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Comparisons Among Various Possible Ways to Accelerate High-Speed Pellets Under Constant Base Pressure

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September 1987

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COMPARISONS AMONG VARIOUS POSSIBLE WAYS TO ACCELERATE HIGH-SPEED PELLETS UNDER CONSTANT BASE PRESSURE

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Abstract. Various possibilities to accelerate a frozen hydrogenic pellet by means of a constant base pressure behind the pellet are examined.

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CONTENTS

1. INTRODUCTION

Various possible ways to accelerate high-speed frozen pellets under constant base pressure are examined. If the goal is to attain a pellet speed of 5 km/s we find the following: 1) we must take account of gas-wall friction. Static pressure programming at the entrance should be placed in operation at a high temperature ($T_b > 2000^oK$) to enable the pellet to survive; otherwise the pressure at the barrel entrance will be too high to be tolerable. 2) Constant reaction thrust, i.a. a "rocket effect", seems to be no basic obstacle if beam technology (a laser is preferred) is available, though the energy deposition problem should be carefully studied. 3) Mass addition programming along the barrel through the slots offers an interesting possibility for using a low-temperature gas, since the gas speed is able to be separated from the pellet speed here.

It appears that refuelling by pellet injection into the fusion plasma will offer a most promising way to sustain quasi-steady thermonuclear reactions. Extrapolation of existing theoretical and experimental results about ablation of a pellet that passes through a high-temperature plasma indicated that a much higher speed is probably needed for post-break-even applications [1,2]. A pellet speed of 5 km/sec seems to be a reasonable choice here to examine possible improvements in pellet injection technologies.

The dynamic properties of frozen deuterium are yet to be determined. This is clearly the best way to fully exploite the potential of pellet acceleration that is based on constant base pressure acceleration (CBPA) with the maximum allowable stress to enable the pellet to survive nearly all along the way.

Three different types of CBPA are examined:

1) Static pressure programming with due consideration taken of friction and heat transfer effects.

2) Constant reaction thrust acceleration by the exhaust from an ablating pellet ("rocket effect").

3) Programmed mass addition of the driving gas during acceleration of the pellet in the barrel.

2. STATIC PRESSURE PROGRAMMING AT THE ENTRANCE OF THE BARREL (FIG. 1)

The basic philosophy for this kind of acceleration is that all the gas following the pellet is to be kept at the same speed as that of the pellet. Since a pressure gradient is needed to accelerate the gas, the pressure gets higher and higher at the entrance during the acceleration process. It was shown [2] that friction can be neglected between the pellet and barrel but must be considered between the gas and wall, especially when a high pellet speed is desired. The motion of the pellet in the barrel is described by

$$M_p \frac{dv_p}{dt} = p_b A_p \qquad (1\text{-}1)$$

If base pressure remains constant, acceleration

$$a_p = \frac{dv_p}{dt} = \frac{p_b A_p}{M_p} = \frac{p_b}{\rho_p \ell_p} = \text{const.} \qquad (1\text{-}2)$$

and

$$v_p = a_p t \qquad (1\text{-}3)$$

$$L = \frac{1}{2} a_p t^2 \qquad (1\text{-}4)$$

From (1-3) and (1-4)

$$L = \frac{v_p^2}{2a_p} \qquad (1\text{-}5)$$

For a fully developed turbulent flow in the boundary layer, the flow of the driving gas can be approximately described by

$$\rho_g \frac{dv_g}{dt} = - \frac{dp_g}{dL} - f\rho_g \frac{v_g^2}{2} \frac{1}{d} \qquad (1\text{-}6)$$

