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Numerical Modelling of Regenerative Liquid Propellant Guns with Annular Piston

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ABSTRACT

The development of regenerative liquid propellant guns (RLPGs) needs due consideration of numerous interdependent parameters that affect its performance. To help in this task, computer simulation was undertaken to predict internal ballistics of a conceptual liquid propellant gun. The expected pressure and other important parameters are documented which serve as an aid to the hardware design of the regenerative liquid propellant guns.

NOMENCLATURE

ε	Energy lost as a fraction of the total energy of subscript term
ν	Ratio of specific heats (gamma)
τ	Time delay between liquid propellant injection and combustion
$\rho(t)$	Density at time t
$\beta(t)$	Bulk modulus at time t
$A(t)$	Area of cross-section
C	Discharge coefficient of liquid through annular vents
$F(t)$	Total force at time t
H_l	Heat lost in the barrel as fraction of total propellant energy
I	Impetus
$K(t)$	Kinetic energy of propellant gases at time t
m	Mass
$M_i(t)$	Mass injected in time t
$M_l(t)$	Mass lost due to leakage in time t
$M_r(t)$	Mass of igniter/propellant reacted in time t
$P(t)$	Pressure at time t
$r(t)$	Rate of combustion of igniter at time t
$T(t), T_f$	Temperature at time t, Flame temperature
$U(t)$	Volume at time t
$V(t)$	Velocity at time t
$x(t)$	Displacement at time t
A & B	Input parameter for bulk modulus

Subscripts

ar, ad	Air in reservoir, air in damper chamber
atm	Atmosphere
c, d, r	Combustion chamber, damper, reservoir
df	Damper fluid
effd, effr	Effective air + fluid in damper, effective air + lp in reservoir
gc	Gases in combustion chamber
lp, ip	Liquid propellant, igniter propellant
lr, ld	Leakage vents in reservoir, leakage vents in damper
pi	Piston
pj	Projectile
rd	Control rod
vr, vd	Vents in reservoir, vents in damper

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1. INTRODUCTION

Regenerative liquid propellant guns (RLPGs) with inline piston have been modelled[1,2]. These guns have several problems and there was a need to implement a new concept incorporating an annular piston and a movable control rod. A schematic of this concept is shown in Fig. 1. The igniter is used to initially pressurise the chamber which causes the control rod to move rearward. The liquid propellant (lp) flows from the reservoir to the chamber through the annulus between the control rod and the annular piston. The annular piston also moves rearward and the annular gap between it and the control rod decides the mass flow rate. The area of the annular piston facing the projectile side is larger than the one facing the liquid propellant side. This differential piston concept ensures that the annular piston keeps moving rearward even when the reservoir pressure is high.

2. MODEL

The model assumes that the initial pressure in the combustion chamber is generated by an igniter burning at a fixed rate. The injection process is controlled by the movement of the annular piston and the control rod. The equations of pressure and temperature in the combustion chamber[3] are given by

$$P_c(t) = \frac{(1-H_1)\,[Mr_{lp}(t)\,I_{lp} + Mr_{ip}(t)\,I_{ip}]}{U_c(t)} - \frac{0.5(V_{gc}-1)\,[(1+\varepsilon_{pj})m_{pj}V_{pj}(t)^2 + (1+\varepsilon_{pi})\,m_{pi}V_{pi}(t)^2]}{U_c(t)} - \frac{0.5(\nu_{gc}-1)\,[(1+\varepsilon_{rd})m_{rd}V_{rd}(t)^2 + K_{gc}]}{U_c(t)} \quad (1)$$

$$T_c(t) = \Big[\frac{(1-H_1)(Mr_{lp}(t)\,I_{lp} + Mr_{ip}(t)\,I_{ip})}{(\nu_{gc}-1)} - K_{gc} - (1+\varepsilon_{pj})\,m_{pj}\,V_{pj}(t)^2 - (1+\varepsilon_{pi})\,m_{pi}\,V_{pi}(t)^2 - (1+\varepsilon_{rd})\,m_{rd}\,V_{rd}(t)^2\Big] \Big[1/\Big(\frac{Mr_{lp}(t)\,I_{lp}}{(\nu_{gc}-1)\,Tf_{gc}} + \frac{Mr_{lp}(t)\,I_{lp}}{(\nu_{gc}-1)\,Tf_{ip}}\Big)\Big] \quad (2)$$

