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SIMULATION OF THE INTERNAL BALLISTICS OF A LIQUID PROPELLANT ENGINE START SYSTEM IN COMPARISON WITH EXPERIMENTAL VERIFICATION

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ABSTRACT

There are several methods for starting a complex mechanical system, for example a liquid propellant engine. One of common methods is the use of solid propellant gas generator that is named solid propellant starter. In this method, a solid propellant motor is used for gas generating and leading it towards power generation turbine. The turbine as an active element, rotates one or several pumps for providing propellants with suitable head and rate for consumers such as liquid propellant gas generator and combustion chamber. After moving of pumps and reaching to nominal conditions, the start system stops. Therefore in order to suitable and optimized designing of starter, the essential parameter is taking into account the downstream resistance of system.

In a complex system such as a liquid propellant engine, the start system is one of the main and important components of engine and it's operation affects directly on the other components of engine. Therefore the optimized designing of it, has special importance. On the one hand, the selection of solid propellant geometry (grain) that exist in this system, is one of main parameters and the most important function in the process of start system designing, because the geometry of solid propellant is determinant of burning area and consequently the burning pattern of solid propellant. Therefore it is an important factor in determining the performance of starting system.

In this paper, the alterations of pressure and thrust of a starter with different solid propellant grains have been simulated and have been compared with experimental results. The very good agreement of theoretical and experimental results indicates that the accuracy of simulation process is excellent.

INTRODUCTION

There are several methods for starting a complex mechanical system, for example a liquid propellant engine (1). One of common methods is the use of solid propellant gas generator that is named solid propellant starter (2, 3, 4) [figure 1]. In this method, a solid propellant motor is used for gas generating and leading it towards power generation turbine. The turbine as an active element, rotates one or several pumps for providing propellants with suitable head and rate for consumers such as liquid propellant gas generator and combustion chamber. After moving of pumps and reaching to nominal conditions, the start system stops. Therefore in order to suitable and optimized designing of starter, the essential parameter is taking into account the downstream resistance of system.

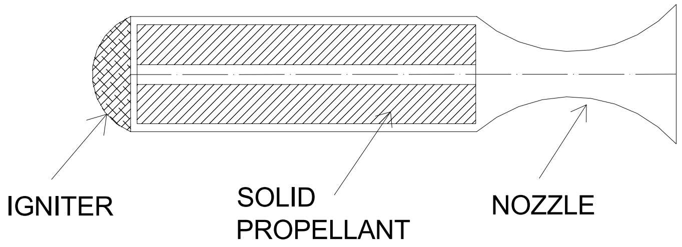

Figure 1: A schematic view of solid propellant starter

In this part, at first, a description of different phenomena that play a role in the process of engine starting, is presented.

According to engine system designing, the operation of start system is before than gas generator operation. From the viewpoint of gas generation resources, turbine operates at three different periods [figure 2].

At period I , only starter generates gas for turbine. At period II , starter and gas generator provide gas for turbine and at period III , only gas generator provide gas for turbine.

The alterations of turbine revolution, violently follows from internal ballistics of starter. If the pressure inside the starter increase, the revolution of turbine will increase and viceversa.

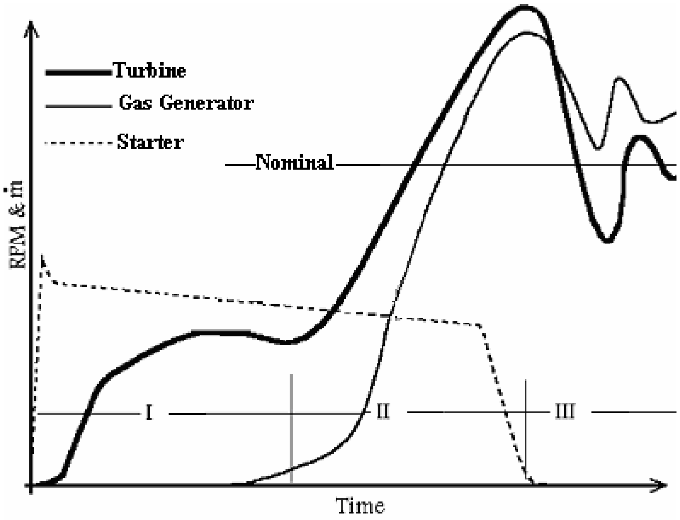

Figure 2 : The process of liquid propellant engine starting

The periode II is started by gas generator operation. In this period, turbine uses from two resources : starter and gas generator. Therefore the generated power of turbine will be the summation of gas generator and starter powers.