Here f is the friction coefficient [4]. Since

$\frac{dv_g}{dt} = \frac{dv_p}{dt} = a_p$ = const. and $v_g = v_p$ for CBPA, (1-6) can be

written as

$$dL = -\frac{dp_g}{\rho_g\ a_p} - f\,\frac{L}{d}\,dL \tag{1-6a}$$

assume the existence of a polytropic relation between the pressure and density as a simplified way to take account of heat transfer

$$\frac{p_g}{p_b} = \left(\frac{\rho_g}{\rho_b}\right)^n = \left(\frac{T_g}{T_b}\right)^{n/n-1} \tag{1-7}$$

integrate (1-6a)

$$f\,\frac{L^2}{2d} + L = \frac{p_b}{\rho_p a_p}\left(\frac{n}{n-1}\right)\left[\left(\frac{p_{g,L=o}}{p_o}\right)^{n-1/n} - 1\right] \tag{1-8}$$

or

$$\frac{p_{g,L=o}}{p_b} = \left\{1 + \left[\left(f\,\frac{\rho_p \ell_p}{\rho_b\ d}\right)\frac{K}{8}\,\bar{v}_p^4 + \frac{1}{2}\,\bar{v}_p^2\right]\right\}\frac{K(n-1)}{n}\Big\}^{n/n-1} \tag{1-8a}$$

here $\bar{v}_p = v_p/C_b$. $C_b = (KRT_b)^{1/2}$, k-specific heat ratio. Without consideration of friction and heat transfer, f = 0 and n = k, Eq. (1-8a) reduces to an ideal CBPA form [5]:

$$\left(\frac{p_{g,L=o}}{p_b}\right)_{f=o,\ n=K} = \left(1 + \frac{K-1}{2}\,\bar{v}_p^2\right)^{K/K-1} \tag{1-9}$$

Typical results of Eq. (1-8a) are shown in Fig. (2). It is clear that in order to keep the maximum pressure at a tolerable level the gas temperature T_b should be kept high enough when high pellet speed v_p is needed. Higher gas temperature means lower gas density and the gas then needs a reduced pressure gradient to accelerate it.

Some numerical results are shown in Table 1.

Table 1.

Examples of $p_{g,L=o}$ for CBPA

v_p		5 km/s	5 km/s	5 km/s
p_b		100 bar (300)*	100 bar (300)	100 bar (300)
T_b		1000 K	2000 K	3000 K
ρ_b	p/RT	2.4×10^{-3} g/cm^3 (7.2×10^{-3})	1.2×10^{-3} (3.6×10^{-3})	0.802×10^{-3} (2.4×10^{-3})
c_b	$(KRT_b)^{1/2}$	2.412×10^5 cm/s	3.411×10^5	4.178×10^5
$\bar{v}_p$	v_p/c_b	2.0726	1.4655	1.1967
ρ_p		0.2 g/cm^3	0.2	0.2
ℓ_p/d		1.0	1.0	1.0
f		0.01	0.01	0.01
n		1.2	1.2	1.2
$\left(\frac{p_{g,L=o}}{p_b}\right)_{f=o}$		11.44	3.825	2.5269
$p_{g,L=o}/p_b$		(25.04)	(6.1947)	(3.58)
$p_{g,L=o}$		9314 bar (7513)	1466 bar (1858)	678.5 bar (1074)
a		10^9 cm/s^2 (3×10^9)	10^9 (3×10^9)	10^9 (3×10^9)
L		125 cm (41.6)	125 cm (41.6)	125 cm (41.6)

(   )* parameters for p_b = 300 bar

With other parameters fixed, from Eq. (1-8a) an optimal base pressure $(p_b)_{opt.}$ exists to make $p_{b,L=o}$ minimum. From

$$\frac{d(p_{g,L=o})}{dp_b} = o$$

$$(p_b)_{opt.} = \frac{f\ K^2}{n} \frac{\rho_p L_p R T_b\ \bar{v}_p^4}{8d} / \left(1 + \frac{1}{2} \frac{K(n-1)}{n} \bar{v}_p^2\right) \qquad (1\text{-}10)$$

From these numerical results it seems reasonable to have a pellet speed of $v_p = 5$ km/s.

1) Pressure loss due to friction is always the dominant part of the pressure gradient.
2) Pellet base gas temperature below 1000 K will make the static pressure (as well as stagnation pressure) at the entrance too high to be tolerable.
3) The pressure programming for pellet base gas temperature above 2000 K is probably tolerable. In this case single-shot injection will be possible only if the pellet could sustain the high pressure. Multi-injection will be very difficult.

