REFERÊNCIA

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THE PRELIMINARY STUDY OF SEVERITY LEVEL OF STRUCTURAL DISCONTINUITIES IN PARAFFIN GRAIN OF HYBRID PROPELLANT ROCKET

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The paper addresses experimental characterization of instant shape of paraffin grain with predefined structural discontinuity in process of combustion and its possible influence on structural integrity of hybrid propellant motor. The one-port paraffin grains with and without artificial crack were subjected to combustion in a hybrid propellant test-motor and considerable discrepancies of temperature on external surface of the non-cracked and the cracked grains were detected. Elevated temperature on the external surface of cracked grain was caused by fast evolution of the crack in direction of motor's casing during combustion process. Thus, it was shown that crack formation causes a local overheating of structural casing that may subsequently jeopardize structural integrity of the motor.

I. INTRODUCTION

Paraffin is one of the potential fuels under investigation at present time for application in hybrid propellant rockets due to some important advantages, among which are good performance characteristics (high regression rate, throttling), non-toxicity, manufacturability and low cost. In accordance with reference[1] paraffin-based hybrid rocket propulsion may find its application in a number of market segments (uppers stages, sub-orbital launch vehicles, tactical missiles, small satellites injection systems, boosters) with possible cost reduction in the mid-term future. The project granted by Brazilian Space Agency was started at the University of Brasilia (UnB) with the primary goal to develop and try out the feasibility of paraffin-based hybrid rocket motor for propulsive decelerator (retrorocket) of SARA reentry capsule, originating a new market segment for hybrid rocket propulsion[2].

However, paraffin is characterized by low mechanical properties as it is shown in the results of probably first experimental study of tensile strength of commercial paraffin wax published in 1935[3]. It was found that tensile strength is in the range 1 – 3 MPa at the temperatures between –10° and 30°C. A maximum is apparently reached at about 0°C and the strength suddenly declines at about –6°C. At this negative temperature, tiny cracks were visible even to the naked eye.

Recent experimental study[4] showed that mechanical properties of paraffin actually are not high (tensile strength 1.03 – 1.38 MPa, modulus of elasticity 200 MPa, percent elongation 0.6-0.8%). Addition of low density LDPE to paraffin in small quantities (2-4%) increases almost three times both strength and stiffness respectively; but absolute values of mechanical properties still remain small. In addition, admixture of paraffin-based fuel with 20% of ethylene vinyl acetate copolymer provided increase of tensile strength up to about 1.6 times and strain up to 2.2 times, however the regression rate decreased about 35%[5].

Other recent work emphasized the brittle behavior of paraffin even at normal temperatures[6]. Addition of 40% of aluminum particles increases slightly the elastic modulus, but the material fails at a strain 15% lower than pure paraffin. The failure strain of the pure paraffin according to the results of tensile tests was near 0.017 (mm/mm).

It is known also that as lower temperature of the material as more brittle it becomes. For hybrid propellant rockets operating in conditions of low temperature, such as those launched from high altitudes (balloon launch, air launch) or applied in upper stages of the launch vehicles (space tugs, orbital transfer vehicles) this effect may essentially prejudice the structural behavior of the grain.

Analytical stress-strain analysis of the one-port paraffin grain under thermal stresses caused by gradual cooling from normal to low temperatures down to –50°C (simulating the cooling process of the hybrid propellant motor during ascend by balloon to launch a rocket from altitudes 20-30 km) revealed that maximal principle stress in the grain is greater than tensile strength of the paraffin[7]. These stresses may cause the cracking of the paraffin grain. Such formation of cracks on the surface of paraffin grain manufactured by centrifugation process with addition of black pigment and carbon black was observed after transferring of paraffin grain from low –195°C to normal temperature environment[8].

In conference papers[9,10] it was mentioned the general drawbacks of paraffin, its sensitivity to various defects. Moreover, the burning conditions, such as elevated thermal and mechanical stresses (temperature 3300K, pressure 40 bars) can provoke cracking and failure of the paraffin grain, which leads to combustion instabilities or even explosion of the rocket; however, no mechanism of such behaviour was described or cited.

At the same time, it was remarked that hybrids are insensitive to cracks or debonding[11,12], since cracking in a hybrid propellant rocket does not lead to catastrophic consequences like in a solid propellant rocket[13]. The disastrous reaction of solid propulsion system to crack formation on the surface of solid propellant grain was described in well-known educative sources[14,15]. As a result of exposure of additional burning surface by cracks in the solid propellant grain where the fuel and oxidizer are intimately mixed, the gas pressure exceeds some critical value over which the case of combustion chamber fails.

In contrast with solid propellant rockets the chamber pressure of a hybrid rocket engine is proportional to oxidizer flow and not to the internal surface area exposed to the flame[16]. Thus, the fuel-grain cracks in hybrids are not catastrophic because burning only occurs down the grain port where it encounters the oxidizer flow. Even if oxidizer and combustion product gases have penetrated the crack cavities of the grain port the reactions would be limited in the cavities and could not generate any significant local pressurization and grain damage. It is considered that heterogeneous reactions of oxidizer with fuel surface are mitigated since the diffusion flame zone protects the fuel surface from the oxidizer-rich core flow. As a result, cracks and other possible imperfections or discontinuities on the surface of the fuel grain do not have a significant effect on the burning (internal ballistics), while even increasing the fuel burning area[17,18]. There were also studies that revealed no burning within cracks or between the grain and casing of combustion chamber[19,20].

