

Microcrystalline paraffin wax as fuel for Hybrid Rocket Engine

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Abstract

The use of the Hybrid Rocket Engines (HRE) overcomes several disadvantages typical of the solid or liquid rocket engines, especially since the paraffin-based fuels have solved the drawback of their low burning rates. Nevertheless, there is still a critical point to be solved regarding the manufacturing of the paraffin fuel grain, such as the formation of cavities, cracks and internal rips due to the shrinkage, which strongly invalidates the mechanical properties and structural integrity of the fuel grain. The present study aims to widely characterize the paraffin wax in order to acquire knowledge useful for the manufacturing of the fuel grain.

1. Introduction

Hybrid rockets are said to combine the advantages of solid and liquid rockets engines. In fact compared to a solid rocket the hybrid is much less sensitive to cracks and de-bonds in the propellant, has a higher specific impulse (Isp) and can be throttled including shutdown and restart on demand. Compared to liquid systems, the hybrid enjoys several advantages, such as the reduced explosion hazard due to the absence of an intimate mixture of oxidizer and fuel, and the absence of regenerative cooling systems for both the combustion chamber and nozzle. Lastly, unlikely a comparable hydrocarbon fueled liquid system, the Isp of HRE (Hybrid Rocket Engines) can be improved by using suitable additives. Additionally, the last generation of fuel for HRE, i.e., the paraffin wax, overcomes one of the few disadvantages of HRE concerning their low burning rates, since it forms a thin, hydro-dynamically unstable liquid layer on the melting surface of the fuel, enhancing the regression rate with entrainment of droplets from the liquid-gas interface. Among the paraffin wax, the microcrystalline formulation, being composed of a predominance of non-linear hydrocarbons, has the advantage to form microcrystals, which guarantee a higher tenacity and then a better workability in comparison to the linear paraffin waxes.

This paper reports a wide characterization of the SASOL 0907 paraffin wax with the aim to acquire the suitable know-how to build-up a paraffin grain without critical defects. In fact, as known [1], the worst case in the manufacturing of paraffin grains is to start from the pure paraffin rather than paraffin with additives, due to the high volumetric shrinkage (about 20-25%) during the cooling of the melted paraffin. This shrinkage causes the formation of cavities, cracks and internal rips, even though the outside grain seems good after unmolding, which strongly invalidate the mechanical properties and structural integrity of the fuel grain, leading to catastrophic failure due to the strong thermal (temperature of about 3300 K) and mechanical (pressure of about 40 bar) loads during the firing tests. For this reason, it is vital to carry out a preliminary wide characterization of the paraffin, devoted to highlight the thermal, physical and mechanical behaviours, knowledge useful to manufacture the paraffin grain. Therefore, Differential Scanning Calorimetry (DSC) was performed with the aim to find out the phase transitions of the selected SASOL 0907 paraffin wax, such as fusion and crystallization behaviours, in order to support the activity devoted to the manufacturing of the paraffin grain. Aimed to highlight the decomposition behaviour and thermal stability of the selected SASOL 0907 paraffin wax, Thermo-Gravimetric Analysis (TGA) was performed, in air and nitrogen atmospheres. Measures of surface tension σ and viscosity μ of the liquid SASOL 0907 paraffin fuel were carried out

in order to assess the entrainment contribution to the mass flow rate, $\dot{m}_{entr} \propto \frac{p_{dyn}^\alpha h^\beta}{\mu_l^\gamma \sigma^\pi}$ where, according to Karabeyouglu [2], [3], p_{dyn} is the dynamic pressure, h the thickness of the melt layer, σ the surface tension and μ_l the melt layer viscosity. Exponents values α , β , γ , π can be found in literature from Gater and L'Ecuyer [4], Nigmatulin et al. [5], and Karabeyouglu [2]. Rheological measurements were carried out using a rotational parallel plate rheometer configuration with the aim to study the viscoelastic properties of paraffin wax in the solid state. This wide characterization was useful to identify the suitable method for the manufacturing of the paraffin grain. In detail, several approaches have been considered, e.g., the slow and controlled solidification under vacuum condition of the molten paraffin wax, or the use of a metallic box, heated through electrical resistance and pressurized with oleodynamic piston, which melt the paraffin pellets with the combined actions of temperature and pressure. Studies have demonstrated that the casting method is not sufficient to guarantee the absence of critical voids and defects. Firing

tests are foreseen on cylindrical grains having length of 25 cm and diameter of 7 cm in order to validate the manufacturing process and to assess the regression rate for the selected fuel paraffin.