3. CONSTANT THRUST BY "ROCKET EFFECT"

If some kind of beam energy could be absorbed by the rear part of the pellet, part of the mass of the pellet will be vaporized, heated and expanded as rocket exhaust. A constant thrust will be applied to the pellet to produce a constant base pressure acceleration if the mass flux and exhaust speed are maintained constant. This is expressed by

$$M_p \frac{dv_p}{dt} = - \frac{dM_p}{dt} v_{ex} = p_b A_p \qquad (2\text{-}1)$$

integrate Eq. (2-1)

$$\bar{v} = \frac{v_p}{v_{ex}} = \ln \frac{M_{po}}{M_p} = \ln \frac{1}{1-\bar{t}} \qquad (2\text{-}2)$$

Here

$$\bar{t} = \frac{t}{\tau} \qquad \tau = \frac{\rho_p \ell_{po} v_{ex}}{p_b}$$

Integrate Eq. (2-2) to get the launch length of the barrel L

$$\bar{L} = \frac{L}{L'} = 1 - (1-\bar{t})[1 - \ln(1-\bar{t})] \qquad (2\text{-}3)$$

with

$$L' = \frac{v_{ex}^2 \ \rho_p \ell_{po}}{p_b}$$

The pellet speed v, launch length L and pellet mass M_p as functions of time in dimensionless forms are shown in Fig. 3.

Typical numerical results are shown in Table 2. (The left one is a D_2 pellet, and right one is a hybrid $D_2 + H_2$ pellet in which the H_2 part is to be burned).

From these numerical results, it is shown that nearly 20% of the initial D_2 pellet mass could remain after a speed of 5 km/s by the reaction force is reached. If a laser is used the beam energy and power rate needed is already well understood, apart from some uncertainty in the absorbing properties of a pellet on the impact of laser energy.

Table 2.

Examples of constant thrust by rocket effect		
v_p	5 km/s	5 km/s
Pellet	D_2	$D_2 + H_2$ (H_2 for propellent)
Final size	ℓ_p 0.5 cm	0.5
	d_p 0.5 cm	0.5
T_{ex}	3000 K	3000 K
V_{ex}	$= (KRT_{ex})^{1/2}$	4.178×10^5
	2.954×10^5 cm/s	
p_b	100 bar	100 bar
M_p	0.0196 g	0.0196 g
M_{po}	$M_p \exp(\frac{v_p}{V_{ex}}) = 0.1065$ g	0.0648 g
$\frac{M_p}{M_{po}}$	0.184	0.3021
ℓ_{po}	2.72 cm	3.877 cm
$-\frac{dM_p}{dt}$	66.47 g/s	47 g/s
t	$\Delta M_p / \left\| -\frac{dM_p}{dt} \right\| = 1.3\times10^{-3}$ s	0.96×10^{-3} s
L	234 cm	192.5 cm
Energy input		
E	2465 J.	2650 J.
W	1.9×10^6 W	2.76×10^6 W
	D_2 burned 2.22 cm	H_2 burned 2.877 cm

4. THE ADDITION OF GAS MASS ALONG THE BARREL (FIG. 4)

The basic idea in adding gas in the barrel is that when the pellet moves forward inside, a correct amount of gas enteres the barrel along the side wall to barely fill the volume evacuated by the pellet and maintain the barrel pressure constant. In that way the pellet will continuously be acted upon by a constant base pressure.

Since

$$M_p \frac{dv_p}{dt} = p_b A_p$$

with p_b = constant.

$$a_p = \frac{dv_p}{dt} = \frac{p_b A_p}{M_p} = \frac{p_b}{\rho_p \ell_p} = \text{const.}$$

$$v_p = a_p t$$

$$L(t) = \frac{1}{2} a_p t^2$$

The total mass that should be filled is

$$M = p_b A_b L(t)$$

Gas flow rate

$$G = \frac{dM}{dt} = p_b A_p \frac{dL}{dt} = p_b A_p v_p$$

$$= p_b A_p a_p t$$

$$= \sqrt{2}\, \rho_b A_p a_p^{1/2} L^{1/2}$$

Here the gas and pellet speeds can be separated, which is not the case in single- or two-stage injectors where the gas and pellet speeds are closely connected.