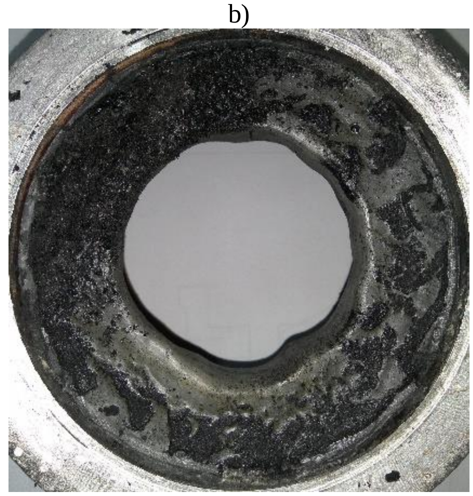
After over 300 tests of the hybrid engine based on the use of a hydrogen peroxide as the oxidizer and polyethylene as the fuel the specialists responsible for the tests concluded that grain cracks had no effect on combustion[17]. Nevertheless, at the same reference it was mentioned that air bubbles casted in the fuel grain could cause considerable disturbances in the flow during hot-fire tests.

According to the given review, cracks may be formed in paraffin grain at conditions of low temperatures, but no critical influence of the cracks on structural integrity of hybrid propellant rocket were found. Some structural discontinuities, such as air bubbles, may affect combustion characteristics of hybrid propellant systems, but there are no information about disastrous consequences.

Meanwhile authors fulfilled routine tests of the hybrid propellant test-motor for propulsive decelerator with free casted one-port paraffin grains and discovered that the shape of paraffin grain with natural radial cracks after couple of seconds of burning differs from the shape of grain without cracks (Figure 1).

a)

b)



c)

Fig. 1: The shapes of the cracked and non-cracked grains after short time burning: a) the cracked grain before burning; b) the cracked grain after burning; c) the non-cracked grain after burning.

According to the given figures, it seems that regression rate of paraffin is increased at the vicinity of cracks, while in the non-cracked grain burning of paraffin is uniform. Subsequent to these results, the following question was raised: what are possible consequences of increased regression rate of the cracked paraffin grain?

Objectives

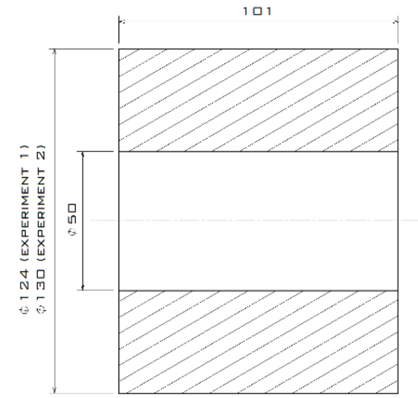
The main target of the presented paper is to reveal the severity level of some structural discontinuities in a small-size fuel grain of hybrid propellant rocket from a structural point of view.

The main objective of the presented study is characterization of the instant shape of paraffin grain with predefined structural discontinuity during combustion process and evaluation of its possible influence on structural integrity of hybrid propellant motor. The objects of the study are: 1) evolution or transformation of the artificial defect in paraffin grain during burning in test-motor; 2) the change of temperature on the external surface of the grain due to presence of the defect. The subject of the study is artificial crack in pure paraffin without any modifiers or additives.

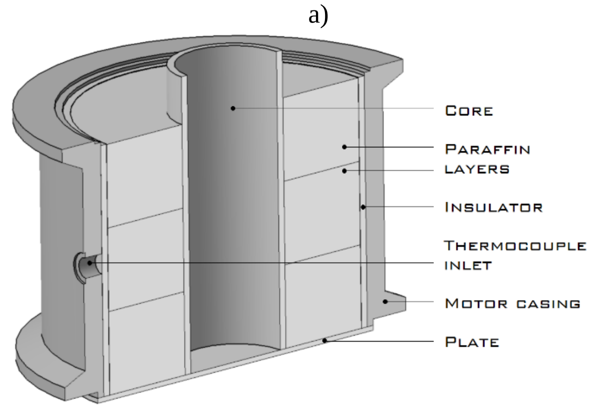
II. METHODOLOGY

The study presented in the paper is consisted from two experiments. Every experiment included two hot-fire tests of hybrid propellant test-motor with one-port paraffin grain. In one of the tests, the grain had structural discontinuity in the form of artificial crack, and in another, the grain was structurally continuous, i.e. without any artificial defect. Nitrous oxide was used as liquid oxidizer in hot-fire tests. The design of hybrid propellant test-motor used for experimental study is described in details in reference[2].

The objective of the first experiment was to measure and compare temperature on external surface of one-port paraffin grain with and without artificial crack during hot-fire test. The centrifugal casting is used for fabrication of relatively small one-port paraffin grains with a good quality[21,22]. However, the manufacture of most rocket propellant charges is based on casting process of a viscous liquid, which is then poured into molds and cured at elevated temperatures, and in general, this fabrication method can be applied for grains of any size[23]. In this study the propellant grain (Figure 2, a) was fabricated in three consequent layers (Figure 2, b) by simple pouring the melted paraffin SOLVEN WAX 140 into cylindrical steel casing of the test-motor with insulator made from Celeron (phenolic resin reinforced by cotton fabric). Free casting by layers helps to avoid formation of considerable defects in paraffin, such like big blowholes and voids. The insulator protects the thermocouple inlet from hot gases.



a)



b)