These equations are differentiated to obtain the required differential equations. The heat lost to the gun is assumed to be a fraction H_1 of the propellant energy. The heat lost during the gun operations due to friction in projectile, annular piston and control rod is assumed to be a fraction of the kinetic energy of the respective part. This fraction is represented

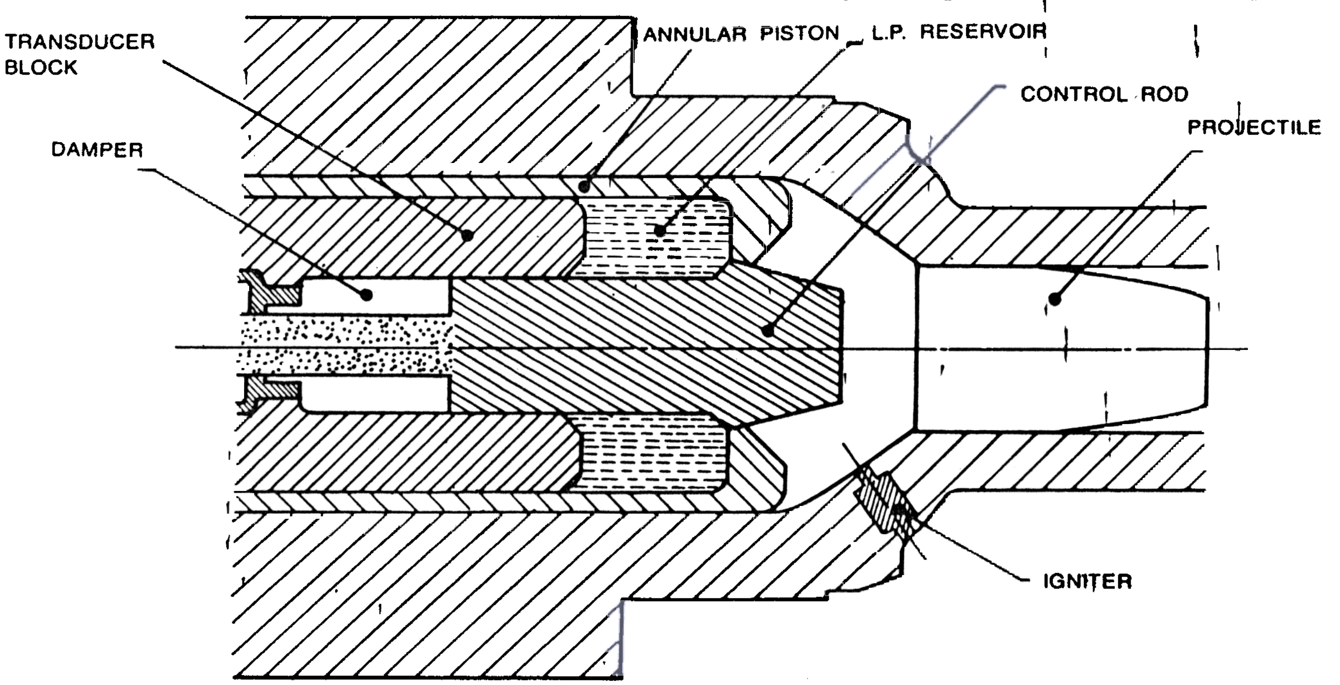

Figure 1. RLPG with annular piston and variable control rod

by ε_{pj}, ε_{pi}, ε_{rd} for the projectile, annular piston and control rod energy, respectively[4]. It is assumed that the entire mass of *lp* entering the combustion chamber reacts instantaneously or after the user input delay. The amount of lp reacted is given by

$$Mr_{lp}(t) = Mi_{lp}(t-\tau) \tag{3}$$

The bulk modulus of the lp in reservoir and damper fluid (df) in damper chamber changes drastically with pressure and is given by[2,4]

$$\beta_{effr} = A + B\,P_r(t) \tag{4}$$

$$\beta_{effd} = A + B\,P_d(t) \tag{5}$$

A and *B* are user input parameters which need to be estimated experimentally. As experimental data were not available, the reported data were used[2,4]