In our case the gas axial speed is very close to zero so that only a much slower radial speed is needed to permit the gas to fill the barrel. In this event, even room temperature gas can be used.

In actual practice, the slot along the barrel should be opened discretely in order to feed in the gas. We examine the most serious case (latest period of launch):

v_p = 5 km/s
p_b = 100 bar
T_b = 300 K
d_b = 0.5 cm

For the last 10 cm length of the barrel, the pellet speed is nearly 5 km/s. The transit time to enable the pellet to pass through is

$$\Delta t = \frac{\Delta L}{v_p} = \frac{10}{5\times10^5} = 20\times10^{-6}\ \text{sec} = 20\ \mu\text{s}.$$

The gas mass should fill the volume swept by the pellet during each increment of time, so that

$$\rho_s A_s v_s \frac{\Delta t}{2} = \rho_b A_b v_p \Delta t$$

subscript s refers to the parameters at the slot, where the gas flow is at the sonic speed. For a simple slot

$$v_s = C_s = (KRT_s)^{1/2} = (KRT_b)^{1/2}$$

$$= (1.4 \times \frac{8.314\times10^7}{2} \times 300)^{1/2} = 1.32\times10^5\ \text{cm/s}$$

and the density ρ_s is the same as ρ_b

$$\frac{\rho_s}{\rho_b} = 1$$

$$A_s = 2A_b \frac{\rho_b v_p}{\rho_s v_s} = 2 \times \frac{\pi}{4} (0.5)^2 \times \frac{5\times10^5}{1.32\times10^5}$$

$$= 1.487 \text{ cm}^2$$

The length of slot L_s is equal to 10 cm, so the width of the slot δ_s = 0.15 cm = 1.5 mm.

The stagnation pressure for the feeding gas

$$p_s^* = p_s(1 + \frac{k-1}{2})^{k/k-1} = 1.9\times p_s$$

$$= 190 \text{ bar } (k = 1.4)$$

5. CONCLUSIONS

If the aim is to have a pellet speed of 5 km/s, we conclude:

1) For static pressure programming at the entrance, the pressure loss due to friction between gas and wall will be the dominant part of the total pressure gradient. Any gas temperature T_b below 1000 K will have a pressure that is too high to be tolerable; if $T_b > 2000$ K it will be possible to make a single shot. Multi-injection will be extremely difficult, because the lower the pressure the higher will be the temperature.

2) If beam technology is available (E ~ 2,500J W ~ 2×10^6W) and energy deposition is not a problem then propulsion by "rocket" reaction force seems to be no basic obstacle. Furthermore, since the exhaust gas from the pellet moves in the opposite direction of the motion of the pellet, friction between gas and wall is even helpful.
3) The addition of mass along the barrel through slots could take place even in room temperature if problems related to receiving signal, triggering, and gas inlet could be solved.

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NOMENCLATURE

a	acceleration
A	area
c	sound speed
d	diameter of barrel
f	friction coefficient
G	gas flow rate
ℓ	length
L	length along barrel
M	mass
n	polytropic factor
p	pressure
R	gas constant
t	time
v	speed
ρ	density