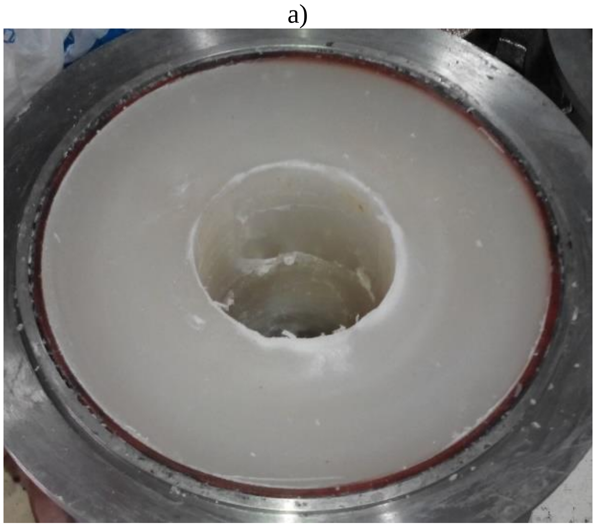
Fig. 2. One-port paraffin grain used for hot-fire tests: a) drawing; b) arrangement of paraffin layers in test-motor at process of grain fabrication (for the first experiment)

Thus, in fact the measurement of temperature in the first experiment was on external surface of insulator and not directly on the surface of paraffin grain.

The structural discontinuity in one of the grains was made by stretching 50 mm wide transparent polypropylene film with thickness near 60 micrometers along the axis of the grain before pouring melted paraffin, so that one edge of the film touched the internal surface of insulator and another – external surface of the core. After pouring and solidification of paraffin, the film was extracted leaving a radial crack along all length of the grain. The thickness of the crack was not uniform along the grain, as it shown in Figure 3, a, and reached in inner layers 0.5 mm. The thickness of a real crack is much less, than artificial one prepared for the study. However, the application of obtained crack was justified, since at some conditions of motor's operation (thermal expansion, for instance) the thickness of crack can increase significantly.

The insulator within the motor casing was oriented in angular direction in such way, that the imaginary front of radial crack would pass through the inlet of thermocouple as it is shown in Figure 4, a. The thermocouple provided the instant value of temperature on the external surface of insulator during the hot-fire test. There were no special orientation of insulator with non-cracked grain, since it is axially symmetric (Figure 3, b).

a)



b)

Fig. 3. The paraffin grain: a) with artificial crack; b) non-cracked

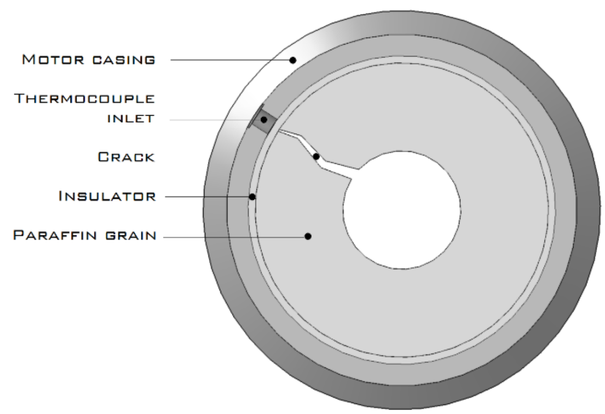
Figure 5 shows arrangement of test-equipment with measuring units in the test-motor. Pressure in combustion chamber of test-motor and feeding line was measured by pressure transmitter of general purpose Danfoss MBS 1750. Temperature was measured by K-type thermocouple ECIL MS11. Duration of hot-fire test was determined by complete burning of paraffin grain installed in separate compartment of motor, called casing (Fig. 5).

All experiments of the study were performed at reduced mass flow rate of oxidizer to avoid erosion of nozzle insert that might affect the pressure drop in combustion chamber. Since the flow meter was not included in the experimental scheme, the calculation of oxidizer-fuel ratio (O/F ratio) was fulfilled approximately by the following formula

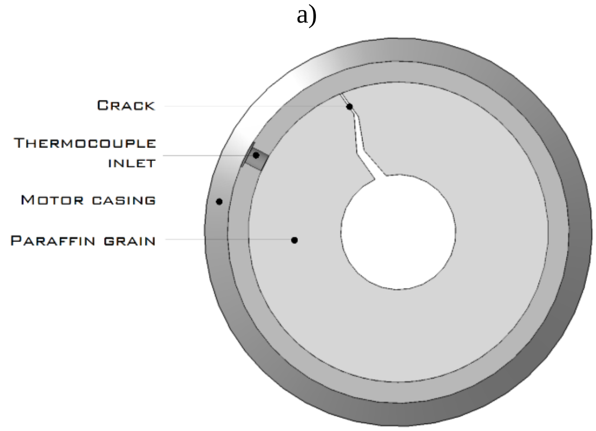
$$O/F = \frac{m_{t.0} - m_t - m_r}{m_{g.0} - m_g} \quad [1]$$

where $m_{t.0}$ – mass of the tank with oxidizer before tests; m_t – mass of the tank with oxidizer after tests; m_r – average mass of the oxidizer in tubes and valves of feeding system; $m_{g.0}$ – mass of the motor casing with paraffin grain before test; m_g – mass of the motor casing with paraffin grain after test.

