Influence of Oxidiser Incorporation in PVC Plastisol Hybrid Fuel

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Hybrid propulsion systems have potential advantage over conventional solid and liquid propulsion systems on large counts, and offer wide application areas in upper stages of space propulsion, auxiliary power plant for military aircraft, and sustainer stages of long-range surface-to-air missiles. Hybrid propulsion systems, however, suffer on low combustion efficiency ground and inherently burn in a fuel rich composition. Incorporation of solid oxidiser has been envisaged as a possible solution to combat the oxidiser deficiency and to improve the combustion efficiency. PVC plastisol has been taken as the hybrid fuel and four oxidisers, namely Potassium perchlorate, Ammonium perchlorate, Potassium nitrate and Ammonium nitrate have been incorporated in the fuel in various percentages by weight upto a maximum of 25 percent. A head-end injection system has been employed and combustion is made to take place in the cylindrical port of the fuel grain of fixed configuration in the stream of gaseous oxygen from commercial high pressure cylinders. Local fuel regression rates, average fuel regression rates, and fuel mass consumption rates have been determined in all cases at the same injection pressure and duration of burning, to study the influence of incorporation of oxidiser in the hybrid fuel on the above parameters. The analysis has been made in the light of existing theories. The influence of Potassium perchlorate is found to be the greatest and that of Ammonium nitrate the least. Incorporationof oxidiser is found to result in the steadily increasing regression and consumption rates with higher percentage of incorporation, except for Potassium nitrate, which is found to yield a maximum value at 15 percent incorporation. Though of considerable consequence, the available oxygen in the incorporated oxidiser, is not the sole influencing parameter.

Keywords: Oxidiser; Plastisol; Hybrid; Propulsion

INTRODUCTION

Chemical energy of compatible constituents is utilised to generate propulsive force in the chemical rocket propulsion. The performance of the chemical rockets depends primarily on the energy content of the chemicals, better known as propellants, however, other factors dictating the choice of propellants for specific mission, include various thermo-chemical properties, besides reliability, ease of handling, availability, and cost.

Solid propellant rockets, employing a mixture of fuel and oxidiser in solid state, find wide application for short duration and medium performance missions, because of their ease of handling, ready to go capability and simplicity. Nevertheless, they suffer a great setback as there remains no control over combustion, making it difficult to stop and restart, or to modulate thrust levels.

Liquid propellant rockets make use of fuel and oxidiser in liquid state, which are stored in separate storage tanks and brought to the combustion chamber with the help of suitable feed system. The liquid propellant rockets are found to be superior than their solid counterpart because of higher specific impulse values, stop-restart capabilities, thrust modulation amenability, cooling possibility, and such other improved features. All the same, liquid propellant rockets are more complex in nature and hazardous in handling, besides the fact that they require longer time for preparation and expensive installation and ground equipments.

Hybrid propulsion system was advanced as a means to overcome the problem areas of the solid and liquid propulsion systems, while retaining the advantages of the both. The solid constituent, generally fuel is held in the combustion chamber in the form of a grain, similar to a solid propellant rocket, whereas the liquid oxidiser is brought to the combustion chamber with the help of a suitable feed system, similar to a liquid propellant rocket.

High specific impulse without suffering on loading density, stop-restart capabilities and thrust modulation amenability of hybrid propulsion system makes it superior to the solid propulsion system. At the same time, with just half the storage tank, feed system and other components, as compared to the liquid propulsion system, the hybrid system is less complex and possess less handling and operation difficulties, and has the freedom of using even the otherwise incompatible fuel and oxidiser, and has non-deterring consequences of cracks, blow-holes or air bubbles in solid grains. The possibility of attainment of very high density specific impulse makes a hybrid propulsion system a viable contender in volume — limited upper stages of space propulsion, and is

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going to find wide application in auxiliary power plant for military aircraft by dint of amenability to thrust modulation and thrust vector control.