SUBSCRIPT

b	base of pellet
p	pellet
o	initial state
ex	exhaust

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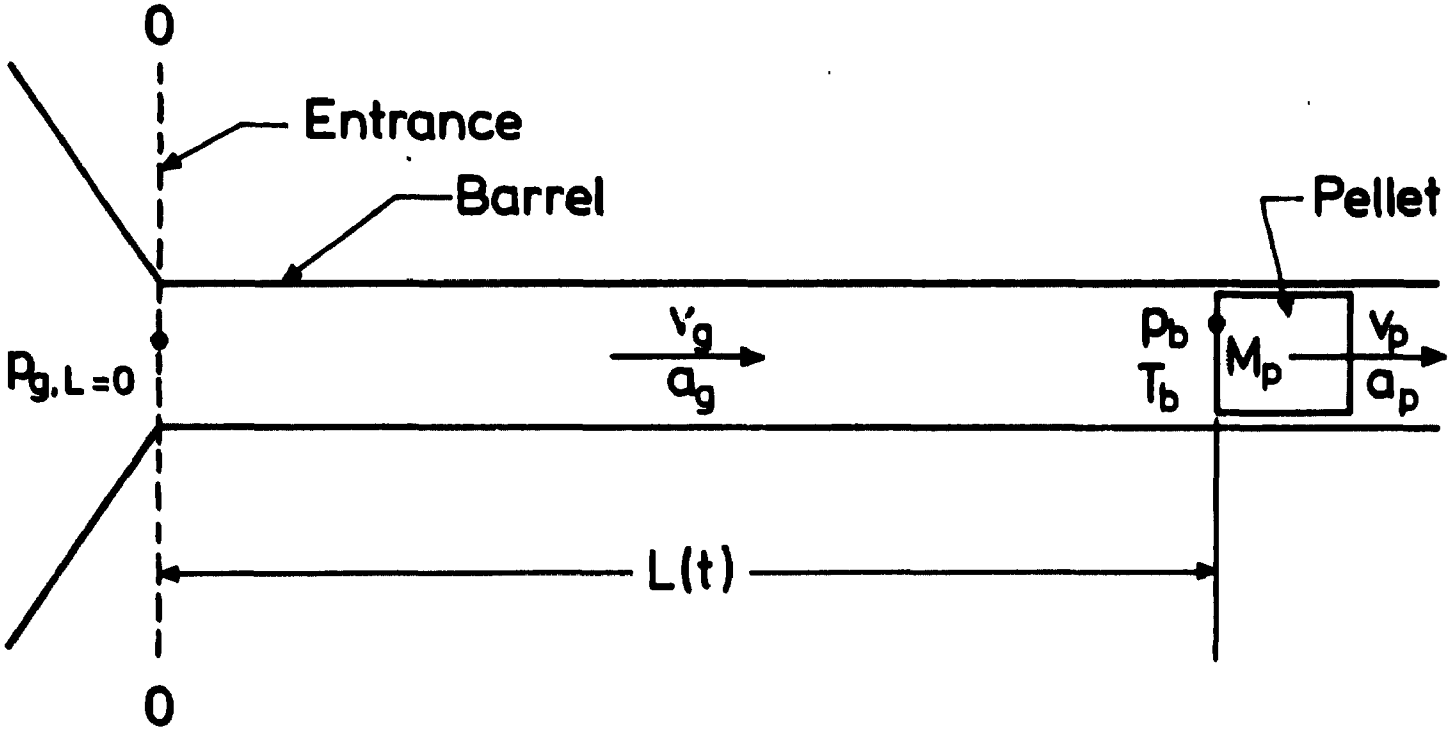

Fig. 1. Schematic diagram of static pressure programming at the entrance of barrel for CBPA.