The objective of the second experiment was visual analysis of the instant shape of port in the intermediate moment of burning. This moment was defined by cease of oxidation flow after 7 seconds of burning. The manufacturing process of the grains was the same as in the first experiment except that pouring of the paraffin by layers was made directly into motor casing. Thus, the insulator was not used in the experiment, since unburned layer of paraffin protected the thermocouple inlet. Test-equipment and experimental setup was the same as in the first experiment except position of thermocouple in relation to crack: it was displaced in 40° clockwise (Fig. 4, b). In addition, thermocouple measured temperature on the external cylindrical surface of the paraffin grain.



a)



b)

Fig. 4. Position of thermocouple in relation to crack: a) in the first experiment; b) in the second experiment

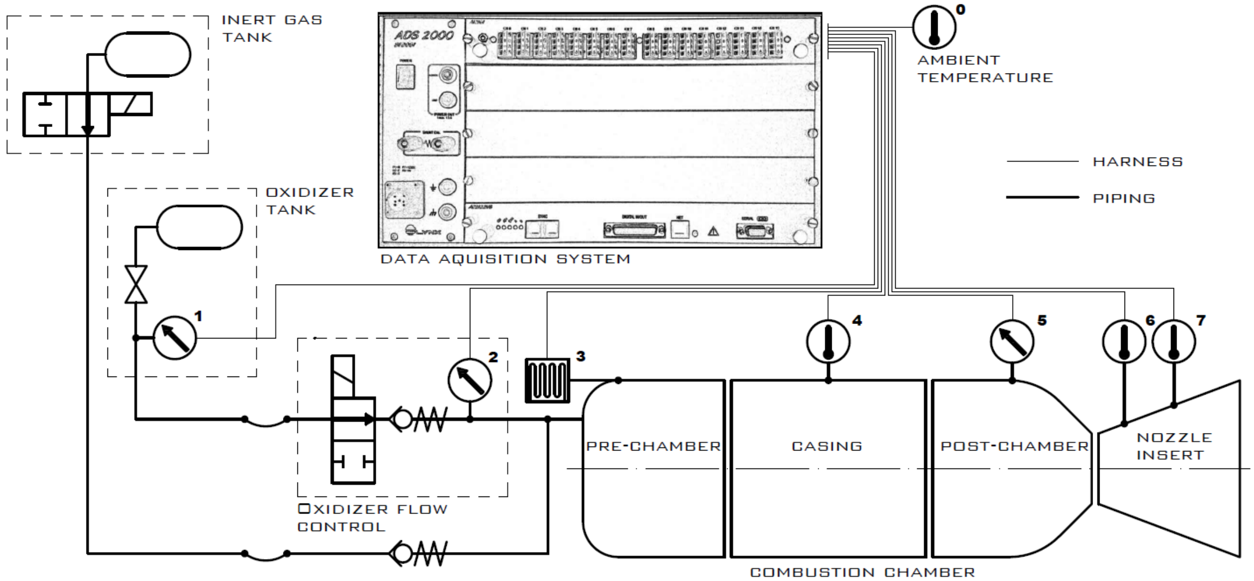


Fig. 5. Scheme of the test-equipment arrangement: 0 – thermocouple for ambient temperature measurement; 1 – pressure transducer in collector; 2 – pressure transducer in feeding line; 3 – load cell; 4 – thermocouple in motor casing; 5 – pressure transducer in combustion chamber; 6 – thermocouple in critical section of nozzle insert; 7 – thermocouple in post-critical section of nozzle insert

III. RESULTS

The test results of the first experiment are presented in the form of plots of pressure and temperature for cracked and non-cracked grains. For the needs of comparison of obtained data, the initial moments of burning of both grains were displaced to the same origin in the plot of pressure of combustion chamber (Fig. 6). The same origin (4.3 s) was used for all other plots of pressure and temperature (Fig. 7-11).

Plot of pressure in combustion chamber was also used to determine burning time, whose values for cracked and non-cracked grains are correspondingly 13.2 and 15.8 seconds. The plot of pressure in feeding line is shown in Figure 7 to explain discrepancy of the pressure in combustion chamber. The evaluated O/F ratio for the test with non-cracked grain was 3.4 and for the cracked one was 2.9.

The comparison of temperature on the surface of heat insulator (thermocouple No. 4 in Figure 5) for both grains is shown in Figure 8. Plots of ambient temperature (Figure 9) measured by thermocouple imbedded in data acquisition system and temperatures in the nozzle insert (Figures 10-11) of the test-motor are also provided as a reference.

The experimental data of pressure and temperature from the second experiment are given in Figures 12-15. According to the plots of pressure, burning time for cracked and non-cracked grains are correspondingly 7.6 and 8.3 seconds.

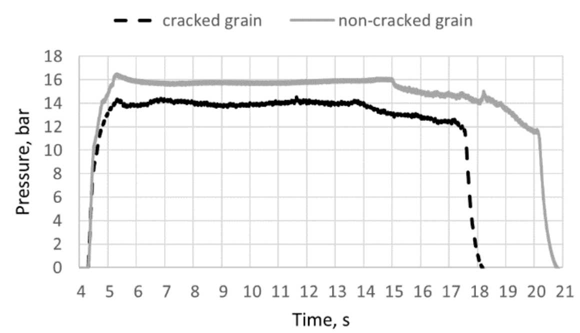


Fig. 6. Comparison of pressure in combustion chamber of the first experiment

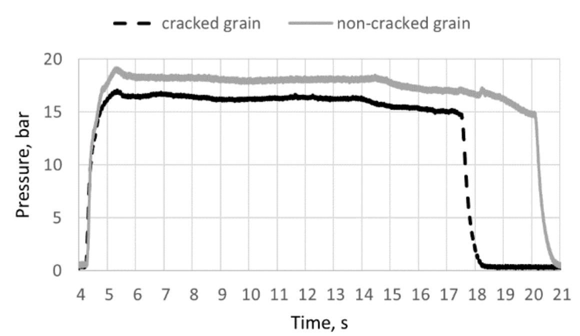


Fig. 7. Comparison of pressure in feeding line of the first experiment

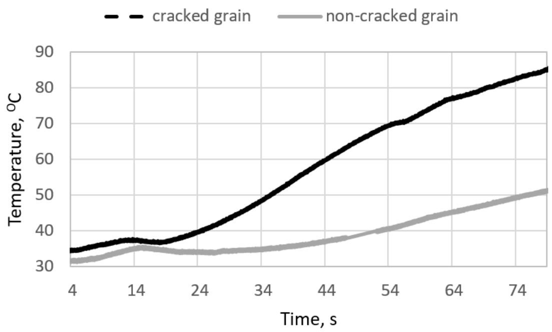


Fig. 8. Comparison of temperature on the external surface of heat insulator of the first experiment