In the broad classification based on the mechanical mode of injection, mixing and combustion, namely head-end injection system and after-burner system, the former is less complex and has attracted attention of the engine developers. In the head-end injection system, the liquid oxidiser is injected from the fore end into the perforation of the fuel grain, stored in the combustion chamber with the help of a suitable system.

In a true hybrid system, the definition is strictly adhered to, and liquid oxidiser is made to react with solid fuel, which has no oxidiser content in it. In this system, the oxidiser gets depleted in the earlier part of the grain resulting into low combustion efficiency and the overall mixture remains fuel rich. Conventional systems come into existence as a result of endeavour to improve upon the combustion efficiency, besides the ease of ignition and favourable ballistic conditions. In this system, small percentage of an oxidiser is incorporated in the fuel grain to make the combustion more complete towards improvement of combustion efficiency.

In the present investigation, an effort has been made to investigate the effect of incorporation of four different oxidisers in varying percentages in the hybrid fuel. Perchlorate and nitrate of ammonium and potassium have been chosen as the oxidisers in conjunction with plastisol of polyvinyl chloride as fuel. The percentage of oxidiser has been varied between 2 and 25 by weight. Fuel grains having cylindrical port have been made to undergo combustion in the stream of commercial oxygen gas at a constant injection pressure of 35.0 kgf/cm^2 for a fixed duration of 10 s. Local fuel regression rates, average fuel regression rates and fuel mass consumption rates were determined in all cases for investigating the effect of incorporation of oxidiser in the fuel.

EXPERIMENTAL

Fuel grains of PVC plastisol were prepared from commercial grade polyvinyl chloride (PVC resin 370, Calico) using laboratory grade dibutyl phthalate (DBP) in equal amount by weight and mixing in a water cooled vertical sigma blade mixer (Atlantic Corporation, USA) of 1 kg capacity by the usual method of mixing, pouring in a suitable cylindrical mould and curing at a temperature of 130°C for 4 h duration. The cured grain of 62 mm outside diameter and 31 mm inside diameter was taken out manually from the mould by light pushing, after having cooled in open atmosphere and trimmed to a length of 250 mm with the help of a sharp knife.

Laboratory grade potassium perchlorate, potassium nitrate, ammonium perchlorate and ammonium nitrate were employed as oxidisers and incorporated in the fuel grain. The oxidisers were dried and pulverized, before adding to the mix of fuel and plasticizer during the preparation of the fuel grain in 2, 5, 10, 15, 20 and 25 percent by weight.

A flanged seamless stainless steel static test motor, with 64 mm internal diameter and 376 mm length with a spiral wound 2 mm × 4 mm rectangular water passage conduit, spiralled over and covered with 2 mm thick stainless steel cover has been used for the investigation. A cup shaped chamber has been employed to serve as the oxidiser chamber to ensure settling down of the high velocity oxygen gas before the actual injection. A stainless steel disc of 10 mm thickness with seven number 1.50 mm diameter orifices, one being placed at the centre and remaining six on 30 mm pcd was used as an injector. Straight cone convergent, divergent nozzle with inlet diameter of 60 mm, throat diameter of 10 mm and exit diameter of 22 mm, fabricated from graphite inserted Al alloy rounds was employed and bolted to the motor with the help of a 12 mm thick stainless steel nozzle retainer ring. Figure 1 shows the sectional view of the assembled and loaded test motor.