With passing of time, gas generator continues to gas generating and with increasing the turbine revolution, the power of pumps will increase and consequently the gas generator will provide the excess gas for turbine. Therefore in this period, the revolution of turbine and gas generation rate by gas generator fortify each other. If the duration of this period becomes long, the turbine will go beyond of design case. Therefore the starter must gradually go out from the gas generating cycle.

Sudden omission of starter will cause the decrease of generating power of turbine and pressure of propellants in pumps and the result of this process, will be the silence of motor. On the other hand, if the starter gets out from this cycle very late, in that case, an overshoot will happen at the cycle performance.

At period III , only gas generator provides the working fluid for turbine and the performance of turbine is directly affected by gas generator performance. In other words, at this period, the starter has no role on turbine behaviour.

On the basis of above mentioned subjects, the ideal pattern of starter performance will be as follows (figure 3).

At first, the starter must produce considerable volume of gas, then must decrease the value of its generation gas.

In order to designing the solid propellant starter, the alteration of pressure inside the starter relative to time must be investigated. As it was said, two important parameters are imposed on the process of starter designing. The first parameter is time duration of starter operation. If this time be short, the downstream system will not operate and if this time be very long, it will have undesired effects.

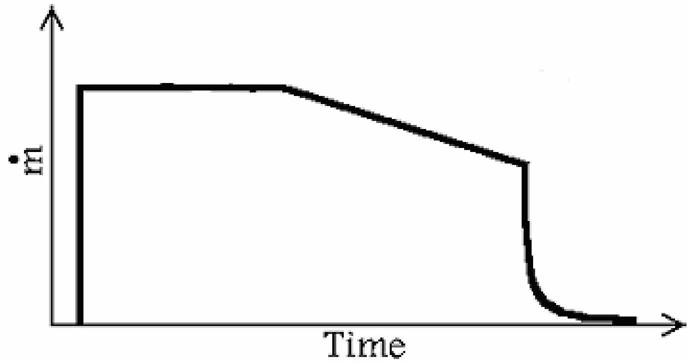

Figure 3 : A schematic design of starter operation

The second parameter is the value of pressure and quality of its alterations during the operation time. At primary moments, starter must deliver abundant power to its downstream (turbine) and at final moments, this this power must be decrease. At this direction, according to requirement, different geometric shapes (grains) of solid propellant can be used. In this paper, three types of them have been introduced (5). Each of these propellants have different burning areas.

The burning area is function of geometric shape of solid propellant and arrangement of propellants in start chamber. These three types are as follow :

a) Cylinderical (figure 4)
b) Telescopic (figure 5)
c) Clustered (figure 6)

In cylinderical type, there is a hollow cylinder of solid propellant that burnes from internal and external and two ends areas.

In telescopic type, there is a hollow cylinder of solid propellant with a not hollow propellant inside it.

In multi cylindrical type, there are several hollow cylinder of solid propellants that burn from all side of their area.

This paper discuss about burning of above mentioned solid propellant and simulates the behavior of them.

ASSUMPTIONS

In order to analysis of starting system performance, the following assumptions are considered (1, 2, 6):

a) The geometric shape of solid propellant at all time of burning is not changed.
b) The pressure value at all points of start chamber is constant.
c) Combustion products are considered as ideal gas.
d) There is not erosive burning.

The last assumption may not be good, but studies on solid propellant starter have shown that there is’nt erosive burning at the working field of starter.