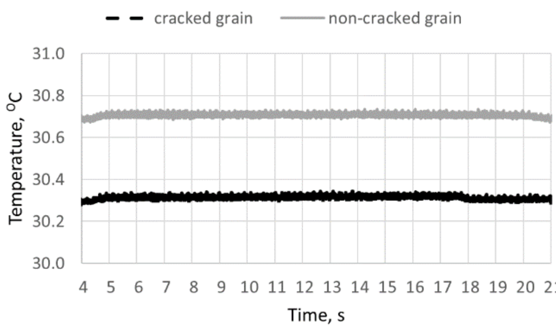


Fig. 9. Data on ambient temperature of the first experiment

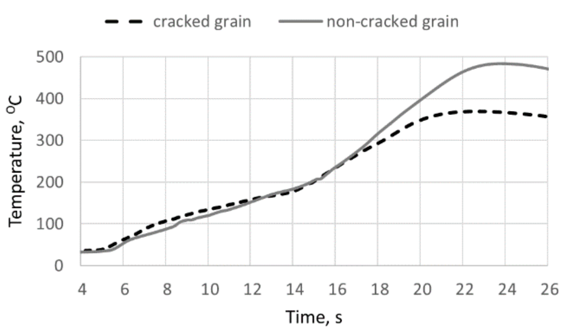


Fig. 10. Comparison of temperature in the critical section of nozzle insert of the first experiment

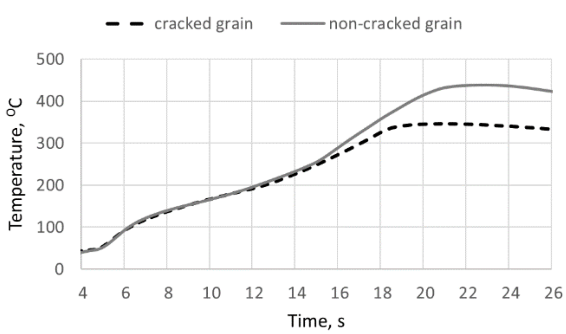


Fig. 11. Comparison of temperature in the post-critical section of nozzle insert of the first experiment

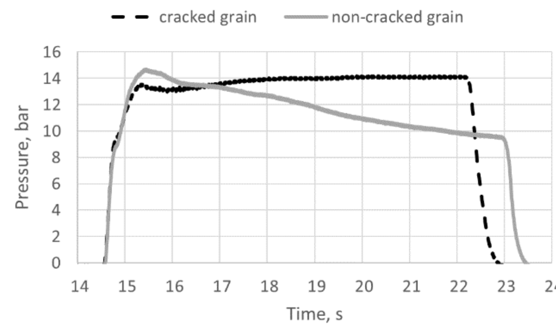


Fig. 12. Comparison of pressure in combustion chamber of the second experiment

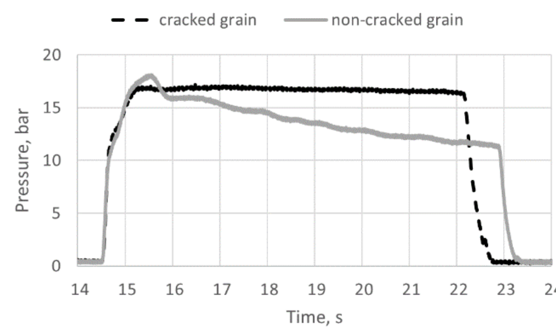


Fig. 13. Comparison of pressure in feeding line of the second experiment

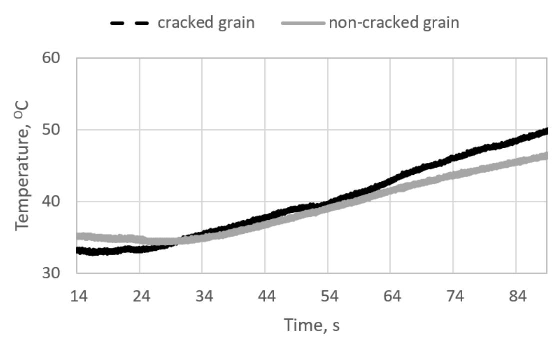


Fig. 14. Comparison of temperature on the external surface of grain of the second experiment

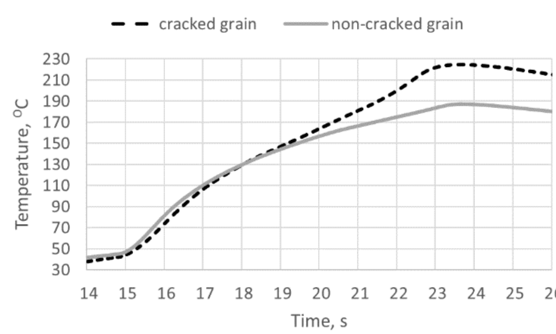


Fig. 15. Comparison of temperature in the post-critical section of nozzle insert of the second experiment

The shapes of cracked and non-cracked grains after hot-fire tests are shown in Figure 16 from the side of nozzle and in Figure 17 from the side of injection. Figures 18-19 give a detailed view of the burned-through sector of the cracked grain near the front of crack and the interface between paraffin layers in cracked and non-cracked grains. The evaluated O/F ratio for the test with cracked grain was 2.3 and for the non-cracked one – 1.7.