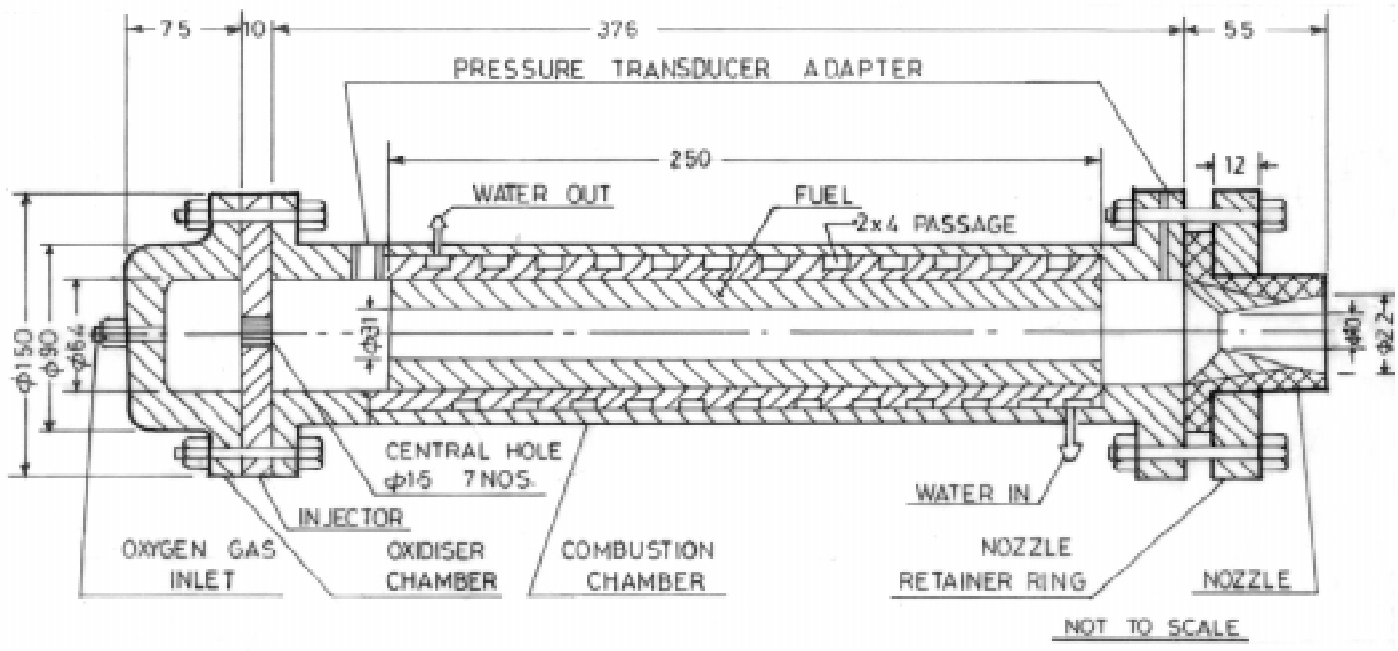


Figure 1 Sectional view of motor assembly with case-bonded grain

The fuel grain was case bonded to the combustion chamber with the help of inhibitor, having clear space of 50 mm on the upstream and 76 mm on downstream side. Thick layer of the inhibitor paste was applied on the wall in the clear space, and the loaded chamber was then kept at 130°C for 1 h duration.

The oxygen gas from commercial high pressure cylinder was employed through a plumbing, with the provisions for pressure regulator, solenoid valve, non-return valve, and a number of hand valves. A diaphragm type dome regulator was used for injecting the oxygen gas at the desired pressure. A two way solenoid valve operated at 32V dc was provided in the line, so that the oxygen gas could be started or stopped instantaneously at the required instant. Use has been made of a pyrotechnic shellac igniter with an ignition delay of 0.2 sec. The igniter is kept loosely in the port of the fuel grain at the upstream side. The schematic of flow diagram has been presented in Figure 2.

The investigation has been carried out on a flexural type horizontal thrust stand. The assembled test motor was mounted on the test bed, and mechanical connections for oxygen supply and water cooling made. A strain gauge type pressure transducer (Encardio — rite, 0-200 kgf/cm^2), used to measure the combustion chamber pressure, was threaded on the motor on the downstream end of the combustion chamber through adapter, and the electrical connections made for recording the pressure time data with the help of a 24 channel UV recorder (Visicorder, Honeywell, USA) which makes use of impression of ultra-violet signals on a photo-sensitive paper. The igniter connections were then made with the firing console, powered by a 12 V dc supply from storage battery.

An injection pressure of 35 kgf/cm^2 has been used throughout. The oxygen gas was made to flow immediately after ignition of the hybrid fuel having taken place. The oxygen gas flow was stopped after a lapse of 10.0 s (+0.2 s, −0.0 s) in all the cases throughout the investigation.