2. Solid Fuel formulations

Four different waxes are considered as potential fuels for hybrid rockets, i.e., H1, C80, 3006 and 0907, all manufactured by the SASOL[®]. They are composed of linear (n), and branched (iso) hydrocarbons, in different percentages, as sketched in Figure 1, the distribution of molecular weights being centred around different values, as shown in Figure 2, where percentages higher than the 10wt% of the maximum abundance is reported as a function of the carbon number, for both linear and branched fractions. Table 1 reports the wax properties declared by the manufacturer SASOL[®] in terms of melting and congealing points, penetration and viscosity. It appears that the H1 formulation consists predominantly of linear alkanes having a large distribution of the molecular weights, i.e., ranging between C₃₂ and C₉₇ centred on C₆₅. SASOL[®] 6003 has an abundance of linear alkane's chains with respect to the branched alkanes, but both molecular weight distributions, i.e., linear and branched alkanes, are centred on the same values. Unlike the other paraffins, the formulation SASOL[®] 0907 is predominantly composed of branched alkanes, whose content is also the highest. Additionally, the molecular weight distribution of the SASOL[®] 0907 branched alkanes is centred on the highest value. For all these reasons, the SASOL[®] 0907 was selected as fuel for hybrid rockets.

Table 1: Wax properties declared by the manufacturer SASOL.

Wax	Melting or dropping point [°C]	Congeaing point [°C]	Oil content [%]	Penetration @ 25°C [1/10mm]	Kinematic viscosity @ 100°C [mm ² /s]	Brookfield viscosity @ 135°C [cP]
H1	112	96-100	-	1	-	6-8
C80	88	78-83	-	6	9.4	-
6003	-	60-62	0-0.5	17-20	-	-
0907	88-102	83-94	0-1.5	4-10	14-18	-

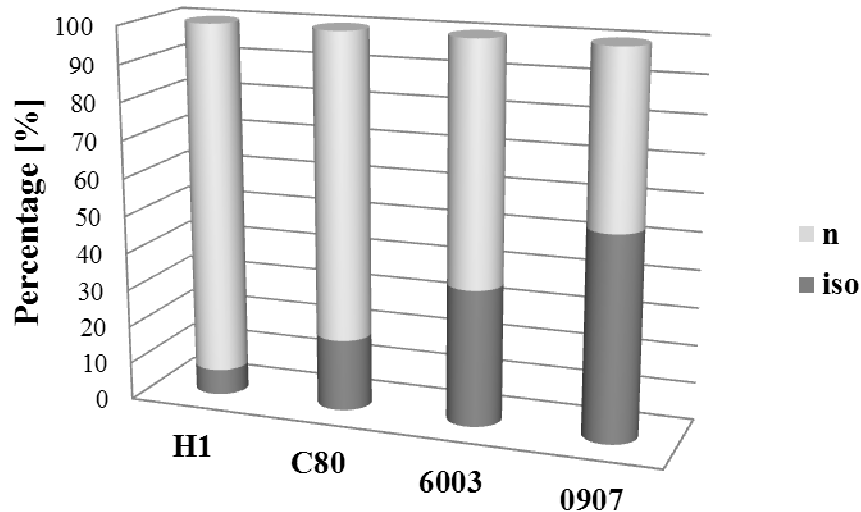


Figure 1: Content of linear (n) and branched (iso) alkanes.