In the case of ullage, the situation is more complicated because of the greater compressibility of air. The effective bulk modulus of lp in the reservoir and damper chamber is given by

$$\frac{1}{\beta_{effr}(t)} = \frac{U_{ar}(t)}{U_{ar}(t)+U_{lp}(t)}\,\frac{1}{\beta_{ar}(t)} + \frac{U_{ar}(t)}{U_{ar}(t)+U_{lp}(t)}\,\frac{}{\beta_{lp}(t)} \tag{6}$$

$$\frac{1}{\beta_{effd}(t)} = \frac{U_{ad}(t)}{U_{ad}(t)+U_{df}(t)}\,\frac{1}{\beta_{ad}(t)} + \frac{U_{ad}(t)}{U_{ad}(t)+U_{df}(t)}\,\frac{1}{\beta_{df}(t)} \tag{7}$$

The bulk modulus of the lp and df is given by Eqns (4) and (5) respectively and that of air is given by the product of its ν and its pressure. As the pressure in the reservoir and damper increases, the air gets compressed. The compression is assumed to be adiabatic and follows the equation

$$P_{ar}\,U_{ar}^{\nu_{ar}} = \text{constant} \tag{8}$$

$$P_{ad}\,U_{ad}^{\nu_{ad}} = \text{constant} \tag{9}$$

The lp and df are considered as compressible and the change in their respective densities is given by

$$\frac{d\rho_{lp}(t)}{dt} = \frac{\rho_{lp}(t)\,A_r\,V_{pi}(t)}{U_r(t)} - \frac{dMi_{lp}/dt}{U_r(t)} - \frac{dMl_{lp}(t)}{U_r(t)} \tag{10}$$

$$\frac{d\rho_{df}(t)}{dt} = \frac{\rho_{df}(t)\,A_r\,V_{pi}(t)}{U_d(t)} - \frac{dMi_{df}/dt}{U_d(t)} - \frac{dMl_{df}(t)}{U_d(t)} \tag{11}$$

The pressures in the reservoir and damper are given by

$$\frac{dP_r(t)}{dt} = \frac{\beta_{effr}(t)\,(A_r\,V_{pi}(t) - C_{vr}A_{vr}(t)\,V_{vr}(t) - C_{lr}A_{lr}(t)\,V_{lr}(t)}{U_d(t)}$$

$$\frac{dP_d(t)}{dt} = \frac{\beta_{effd}(t)\,(A_r\,V_{rd}(t) - C_{vd}A_{vd}(t)\,V_{vd}(t) - C_{ld}A_{ld}(t)\,V_{ld}(t)}{U_d(t)}$$

The pressure in the combustion chamber and the pressure in the lp reservoir generates forces which act on either side of the annular piston. The equations of motion of the piston are given by

$$\frac{dV_{pi}(t)}{dt} = \frac{P_c(t)\,(A_{pi}-A_{vr}(t)) - P_r(t)\,(A_r - A_{vr}(t))}{m_{pi}} \tag{14}$$

$$\frac{dx_{pi}(t)}{dt} = V_{pi}(t) \tag{15}$$

The pressure in the combustion chamber and damper generates forces which act on the control rod. The equation of motion of control rod is given by

$$\frac{dV_{rd}(t)}{dt} = \frac{P_c(t)\,(A_{pi}-A_{vr}(t)) - P_d(t)\,(A_d)}{m_{rd}} \tag{16}$$

$$\frac{dx_{rd}(t)}{dt} = V_{rd}(t) \tag{17}$$

The only force acting on the projectile is due to the pressure in the combustion chamber. The equations of motion are given by