A total of 25 successful test firings were made during the course of investigation. Pure PVC plastisol fuel grain was employed in the first test firing to form the basis for the purpose of finding the influence of incorporated oxidisers. For each oxidiser, a total of six test firings were done one for each weight percentage of 2, 5, 10, 15, 20 and 25 respectively.

After each test firing, a considerable time was allowed for the motor to cool off to the ambient temperature. After disconnecting all the electrical connections, gas supply and coolant water supply, the motor was removed from the test bed, and subsequently dissembled. The fuel grain was then taken out from the combustion chamber by releasing the inhibitor bond with the help of a sharp edged thin metallic rod manually. The inhibitor layer on the exterior of the fuel grain was carefully peeled off with the help of a sharp knife.

The remaining fuel grain was weighed accurately after cleaning. The average fuel mass consumption rate for the particular composition of the fuel grain was calculated from the difference in the initial and final weight, averaged in the actual duration of burning. The oxidiser mass flow rate was computed by the difference of oxygen cylinder pressure at the beginning and end in the similar manner, and the oxidiser mass flow rate has been found to be 15.5 gm/s (± 0.21 gm/s).

Each fuel grain was longitudinally cut and a slice of about 25 mm width was taken out by making a parallel longitudinal cut. The remaining web at ½" (12.5 mm) interval was measured with the help of micrometer of least count = 0.01 mm. The local regression rates were computed by averaging the web consumed over the actual duration of burning for each composition of the hybrid fuel. The average regression rates were computed from weight loss and average port diameter during each test.

RESULTS AND DISCUSSION

The local regression rate data for the various hybrid fuels have been plotted as a function of dimensionless axial distance from the leading edge in Figure 3 to Figure 6 for the cases of incorporation of the four oxidisers, along with the regression rate variation of pure PVC plastisol.

The regression rate for pure PVC plastisol has been found to decrease continuously from a value of 6.40 mm/s at the leading edge to 4.45 mm/s at a distance of about 0.75 length of the grain followed by a gradual increase to 5.30 mm/s at the

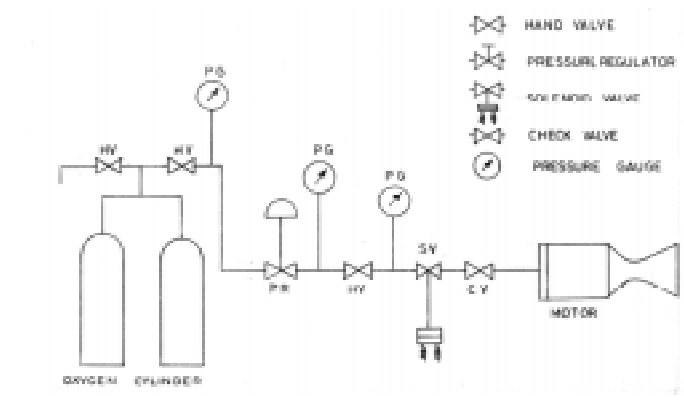


Figure 2 Flow schematic of experimental hybrid test (static) motor

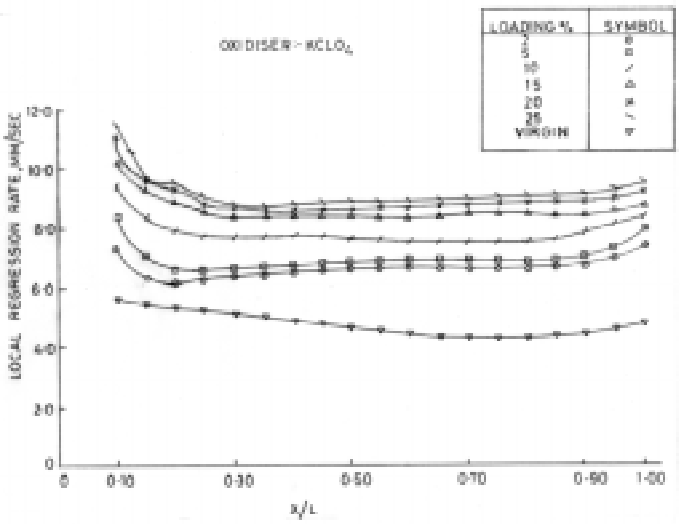


Figure 3 Local regression rate against X/L (oxidiser : $KClO_4$)