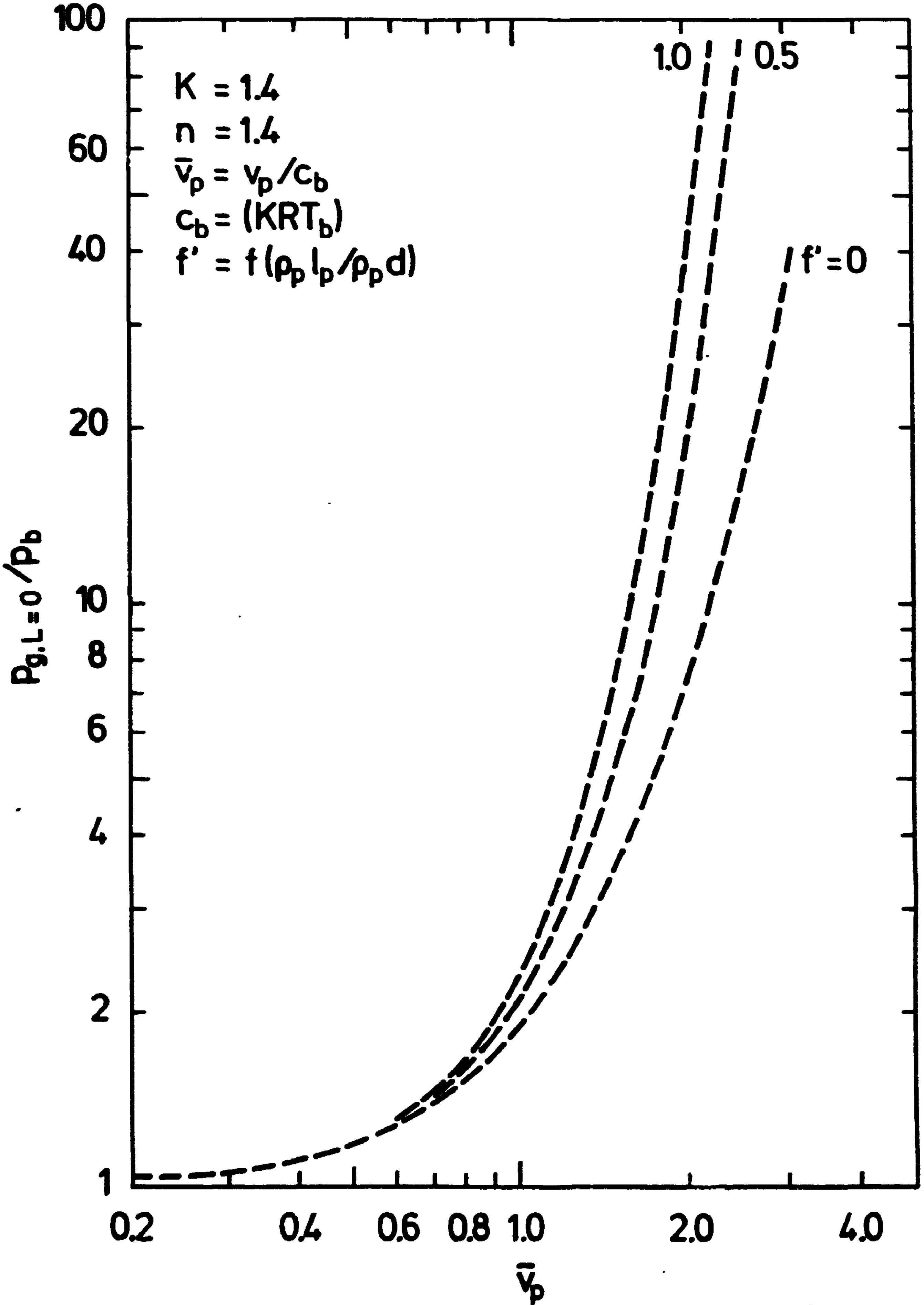

Fig. 2a. Static pressure programming at the entrance of barrel for CBPA.