$$\frac{dV_{pj}(t)}{dt} = \frac{P_c(t)\,A_{pj}}{m_{pj}} \tag{18}$$

$$\frac{dx_{pj}(t)}{dt} = V_{pj}(t)$$

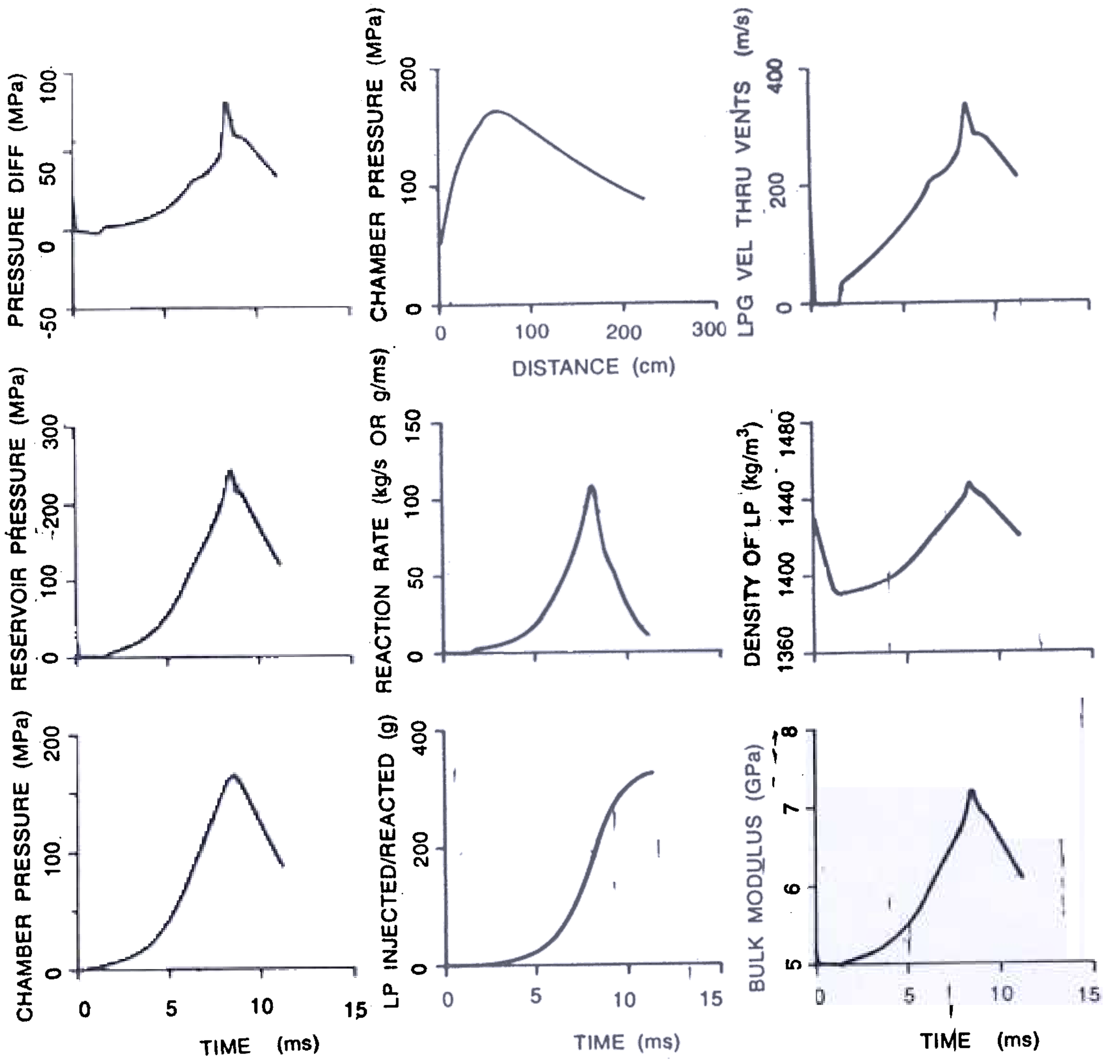

Figure 2. Time development of various int rior ballistic parameters of 30 mm RLPG

The initial velocity and displacement of both the projectile and the piston are zero. The projectile is assumed to be stationary till a shot-start pressure is reached, which depends on the projectile design. These define the starting conditions for Eqns (14)-(19). The area of the vent depends on positions of the control rod and the annular piston and is given by

$$A_{vr}(t) = f(x_{pi}(t), x_{rd}(t)) \tag{20}$$

The pressure difference across piston head causes the liquid propellant to be injected into the chamber and the mass flow rate is given as

$$\frac{d\,Mi_{lp}(t)}{dt} = C_{vr}\,\rho_{lp}(t)\;A_{vr}(t)\;V_{vr}(t) \tag{21}$$

In cases where there is some leakage of lp from the gun due to seal failure, the mass of lp lost is given as

$$\frac{d\,Ml_{lp}(t)}{dt} = C_{lr}\,\rho_{lp}(t)\,A_{lr}(t)\;V_{vr}(t) \tag{22}$$