aft end. The high regression rate near the leading edge may be attributed to the high oxidiser concentration as well as the heterogeneous surface reaction by the direct impingement of the oxidising gases. The intensity of the heterogeneous surface reaction by the direct impingement of the oxidising gases decreases as the distance from the leading edge increases and such reactions would cease to take place after a certain distance along the fuel grain. This is marked by the decreasing trend and the obtained minimum value at a certain distance down the leading edge.

The local regression rate, r is primarily determined by the local mass flux, G. The value of G at any position, x downstream the leading edge includes the oxidiser entering at the head end of the fuel grain plus all the fuel entering the port upstream of x. Thus, the local G is inversely proportional to the instantaneous local port cross section caused by regression, as well as the local regression rates at all locations upstream of x.

The regression rate of hybrid fuel is controlled by the diffusion flame transport of the oxidiser mass and the total heat flux, received at the fuel surface from the flame zone. As the distance from the leading edge increases along the length of the fuel grain, more and more fuel is inducted in the flame zone and the mass flux is increased. The increased mass flux is responsible for a higher heat flux, in spite of the fact that the oxidiser concentration decreases with the increase in the distance from the leading edge. The local regression rate variation may be viewed in the light of the above.

The local regression rate of the hybrid fuel is found to increase with the incorporation of oxidiser at all locations. Higher the oxidiser incorporation, higher is the value of the regression rate at any specified location. Besides, all the curves show an upward trend towards the downstream end of the grain.

The enhancement of the regression rate with the higher solid oxidiser loading in the hybrid fuel is as per expectation. The hybrid fuels are known to burn in a rather fuel-rich mixture ratio, *ie*, a good portion of the fuel emanating in the process of sublimation or pyrolysis is exhausted unreacted. The incorporation of the solid oxidiser in the fuel ensures more handy availability of the oxidiser for the fuel to undergo chemical reaction. In the process, higher heat of combustion is realized, thereby raising the combustion temperature and heat flux. The increasing trend of regression rate towards the downstream end of the fuel grain in all cases may be taken as a clear indication of availability of sufficient oxidiser in the flame zone even at the aft end.

The effect of loading of solid oxidiser on local regression rate enhancement is less pronounced at higher weight loading of the oxidiser. This is as per expectation in the light of the combustion mechanism of hybrid propellants. The increase in heat flux with oxidiser incorporation would cease to be as effective with greater oxidiser loading beyond certain value, because the solid oxidiser would undergo degradation only upto the extent of the surface temperature attained, while complete combustion would take place in the flame zone, where the diffusion mechanism is the controlling factor.

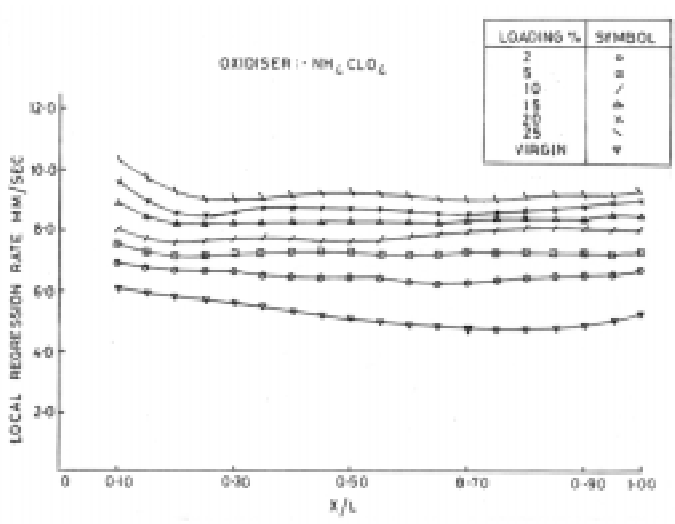


Figure 4 Local regression rate against X/L (oxidiser : NH_4ClO_4)

