for all propellants in practical firing, the rate of fall of pressure due to heat loss to the walls of the closed vessel exceeds the rate of rise of pressure due to propellant burning. All burn point (ABP) reaches early after reaching P in an ideal case than that of practical firing taking into account the heat loss. After all the propellant is burnt, the hot gases continue to lose the heat to the walls of the closed vessel, the pressure continue to fall until after about 2 to 3 s, the temperature and pressure fall are so low that carbon deposits and water condenses on the walls of the closed vessel. Pressure-time recorded under actual firings conditions looks like curve B as shown in Fig. 2.

Actual heat loss can be determined by writing energy balance equation as:

Heat generated by the propellant	=	Amount of heat gained by the closed vessel by conduction
	+	heat loss from walls of the closed vessel to the surrounding by convection
	+	heat loss (H)

$$F\,C = m\,C_v\;(\Delta T) + h\;A\,(\Delta T) + \Delta H \qquad (7)$$

$$\Delta H = F\,C - m\;C_v\;(\Delta T) - h\;A\,(\Delta T)$$

where

A = Surface area of the closed vessel

π = d x l m^2

$$C_v = \frac{C_p}{\gamma}$$

5. ESTIMATION OF PERCENTAGE HEAT LOSS

Percentage heat loss in the mathematical form can be estimated as

$$\begin{pmatrix}\text{Percentage}\\ \text{Heat Loss}\end{pmatrix} = \left[\frac{Q - \Delta H}{\Delta H}\right] \times 100 \text{ per cent} \qquad (8)$$

6. RESULTS AND DISCUSSION

Some of the energy is lost in expanding the closed vessel and also compressing the material used in the closing plug. It is estimated that this energy loss is maximum of the order of one per cent of the total energy. This is termed as the strain energy and is theoretically proportional to pressure at any instant of time t and surface area of the inner walls of the closed vessel.

The heat loss by transient phenomenon is neglected since the walls of the closed vessel are subjected to heat for a short duration (of the order of ms). The values of Q, i.e., energy generated by propellant, heat gained by the closed vessel, and heat loss from the walls of the closed vessel are estimated as 8160 J, 1.4608 J, and 6685 J using Eqns (6) and (7), respectively.

Table 1 gives one particular case study in which percentage heat loss is estimated for double-base propellant for use in power cartridge using Eqn (8).

Table 1. Percentage heat loss estimated for double-base propellant for use in power cartridge

Volume of vessel (cc)	210
Propellant type	MEX – VU(M)
Charge weight of propellant (g)	8.0
Energy generated by propellant (J)	8160
Heat gained by vessel (J)	1.468
Heat loss (J)	6685
Percentage heat loss (%)	22

7. CONCLUSIONS

The firing curves A and B clearly indicate that the heat is lost at every instant of time. The heat loss follows the exponential pattern. The estimation of percentage heat loss to the walls of vessel can be computed for any power cartridges with known charge mass of explosive and volume of the closed vessel using energy balance equations. The experimental results obtained are nearly matching and validated with the theoretical results based on the assumptions. This heat loss helps in design of power cartridge and also to know how much energy of the propellant can be utillised for reliable and effective operation in actual aircraft system and sub-systems. This is the basic approach that can be used for design of propellant-actuated devices.

ACKNOWLEDGEMENTS

Authors are grateful to Shri A.S. Rajagopal, Director, Armament Research and Development Establishment, Pune, for his kind permission to publish this work. The authors also extend their sincere thanks to Shri J.K. Bansal, Scientist G, Associate Director, for his invaluable guidance and support.

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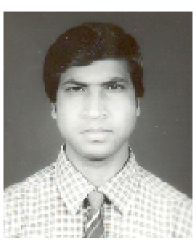

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