The damper fluid also ejects from the damper chamber to an auxiliary chamber and its mass is given by

$$\frac{d\,Mi_{df}(t)}{dt} = C_{vd}\,\rho_{df}(t)\;A_{vd}(t)\;V_{vd}(t) \tag{23}$$

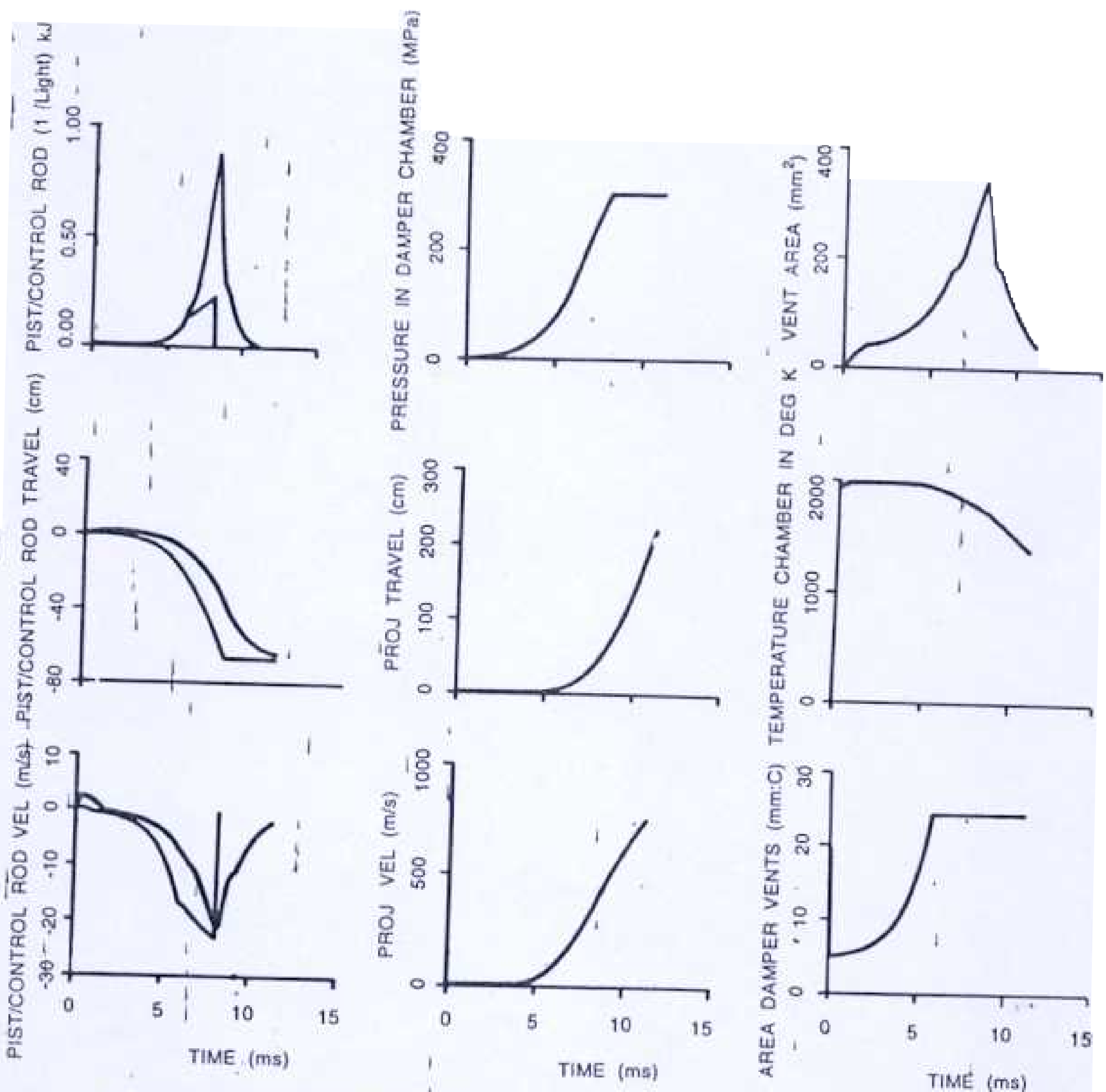

Figure 3. Time development of various interior ballistic parameters of 30 mm RLPG