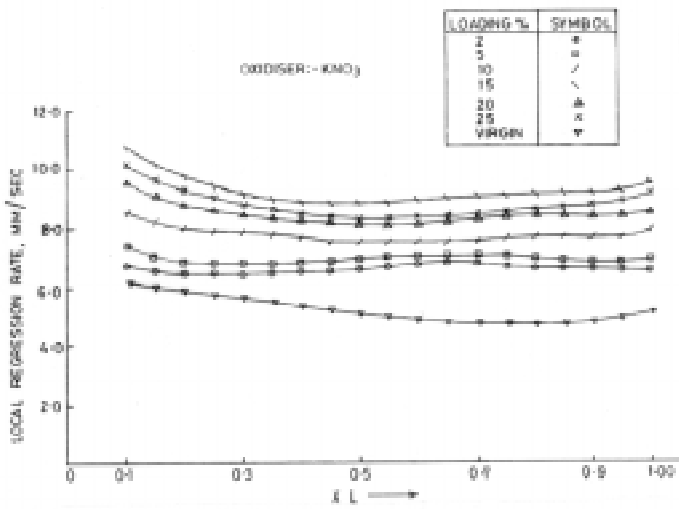


Figure 5 Local regression rate against X/L (oxidiser : KNO_3)

The regression rate data in the case of various weight loading of ammonium perchlorate and potassium nitrate have been presented in Figure 4 and Figure 5 respectively. In both the cases, the local regression rate is found to increase at all locations along the fuel grain with the increase of oxidiser loading, except in the case of potassium nitrate, where the maximum value is obtained at 15 percent weight loading of the solid oxidiser in the hybrid fuel. The striking difference in the behaviour of potassium nitrate points is the possibility of this particular composition yielding maximum heat flux, however no attempt has been made to explore the actual mechanism of surface reaction and final combustion in the flame zone.

The regression rate data in the case of ammonium nitrate has been presented in Figure 6. The maximum value of the regression rate has been obtained in the case of 10 percent oxidiser incorporated fuel grain, besides regression rate values of 25 percent loading having lower value than those of 20 percent loading. The more intriguing fact evidenced in this case is that the 15 percent oxidiser incorporated grain has a

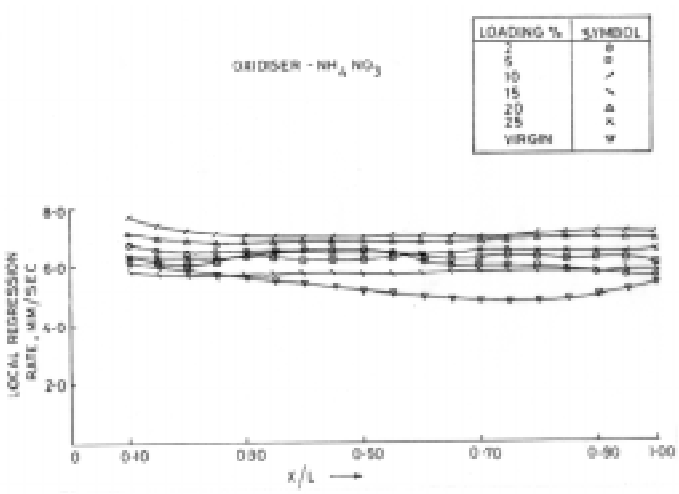


Figure 6 Local regression rate against X/L (oxidiser : NH_4NO_3)