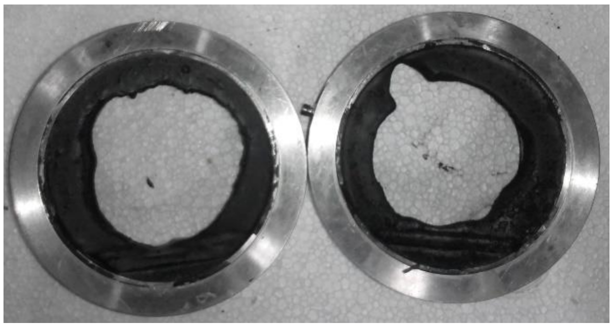
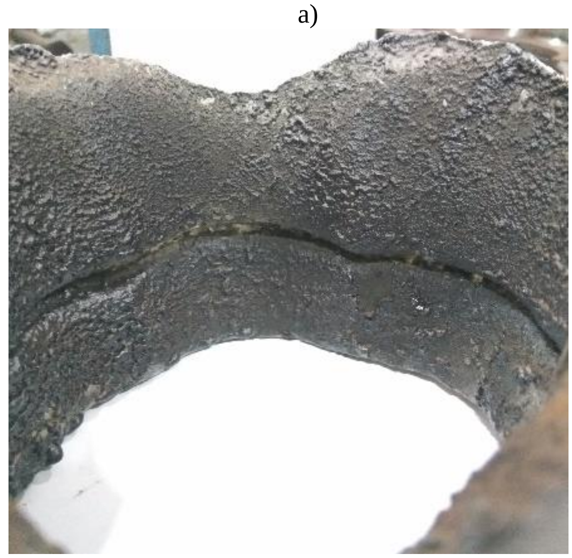


Fig. 16. The shapes of non-cracked (left) and cracked (right) grains in motor's casing from the side of nozzle (the second experiment)

Fig. 17. The shapes of non-cracked (right) and cracked (left) grains from the side of injection (the second experiment)

Fig. 18. Detailed view of burned-through sector with a crack in the paraffin grain

a)



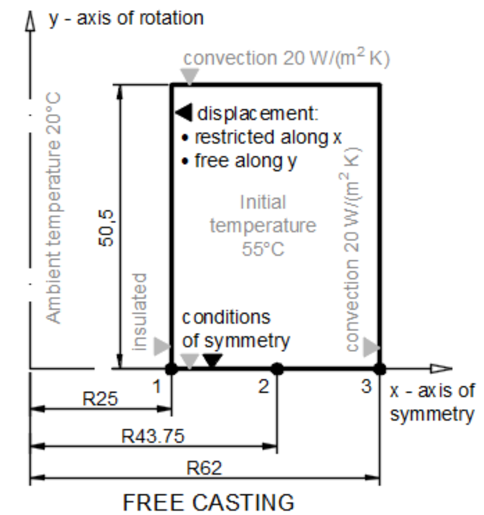
b)

Fig. 19. Circumferential fissure formed due to burning in the interface between paraffin layers in the cracked grain (a) and non-cracked grain (b)

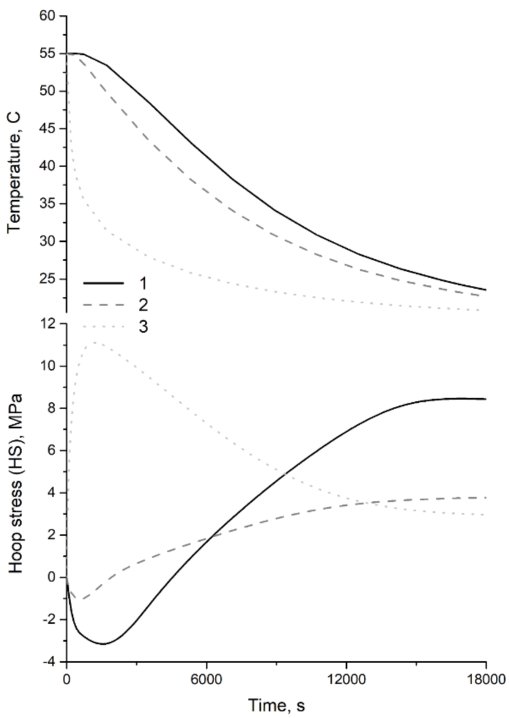
IV. DISCUSSION

To begin with, it is necessary to identify the reason of crack formation in the free-casted paraffin grain (Figure 1, a). It was considered that the crack appears due to thermal shrinkage of paraffin grain after casting, or by other words, due to elevated hoop stresses occurring as a result of cooling process.

The model was developed for finite element analysis (FEA), where the result of transient thermal analysis in form of temperature distribution in paraffin grain during cooling process with duration of 5 hours was used as one of the boundary conditions for structural transient analysis to determine hoop stress distribution. Figure 20, a shows a 2D axisymmetric model of a grain with dimensions taken from Figure 2, a after free casting.



a)



b)

Figure 20. The results of FEA for free casting: a) axisymmetric 2D model of paraffin grain with thermal and structural boundary conditions, b) distribution of temperature and hoop stresses in the model

In the suggested 2D model, at the initial moment of time paraffin with initial temperature of melting point 328 K (55°C) is placed into motor casing.