The area of the damper is also a variable which depends on the control rod position and is given as

$$A_{vd}(t) = f[\, x_{rd}(t)\,] \tag{24}$$

If there is some leakage of df due to seal failure, then the mass of df lost is given as

$$\frac{d\,Ml_{df}(t)}{dt} = C_{ld}\,\rho_{df}(t)\,A_{ld}(t)\,V_{ld}(t) \tag{25}$$

The coefficient of discharge of the lp and df varies between 0 and 1 and is a user input. The velocities of lp and df flowing through their respective vents are given by

$$V_{vr}(t) = \sqrt{\frac{[\,2\,(P_r(t) - P_c(t)\,]}{\rho\, lp(t)}} \tag{26}$$

$$V_{vd}(t) = \sqrt{\frac{[\,2\,(P_d(t) - P_{atm}\,]}{\rho_{df}(t)}} \tag{27}$$

The velocity of the leakage of lp and df is given by

$$V_{lr}(t) = \sqrt{\frac{[\,2\,(P_r(t) - P_{atm}\,]}{\rho_{lp}(t)}}$$

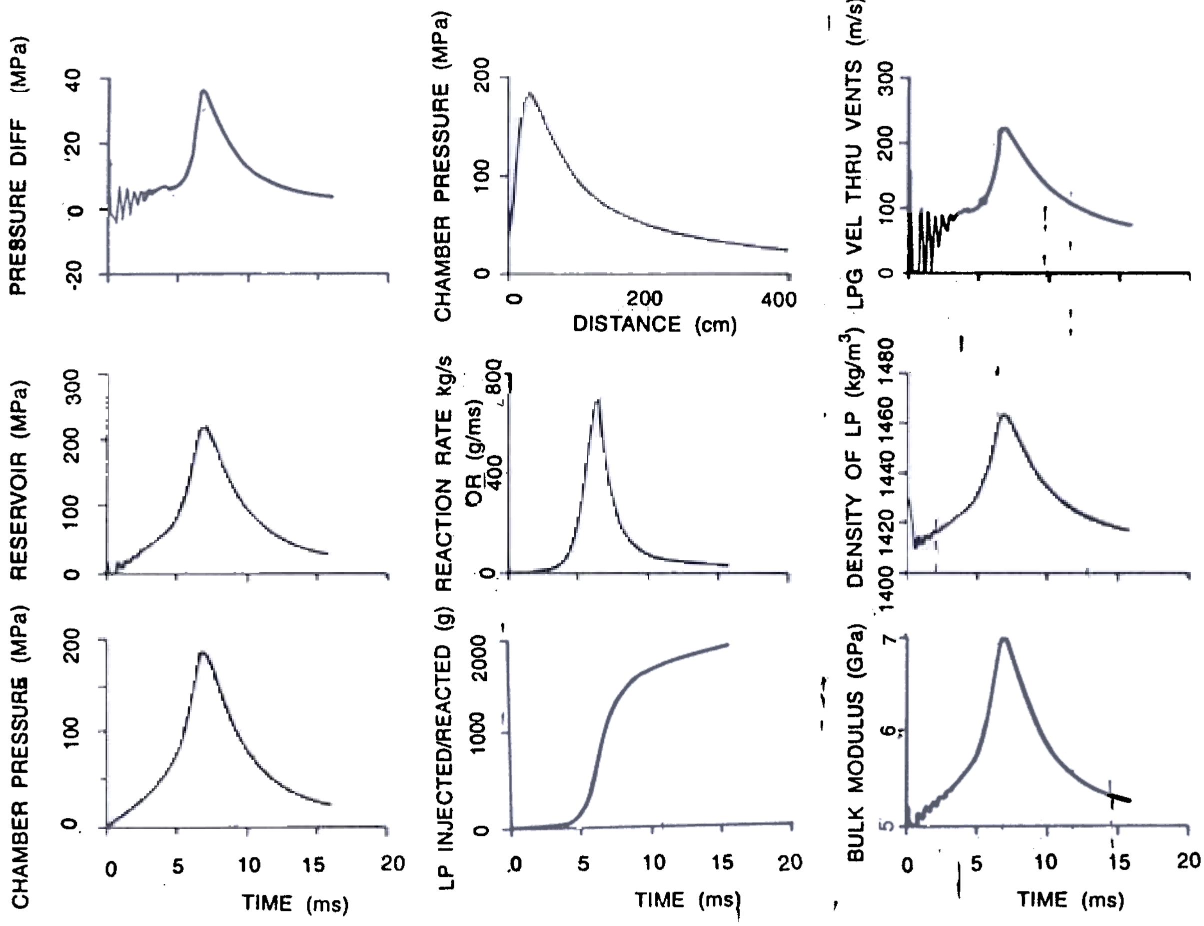

Figure 4. Time development of various interior ballistic parameters of 105 mm RLPG

$$V_{ld}(t) = \sqrt{\frac{[2(P_d(t) - P_{atm}]}{\rho_{df}(t)}} \qquad (29)$$

The mass flow rate of the igniter lp is a user-defined constant and lasts till the entire igniter lp is exhausted.