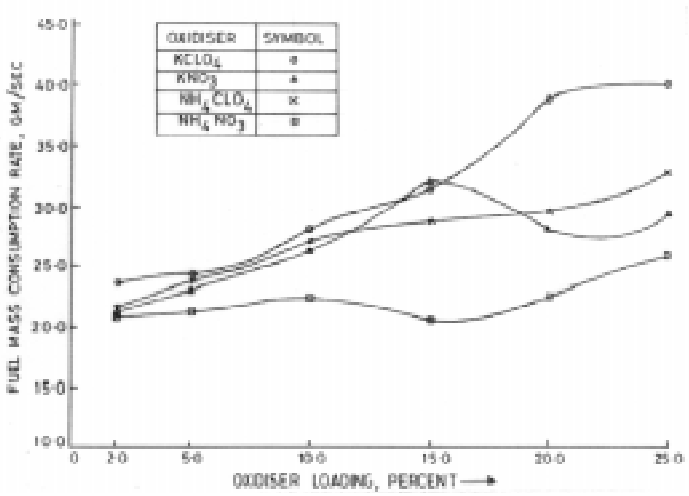


Figure 8 Fuel mass consumption rate against oxidiser loading

peculiar out of way trend of variation along the length. The regression rate values have also been found to be within a narrow range, varying between 0.57 mm/s and 0.70 mm/s for most of the portion of the fuel grain, suggesting that ammonium nitrate would not serve to augment the heat flux or to enhance the combustion efficiency of hybrid systems.

The average fuel regression rate and the fuel mass consumption rate for all oxidisers at different percentages of incorporation have also been computed and presented in Figure 7 and Figure 8 respectively. While the average regression rate of pure PVC fuel has been found to be 5.17 mm/s, the maximum value of the average fuel regression rate has been found to be 10.01 mm/s and 9.45 mm/s at 25 percent oxidiser loading of potassium perchlorate and ammonium perchlorate respectively. In the case of incorporation of potassium nitrate, the maximum value of 9.32 mm/s has been found with 15 percent, and for ammonium nitrate, a value of 6.83 mm/s at 20 percent.

With the increase of oxidiser incorporation, the heat of combustion, as also the available oxygen in the flame zone is bound to increase, contributing towards raising the flame

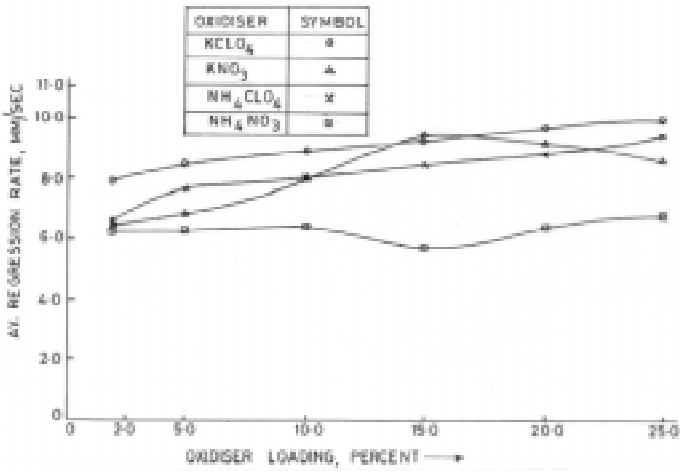


Figure 7 Average regression rate against oxidiser loading percent

temperature and the heat flux. The regression of fuel is dictated by the heat available on the burning surface to flame zone and to effective heat of gasification of the regressing fuel. The burning surface temperature would determine the extent to which the thermal degradation of the oxidiser would have taken place, and the extent of surface reaction with the available fuel around in liquid and gaseous phases. It is obvious that greater incorporation of oxidiser would increase the heat flux of the combustion gases in the flame zone, at the same time, it would decrease the effective heat of gasification.

The above discussion is true for potassium perchlorate and ammonium perchlorate oxidiser to entire range of oxidiser incorporation upto 25 percent, and also to potassium nitrate and ammonium nitrate upto 15 and 10 percent respectively. Potassium nitrate at 15 percent yields in lower regression rate, followed by a maximum value at 20 percent and again decreasing for 25 percent incorporation. The heat of combustion and flame temperature should increase with higher oxidiser content. However, the blocking effect and heat of gasification might be responsible in resulting into lower values of regression rates.