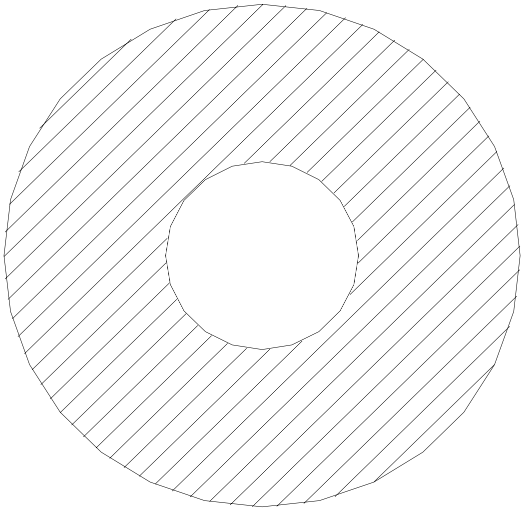

Figure 4 : Cylinderical grain

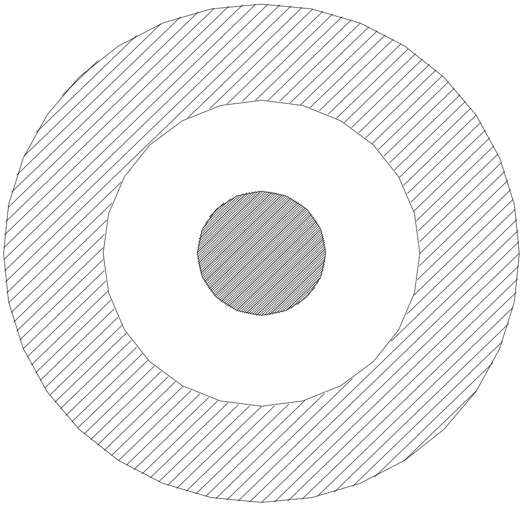

Figure 5 : Telescopic grain

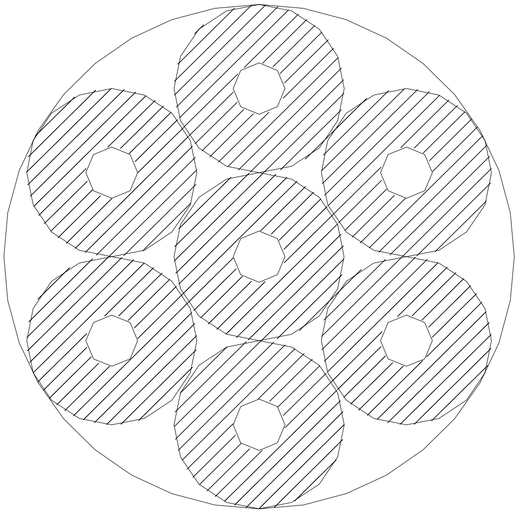

Figure 6 : Clustered grain

GOVERNING EQUATIONS AND MODELING

It is obvious that the generation rate of gas products due to combustion is equal to the consumption rate of solid propellant. Therefore it can obtain by using the following expression (7) :

$$\dot{m}_g = \rho_b A_b r \qquad (1)$$

that :

$\dot{m}_g$ = The generation rate of combustion products

ρ_b = Density of solid propellant

A_b = Burning area

r = Burning rate

The last parameter (r) is a function of chemical composition of solid propellant and some conditions inside the combustion chamber and is determined experimentally.

These conditions consist of : initial temperature of solid propellant, combustion pressure and velocity of gas products due to combustion on the solid propellant area.

The burning rate generally is approximated by the following expression :

$$r = aP_o^n \qquad (2)$$

That P_o is pressure inside the combustion chamber and a & n are parameters that obtain from experiment data (figure 7).