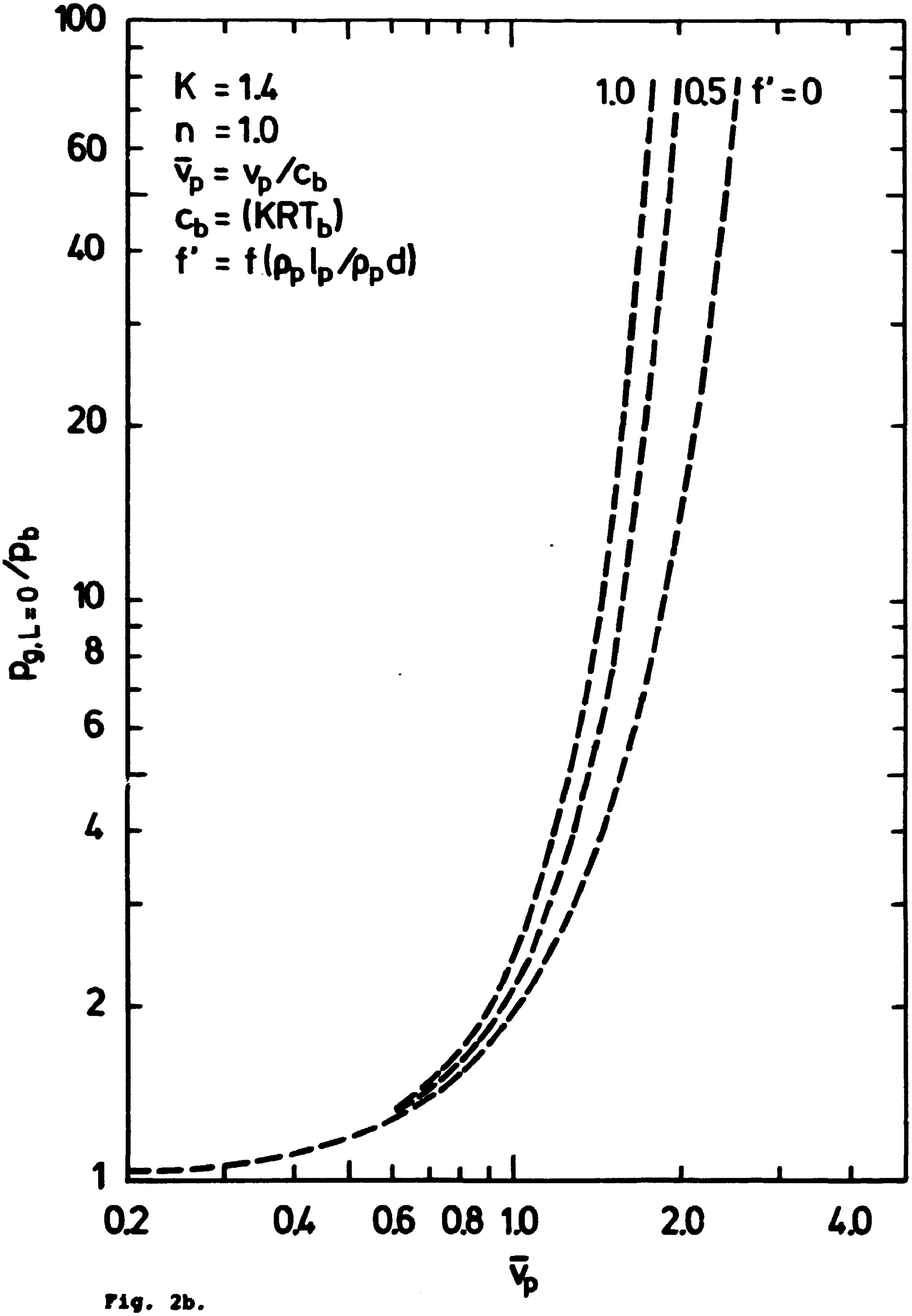
K = 1.4
n = 1.0
$\bar{v}_p = v_p / c_b$
$c_b = (KRT_b)$
$f' = f(\rho_p l_p / \rho_p d)$
1.0
0.5
f' = 0
100
60
40
20
10
8
6
4
2
1
$p_{g,L=0}/p_b$
0.2
0.4
0.6
0.8
1.0
2.0
4.0
$\bar{v}_p$

Fig. 2b.