The trend of the curves for the fuel mass consumption rate as well as the values at the various percent incorporation for all oxidisers are found to be similar to those in the case of average regression rate variation. The mass consumption rate of fuel is directly proportional to the regression rate for identical port size and mass density of fuel grains. With the small change in port size for burning duration of 10 s and small variation in mass density by replacing PVC component with oxidisers of comparable densities, it is but obvious that the variation in the mass consumption rate would not be very different than in the average regression rate.

The most important parameter that could be taken into consideration is the oxygen content of the respective oxidiser incorporated into the hybrid fuel, which should be available for liquid and gas phase reaction with the fuel at the regressing surface soon after the pyrolysis/decomposition/sublimation of the fuel. This would also enhance the combustion

efficiency resulting into a higher heat flux available in the flame zone for increased heat transfer to the regressing surface. The available oxygen of the incorporated oxidiser, however, does not seem to be the sole factor, controlling the exact influence on the combustion parameters of the hybrid fuel. Potassium perchlorate has 46.192 percent of available oxygen by weight, while ammonium perchlorate has a value of 34.043, and ammonium nitrate has the lowest at 19.988. While this explains the relative value of regression rates of PVC plastisol hybrid fuels incorporating these oxidisers, neither the rates are in any proportion nor the change in percentage incorporation of a particular oxidiser has any linearity in augmentation of the regression rate. Similarly, potassium nitrate which has 39.563 percent of available oxygen, does not influence the regression rate more than ammonium perchlorate, which has a value of 34.043. It is envisaged that the temperature of the combustion zone, thermal degradation of the oxidiser at the surface, heat of gasification of the fuel, and the blocking effect due to the constituents would also play a major role in determining the regression rate.

CONCLUSION

1. The regression rate of PVC plastisol hybrid fuel, both pure PVC and with oxidiser incorporation, is found to decrease from a maximum value at the leading edge upto a distance, after which the regression rate data adopts approximately the same value, and in some cases an increasing trend towards the aft end.

2. The regression rate of the hybrid fuel is found to be augmented by incorporation of oxidiser in the fuel.

3. Incorporation of oxidiser is found to result in increasing regression and consumption rates with increasing oxidiser incorporation, except for the case of potassium nitrate, which is found to yield a maximum value at 15 percent incorporation.

4. The influence of potassium perchlorate is found to be the greatest and that of ammonium nitrate the lowest.

5. The influence of potassium perchlorate incorporation is of greater consequence as compared to nitrate incorporation in PVC plastisol hybrid fuel.

6. The available oxygen in the incorporated oxidiser is found to be of considerable consequence, however, it is not the sole influencing parameter.

REFERENCES

1. S S Penner. 'Chemical Rocket Propulsion and Combustion Research.' *Monograph, Gordon and Breach*, 1962, pp 145-153.

2. S Fineman. 'Some Analytical Consideration of the Hybrid Rocket Combustion Problem.' *MS Thesis*, *Princeton University*, 1962.

3. G Marxman and M Gilbert. 'Turbulent Boundary Layer Combustion in the Hybrid Rocket.' *Ninth Symposium (International) on Combustion*, *Academic Press*, 1963, pp 371-372.

4. E Miller. 'Hybrid Rocket Combustion Regression Rate Model.' *AIAA Journal*, vol 4, no 4, April 1966, pp 752-753.

5. R N Kumar and D G Stickler. 'Polymer Degradation Theory of Pressure Sensitive Hybrid Combustion.' *XIIIth Symposium (International) on Combustion*, *Combustion Institute*, Pittsburgh, 1971, pp 1059-1072.

6. A K Chatterjee and P C Joshi. 'Pressure Dependence of PVC Plastisol Burning in Gaseous Oxygen Stream.' *Journal of Spacecraft and Rockets*, vol 14, no 6, June 1977, pp 378-379.

7. A K Chatterjee, P C Joshi and T Prabhakar. 'An Experimental Investigation of Aniline Formaldehyde — Fuming Nitric Acid Combustion.' *Journal of Aeronautical Society of India*, vol 29, no 3-4, December 1978, pp 137-140.