$$Mr_{ip}(t) = r(t) * t \qquad (30)$$

The corresponding change in chamber volume is given by

$$\frac{dU_c(t)}{dt} = x_{pi}(t) A_{pi} + V_{pj}(t) A_{pj} \qquad (31)$$

3. RESULTS AND DISCUSSION

Equations (1-31) are solved simultaneously on a computer, using modified Euler's method. The code was written in C-language. The software predicts the peak pressure in both chamber and reservoir, velocities of pistons and projectiles, injection rates of lp and df, etc., for different input parameters. The input parameters used in the case of 30 mm and 105 mm guns are given in Table 1. The output parameters include the time development of chamber, reservoir and damper pressure and velocity and position of the projectile, annular piston and control rod. The program also gives the mass of lp injected, reacted and accumulated. Variation in injection, vent areas and the corresponding velocity and mass of df and lp ejected out through different vents are also included in the output. The time development graphs of these parameters are given in Figs 2 and 3 for 30 mm and in Figs 4 and 5 for 105 mm gun, respectively.

5. CONCLUSION

The program developed above is useful in designing an RLPG having an annular piston with

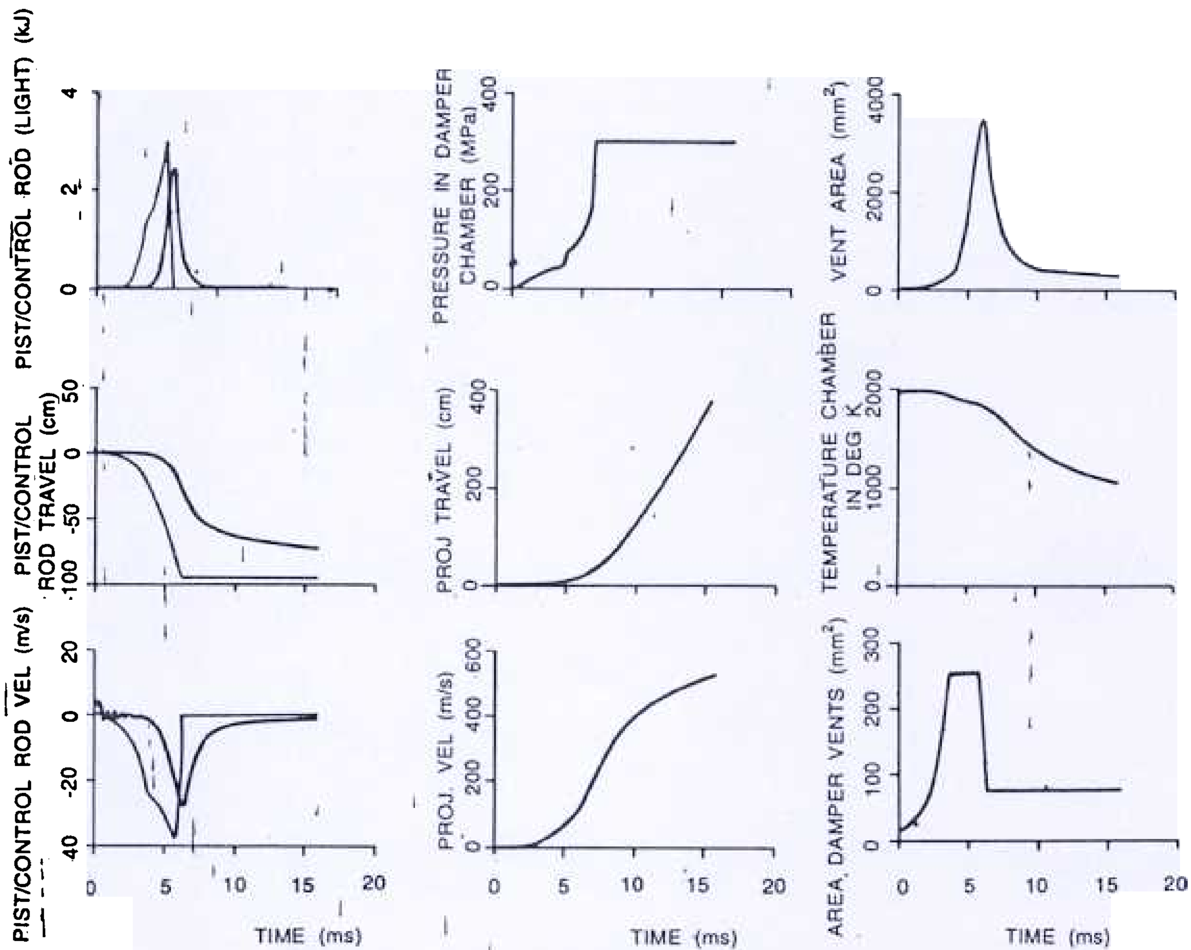

Figure 5. Time development of various interior ballistic parameters of 105 mm RLPG

a movable control rod. The program serves the general purpose and is also applicable to model either 30 mm, 105 mm or 155 mm guns. Unlike the inline piston where the injection vent area is constant, the annular piston gives a possibility of variable injection vent. It is possible to control the injection processes and thus the combustion by selecting suitable damper vent area. It could also be used for conducting sensitivity studies, which may be used as a basis for finalising the hardware design. Efforts towards the validation and improvement in the model are under study.

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Table 1. Input parameters of RLPG