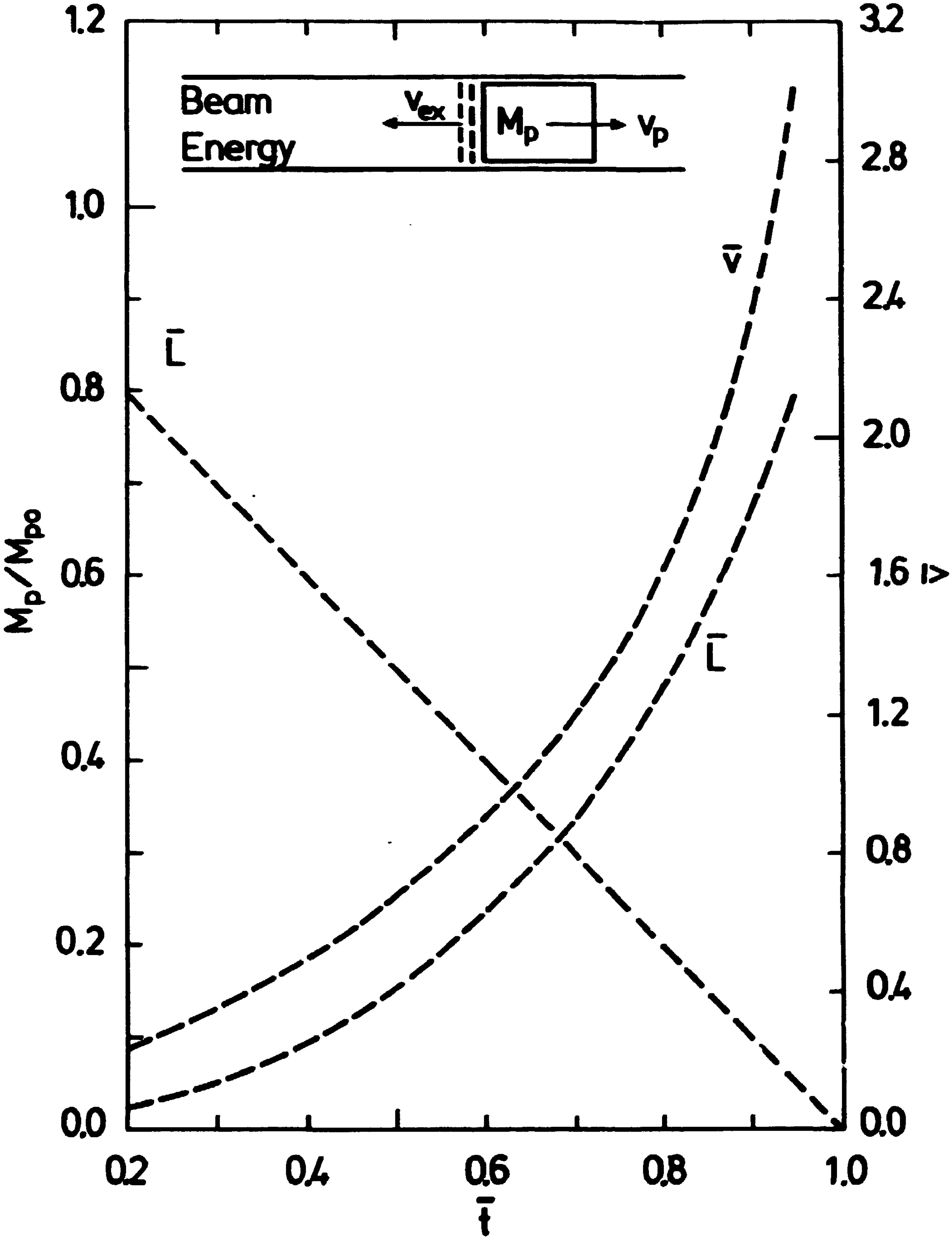

Fig. 3. Constant thrust by rocket effect.

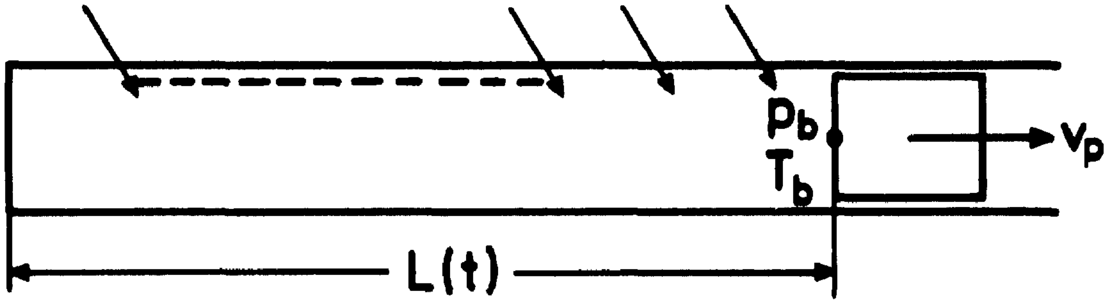

Fig. 4. Gas mass addition programming along the barrel.

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Pages 26 **Tables** 2 **Illustrations** 5 **References**

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