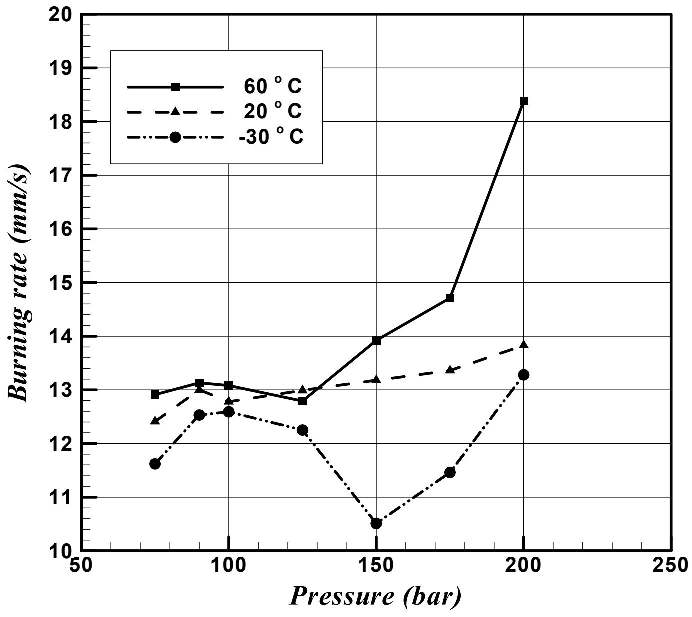

Figure 7 : Experimental alterations of Burning rate versus pressure at different temperatures

Both nozzle mass flow rate and gas generation rate, are violently function of combustion chamber pressure that it depends on the mass of gas inside start chamber. The gas generation rate ($\dot{m}_g$) obtaines by expressions (1) and (2).

The rate of stored gas inside the combustion chamber is :

$$\frac{dM_s}{dt} = \frac{d}{dt}(\rho_o V_o) \tag{3}$$

That ρ_o is instantaneous density of gas and V_o is instantaneous volume of gas inside chamber.

With due consideration to burning area retrogression $(\frac{dV_o}{dt} = rA_b)$, we have :

$$\frac{dM_s}{dt} = \rho_o r A_b + V_o \frac{d\rho_o}{dt} \tag{4}$$

The nozzle mass flow rate is obtainable from the following expression :

$$\dot{m}_n = \frac{P_o}{\sqrt{RT_o}}\sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} A^* \tag{5}$$

With due consideration to mass conservation law, we have :

$$\dot{m}_g = \frac{dM_s}{dt} + \dot{m}_n \tag{6}$$

or :

$$\rho_p A_b r = \rho_o A_b r + V_o \frac{d\rho_o}{dt} + \dot{m}_n \tag{7}$$

By using of expressions (2) and (5) we can write :

$$\rho_p A_b a P_o^n = \rho_o A_b a P_o^n + V_o \frac{d\rho_o}{dt} + \frac{P_o}{\sqrt{RT_o}}\sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} A^* \tag{8}$$

The derivative of density is as follows :

$$\frac{d\rho_o}{dt} = \frac{1}{RT_o}\frac{dP_o}{dt} \tag{9}$$

After replacing expression (9) in expression (8), we have :

$$\frac{V_o}{RT_o}\frac{dP_o}{dt} = A_b a P_o^n(\rho_p - \rho_o) - \sqrt{\frac{\gamma}{RT_o}\left(\frac{2}{\gamma+1}\right)^{\frac{(\gamma+1)}{(\gamma-1)}}} A^* P_o \tag{10}$$

The exit rate of mass from the start chamber is function of chamber pressure, nozzle throat area, downstream pressure and also thermophysical properties of combustion products.

THE SOLUTION METHOD

In order to computing the ballistic parameters of start system, a computer program has been wrote that uses the fourth-order Runge-Kutta method for solving the above differential equation. The values of input parameters have been presented in tables (1) to (4).

0.269	Solid Propellant Inner Diameter
0.882	Solid Propellant Outer Diameter
0.865	Solid Propellant Length

Table 1 : Cylinderical Propellant Dimensions

0.269	Inner Diameter of Exterior Propellant
0.882	Outer Diameter of Exterior Propellant
0.865	Length of Exterior Propellant
0.108	Outer Diameter of Interior Propellant
0.865	Length of Interior Propellant

Table 2 : Telescopic Propellant Dimensions

Note : all of geometric dimensions, have been dimensionlessed by characteristic lengths and diameters.

The thermo-physical properties of combustion products have been determined by combustion analysis softwares and presented in table (5). Also the effect of igniting system has been measured by an experiment (figure 8) and is used as an input data for computer program.

ANALYSIS OF RESULTS

The obtained results from mentioned computer program have been compared in table (6). In figure 9, the graph of pressure versus time for three types of propellant have been presented. With increasing the burning area, the value of pressure is increased and the burning time is decreased.

The trend of thrust alterations is like as pressure. Sudden increase at the beginning of graphs is because of considering the effect of igniting system.