Due to free convection (heat transfer coefficient 20 $W \cdot m^{-2} \cdot K^{-1}$ and surrounding temperature 293 K) the grain begins to cool down principally through two end surfaces and external cylindrical surface (Figure 20, a). The last boundary condition does not describe a real process accurately, but it can be explained by initial contact with steel casing and subsequent shrinkage of the grain and detachment of its external cylindrical surface from metal casing. Insulated internal surface is ensured by the core (Figure 2, b) made from material with relatively low heat conductivity (thick-walled PVC tube was used to form a circular port in the tested grains). Because of non-uniform cooling (Figure 20, b), the outer layers of the grain (point 3) cool down rapidly, meanwhile internal layers are still hot, paraffin is in a highly plastic state and it is compressed by outer layers. Over time, internal layers (point 1) cool down but the core does not permit internal layers to shrink. As a result, cooled internal layers suffer high hoop stresses that lead to crack formation along radial direction of the grain. Crack formation does not occur at external layers at the beginning of cooling process ($\tau \approx 1500$ s), where the hoop stress have maximal value (point 3). Presumably, at this moment, the temperature of outer layers is still high and paraffin suffers plastic deformations.

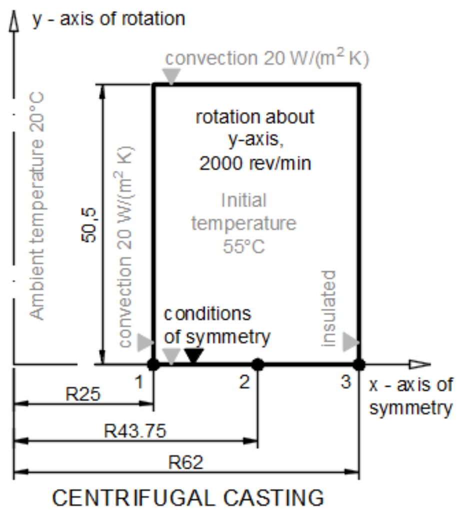
It is important to note, that the model is based on elastic properties of paraffin, thus it does not simulate accurately the cooling process of a grain, but can be used for preliminary evaluation of hoop stresses due to shrinkage. It is expected that stresses are greatly overestimated in the suggested model, since 1) viscoplastic properties of paraffin were not considered, 2) it was assumed that paraffin at initial moment of time is not liquid.

The following properties of paraffin, which are considered as independent of temperature, were used for FEA: Young's Modulus[4] 0.2 GPa, Poisson's ratio 0.499 (it is accepted that paraffin is practically incompressible), isotropic thermal conductivity[24] 0.15 $W \cdot m^{-1} \cdot K^{-1}$, specific heat[24] 2384 $J \cdot kg^{-1} \cdot K^{-1}$. Only coefficient of thermal expansion was considered as a function of temperature in FEA (Table 1).

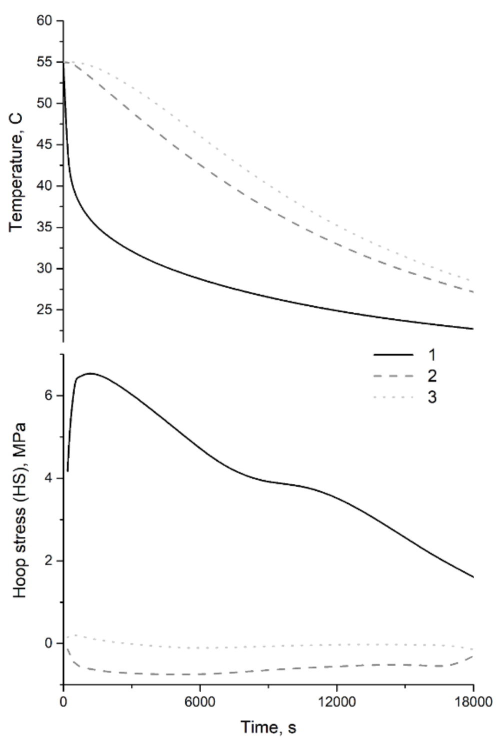
Temperature, K	CTE, 1/K
268	0.00044
271	0.00065
273	0.00065
278	0.00062
283	0.00071
288	0.00069
293	0.00071
298	0.00109
301	0.00191

Table 1: Coefficient of thermal expansion[25]

In the 2D axisymmetric model of centrifugal casting (Figure 21, a), thermal and structural boundary conditions are different from the ones of previous model: 1) external cylindrical surface of grain is insulated (casting directly into motor's casing with thermal insulation); 2) deformations for both internal and external cylindrical surfaces are not restricted (it is assumed that paraffin grain is not bonded to motor's casing while it contracts inwards due to thermal shrinkage).



a)



b)

Figure 21. The results of FEA for centrifugal casting: a) axisymmetric 2D model of paraffin grain with thermal and structural boundary conditions, b) distribution of temperature and hoop stresses in the model

In the case of centrifugal casting, fast cooling of internal layers provokes their contraction, which is restricted by hot outer layers. It causes high hoop stresses at the beginning of cooling process (Figure 21, b). These stresses are relaxed with time due to cooling and contraction of outer layers. In real process, these stresses should not be so high since outer hot layers deform plastically without preventing contraction of cooled internal layers. Since outer layers do not encounter any restrictions for contraction, the stresses here are close to zero.