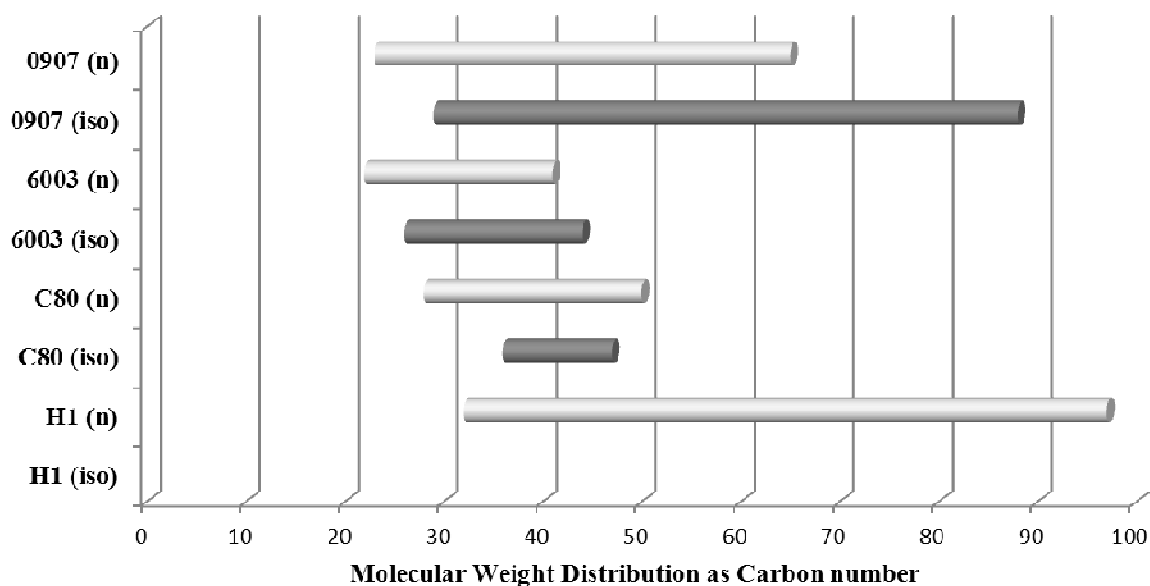


Figure 2: Molecular weight distribution (higher than the 10wt% vs the maximum abundance) as Carbon number in linear (n) and branched (iso) fractions.

The high fraction of branched iso-alkanes might confer the advantage to form microcrystals, which guarantee higher fracture toughness and then a better workability in comparison with the linear paraffin waxes. In fact, according to the Griffith theory [6], more elevated fracture toughness allows the application of higher critical stress on the solid grain, provided that the critical size of internal micro-cracks and of other microstructural defects, voids, and rips are kept constant.

3. Experiments

3.1 Differential Scanning Calorimetry (DSC)

The Differential Scanning Calorimetry (DSC) measurements were performed with a DSC Q20 of TA Instruments, following the test matrix summarized in Table 2. In order to have a suitable baseline for the integration, each test was performed first of all cooling the paraffin wax down to 0°C, and then heating it up to 120°C at different heating rates, i.e., 2, 10 and 40°C/min. Aimed to study the effect of the cooling rate on the formation of the paraffin crystals, the SASOL® 0907 paraffin wax was heated at 10°C/min, then cooled at different cooling rates, namely 2, 10 and 40°C/min, and then re-heated at 10°C/min.

In Figure 3 results related to the different heating rates of paraffin pellets are shown. It highlights that the slower is the heating rate the more defined and shifted at lower temperatures are the melting peaks. Nevertheless, in spite of the heating rates, the thermograms overall profile shapes do not change, whereas the shift in temperature and the sharpness of peaks could be largely ascribed to the thermal inertia of the paraffin wax occurring when it is heated at high heating rates. Figure 4 shows the thermograms corresponding to the different cooling rates of paraffin melted at 10°C/min. It is worth noting that no relevant differences can be observed. Finally, Figure 5 highlights that the thermograms related to the heating at 10°C/min after different cooling rates, are quite overlapped upon the overall temperature range, except at about 90-100°C, which could be due to the melting process of the alkanes at highest molecular weights.

The three melting peaks (see values in Table 3) correspond to the maxima of the molecular weight distributions of linear and branched alkanes (data not shown for brevity). These melting peaks differ slightly from those reported in literature [6], since at a heating rate of 10°C/min a value of $T_{m,1}$ equal to 67°C instead of 59.7°C; $T_{m,2}$ equal to 81°C instead of 82.1°C, and $T_{m,3}$ equal to 97°C instead of 98.9°C [7] were obtained. Slight differences appear also during the cooling ramp, therefore a value of 54°C instead of 47.1°C for the $T_{c,1}$, a value of 74 instead of 70.0°C for the $T_{c,2}$,

and a value of 83 instead of 83.8°C for the $T_{c,3}$, were assessed. The wide melting and solidification ranges are due to the high percentage of branched alkanes which gradually undergoes the phase transition [7]. In summary, lesson learned from these analyses is that at atmospheric pressure the paraffin pellets are completely melted at 110°C, independently from the heating rate, and that the thermal treatment used to manufacture the fuel grain once melted slightly affect the crystals structure.