In graphs related to telecopic propellant, there is a fracture in performance curve. This fracture is because of quick finishing of interior propellant of this grain. Of course we can adjust the interior propellant diameter and its length for increasing or decreasing the level of pressure and ommission of fracture; this subject is related to system requirements.

0.134	Propellant Inner Diameter	N=2
0.441	Propellant Outer Diameter	
0.865	Propellant Length	
0.125	Propellant Inner Diameter	N=3
0.409	Propellant Outer Diameter	
0.865	Propellant Length	
0.111	Propellant Inner Diameter	N=4
0.365	Propellant Outer Diameter	
0.865	Propellant Length	
0.090	Propellant Inner Diameter	N=7
0.294	Propellant Outer Diameter	
0.865	Propellant Length	

Table 3 : Clustered Propellant Dimensions

1	Inner Diameter of Start Chamber
0.169	Nozzle Throat Diameter
0.263	Nozzle Exit Diameter
1	Length of Start Chamber

Table 4 : Geometric Dimensions of Start Chamber

In order to investigating the accuracy of simulation program, the results of computer program execution and experimental data have been compared in figures (10) & (11). The results of simulation and experimental data have good conformity. As a result, in the event that the design parameters of starting system is known, this program can design starter with a good accuracy.

2455.9	K	Temperature of Combustion Products
1560	Kg/m^3	Propellant Density
351.141	J/kg.K	Gas Constant of Combustion Products (R)
1.245	---	Specific Heats Ratio (γ)

Table 5 : The characteristics of solid propellant

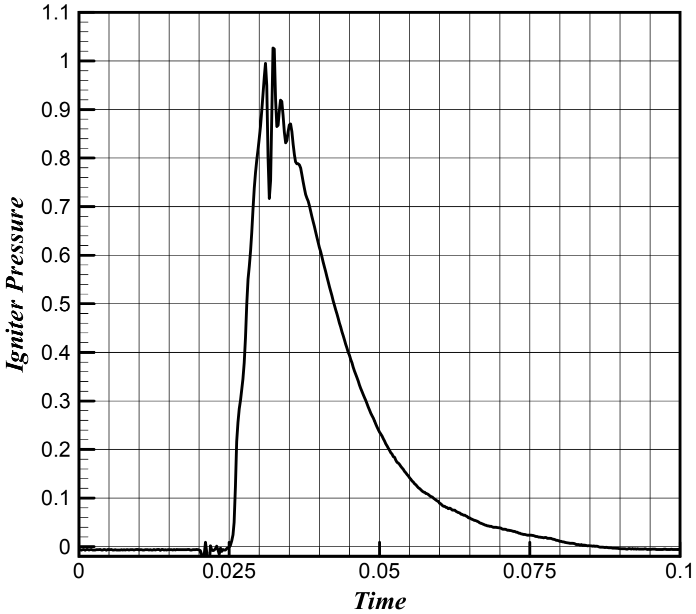

Figure 8 : Experimental data of ignition system (pressure versus time) [dimensionless]

The mentioned computer program takes into consider a factor for all sides of solid propellant (inner, outer ands areas); Then user, with due consideration to the system requirements, by selecting the type of grain and its areas that must be burned, can obtain the desired performance curve.

ANALYSIS OF RESULTS

The obtained results from mentioned computer program have been compared in table (6). In figure 9, the graph of pressure versus time for three types of propellant have been presented. With increasing the burning area, the value of pressure is increased and the burning time is decreased.

Max. Mass Flow Rate	Max. Thrust	Max. Pressure	Burning Time	Grain Type
1	1	1	1	Cylinderical
1.078	1.058	1.079	0.998	Telescopic
0.859	0.841	0.859	0.474	Clustered N=2
1.231	1.210	1.231	0.425	Clustered N=3
1.479	1.456	1.478	0.373	Clustered N=4
2.129	2.102	2.129	0.288	Clustered N=7