The model explains absence of radial crack formation in a grain after centrifugal casting, but still requires detailed elaboration for accurate stress distribution. It is necessary to note, that rotational velocity does not have a great influence on final values of stresses.

Results of the first experiment show the influence of crack formation on the temperature on insulator's external surface (Figure 8): the temperature in cracked grain rises faster than in non-cracked grain after burning period. Inertia in temperature growth is due to presence of heat-insulator. Figure 9 shows the data on ambient temperature from thermocouple embedded into data acquisition system; there is barely visible reaction of the system on data collection process that does not have significant influence on instrument readings in comparison with instrument error ±2.2ºC of the thermocouples installed in test-motor. Ambient temperature in surroundings of test-bench does not have significant influence on the detected temperature difference also, since its initial value for the test with cracked and non-cracked grain is 34.4°C and 31.5°C respectively, i.e. difference in initial ambient temperature of the tests is less than 3°C.

It is obvious that the presence of crack diminishes the residual thickness of the paraffin grain, which serves as a thermal insulator. Thus, the local temperature of casing ahead of direction of crack propagation is higher, than in the casing with the non-cracked grain. The temperature difference after 60 seconds from the ignition moment is above 30°C that may cause unpredicted local overheating of the structural casing even in such small motor that was used for experiment. Afterwards the overheating may influence local structural integrity of motor casing.

The temperature difference can be even higher than the one revealed in the experiment because of the following principal reasons: 1) increase of burning time in a motor with a higher total impulse; 2) achievement of optimal O/F ratio that increases the temperature of gases in combustion chamber; 3) removal of heat insulator in grain's compartment and its compensation only by the walls of unburned paraffin with low heat conductivity.

Figure 6 shows that pressure in the test with non-cracked grain was higher than in the test with cracked grain, thus combustion process did not have influence on temperature difference. This pressure difference was caused by higher pressure inside the nitrous oxide cylinder (Figure 7) for the test with non-cracked grain (it can be explained by low quantity of oxidizer in cylinder and by order of test execution: the first test was with non-cracked grain). Higher pressure in the test with non-cracked grain apparently provoked higher temperature in critical and post-critical part of the nozzle insert (Figures 10 – 11) measured by thermocouples 6 and 7, whose position in motor shown in Figure 5.

Also by inspection of Figures 6 and 7, it becomes clear that the presence of crack does not affect the pressure in combustion chamber. However, the presence of crack could decrease the burning time.

In the second experiment, it was shown that temperatures on the external surface of paraffin grain are practically the same during burning process for both types of paraffin grain (Figure 14). It is the expected result, since in the cracked grain the temperature was measured at some distance from the crack's tip. The slight increase of temperature at the end of burning could be caused either by heat transfer in circumferential direction of the steel casing or by higher pressure in combustion chamber (Figure 12). Figure 15 shows that higher pressure in the test with cracked grain apparently provoked higher temperature in post-critical part of the nozzle insert measured by thermocouple 7. Like in previous experiment, the profiles of pressure curves of the combustion chamber are the same as in oxidizer feeding line (Figure 13).

Comparison of temperature data in post-critical part of nozzle insert given in Figures 11 and 15 shows that the curves from different experiments coincide within the error limits 5 – 10°C in the first 7 seconds of burning. Such behaviour indicates a good reproducibility of burning conditions in all fire tests of the study.

The shape of the burned grain in proximity of crack (Figures 16 – 18) gives a wrong perception that there is a rise of radial regression rate in vicinity of the crack. Regression rate of paraffin remains the same for all points of the grain; the burn-through that occurred in the grain was caused by entrance of oxidizer within crack. Thus, the burning occurs within cracks and this is contrary to what has been stated in references[19,20].

It is important to note that the interfaces between paraffin layers also have marks of intensified burning (Figure 19), although they are not so explicit like in the case of radial crack. The intensified burning was caused by small local structural discontinuities present in interface between layers in form of small voids and pores. The depth of the grooves is much less than the variation of residual thickness around the grain circumference; therefore, it is assumed that this type of structural defect cannot provoke significant changes in temperature of motor casing.

V. CONCLUSION

Considering the results obtained in the study, it is impossible to claim in general that cracks and other possible imperfections or discontinuities in solid propellant grain of a hybrid propulsion system have a significant influence on the burning process or may cause catastrophic malfunction of propulsion system. However, there were revealed some conditions in process of manufacturing, at which a radial crack is formed in a relatively small solid propellant grain and it was shown how the crack might cause a local overheating of structural casing and subsequently jeopardize structural integrity of the motor. Severity level of the radial crack is not high, since its formation does not lead to catastrophic failure like in a solid propulsion system. Application of structural materials insensitive to determined levels of temperature fluctuations, compensation by increase of insulator's thickness, implementation in solid grain crack-stoppers in form of intermediate circumferential layers are among possible solutions to avoid overheating of motor casing. Nevertheless, such solutions either increase weight of a motor or make a system more complicated, thereby prejudicing one of the most important advantages of a hybrid propulsion system.

It was shown also that presence of radial crack can change the initial shape of grain's port, since the burning occurs within crack.

Thus, the problem of crack formation in propellant grain of a hybrid propulsion should not be avoided or ignored, and requires more detailed analysis of structural integrity of a paraffin grain at various operating conditions. Also would be interesting to study how structural discontinuities of various types and sizes may affect the temperature distribution in a hybrid motor casing.

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