Input parameters	30 mm gun	105 mm gun	Units
Accumulation delay	0.00	0.0	μs
Area of vents damper	24.335	253.0	mm^2
Bore of barrel	30.0	105.0	mm
Bore of chamber	85.0	177.0	mm
Bulk modulus of *df*	5000.0	5000.0	MPa
Bulk modulus of *lp*	5000.0	5000.0	MPa
Density of *df*	1.0	1.0	g/cc
Density of piston/rod material	8000.00	8000.0	kg/m^3
Density of propellant	1.430	1.430	g/cc
Diameter (outer) of annular piston	85.0	177.0	mm
Diameter of annulus of piston	32.0	74.0	mm
Diameter of control rod damper portion	15.0	25.0	mm
Diameter of control rod reservoir portion	33.0	70.0	mm
Discharge coefficient vents *lp*	0.850	0.850	
Flame temperature of *lp*	2200	2200	K
Fraction of energy lost in friction by annular piston	0.1	0.1	
Fraction of energy lost in friction by projectile	0.1	0.1	
Fraction of energy lost in friction by control rod	0.1	0.1	
Heat loss fraction in barrel	0.100	0.1	
Impetus of liquid propellant	0.9	0.9	kJ/g
Impetus of igniter propellant	0.900	0.9	kJ/g
Initial pressure in damper reservoir	0.1	0.1	MPa
Inner diameter of annular piston	75.0	167.0	mm
Larger diameter of control piston head	41.0	84.0	mm
Length of barrel	2.260	4.0	m
Length of control piston head	24.0	45.0	mm
Length of damper chamber	70.0	100.0	mm
Length of piston	200.0	210.0	mm
Length of reservoir chamber	70.0	100.0	mm
Length of rod damper portion	110.0	127.0	
Length of rod reservoir portion	100.0	120.0	mm
Mass of *df*	47.5	335.6	g
Mass of igniter propellant	10.0	170.0	g
Mass of projectile	680.0	17000	g
Mass of propellant	356.4	2580.6	g
Pressure dependence factor beta	9.0	9.0	
Ratio of specific heat (gamma)	1.3	1.3	
Shot-start pressure of projectile	25.0	25.0	MPa
Smaller diameter of control piston head	10.0	60.0	mm
Total igniter propellant energy	27.3	463.6	kJ
Total mass of annular piston	3.810	6.337	kg
Total mass of control rod	0.839	4.191	kg
Volume of chamber	500.0	2000.0	cc
Volume of *df*	47.5	335.6	cc
Volume of *lp* reservoir	249.3	1804.0	cc
Ullage *df*	0	0	%
Ullage liquid propellant reservoir	0	0	%

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