Table 6 : Comparison between the results of computer program

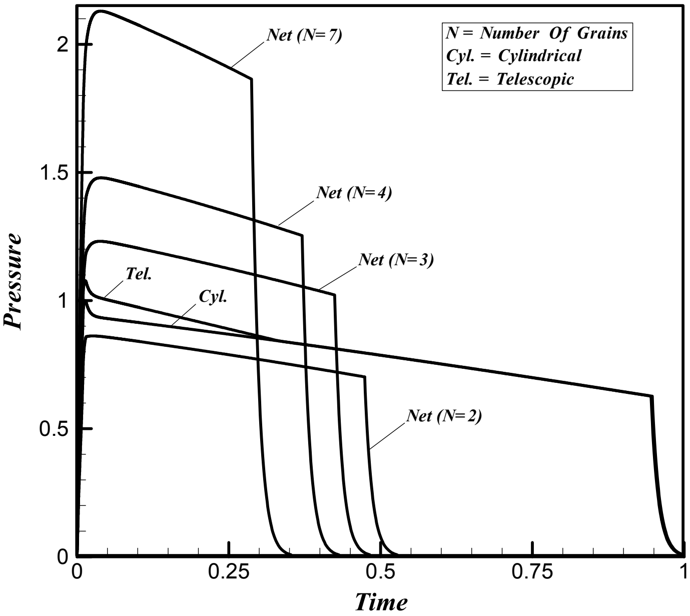

Figure 9 : Pressure versus time (for all mentioned grains) [dimensionless]

The trend of thrust alterations is like as pressure. Sudden increase at the beginning of graphs is because of considering the effect of igniting system.

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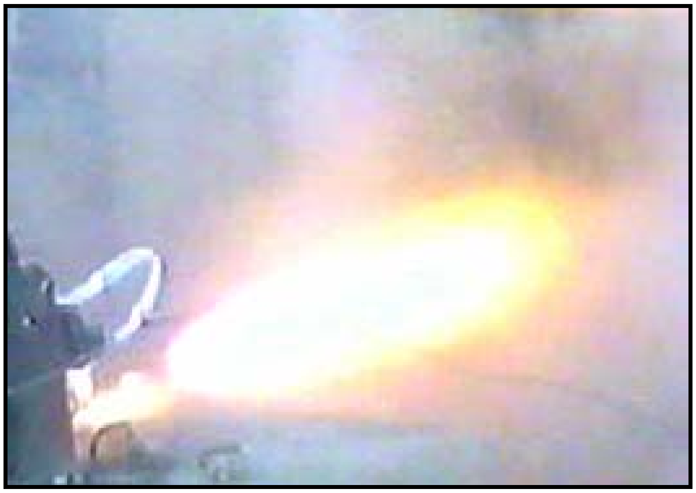

Figure 10 : A view of operation test

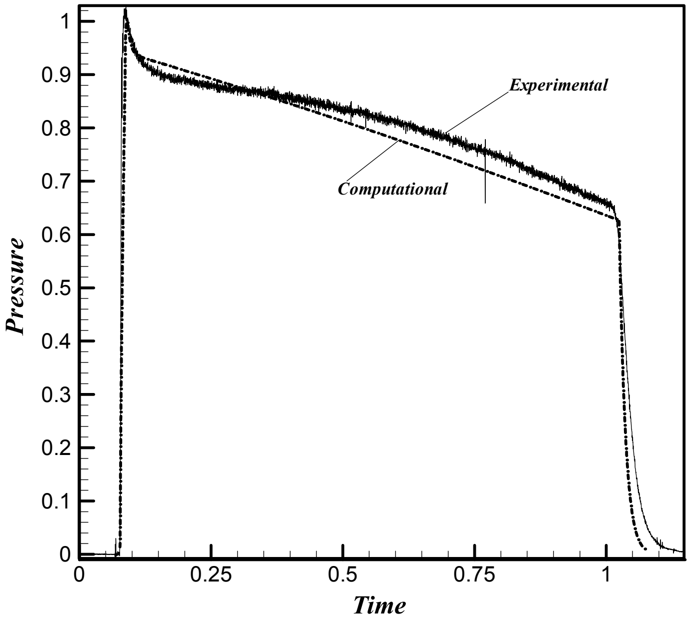

Figure 11 : The comparison between experimental and theoretical results [dimensionless]

The mentioned computer program takes into consider a factor for all sides of solid propellant (inner, outer ands areas); Then user, with due consideration to the system requirements, by selecting the type of grain and its areas that must be burned, can obtain the desired performance curve.

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