Table2: DSC test matrix.

Test	Heating rate [°C/min]	Cooling rate [°C/min]	Heating rate [°C/min]
1	10	2	10
2	10	10	10
3	10	40	10
4	2	-	-
5	40	-	-

Table 3: Parameters obtained from DSC measurements.

Heating/Cooling rate [°C/min]	$T_{m,1}$ [°C]	$T_{m,2}$ [°C]	$T_{m,3}$ [°C]	$T_{c,1}$ [°C]	$T_{c,2}$ [°C]	$T_{c,3}$ [°C]
2	60	78	102.5	54	74	85
10	67	81	97	54	74	83
40	87	95.5	-	51	67	77

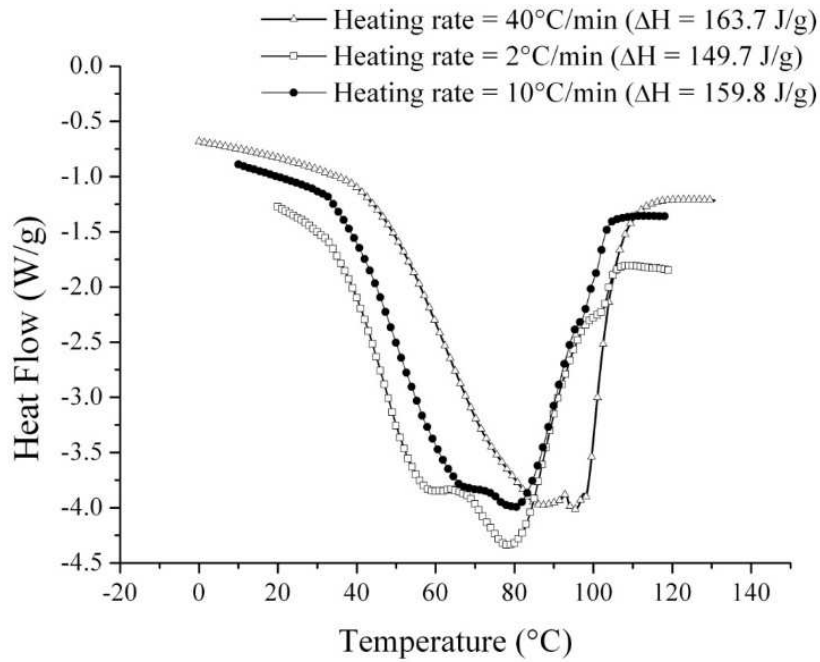


Figure 3: DSC thermograms at different heating rates.

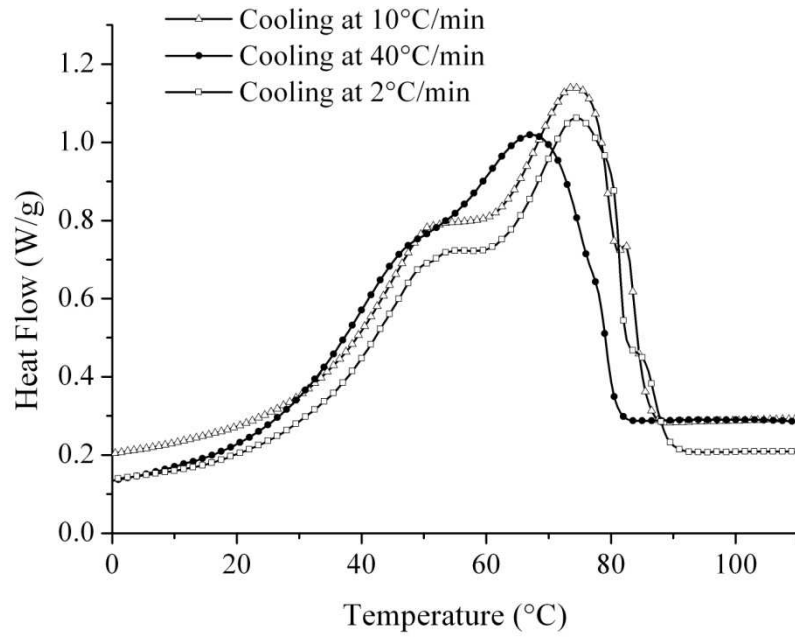


Figure 4: DSC thermograms at different cooling rates.

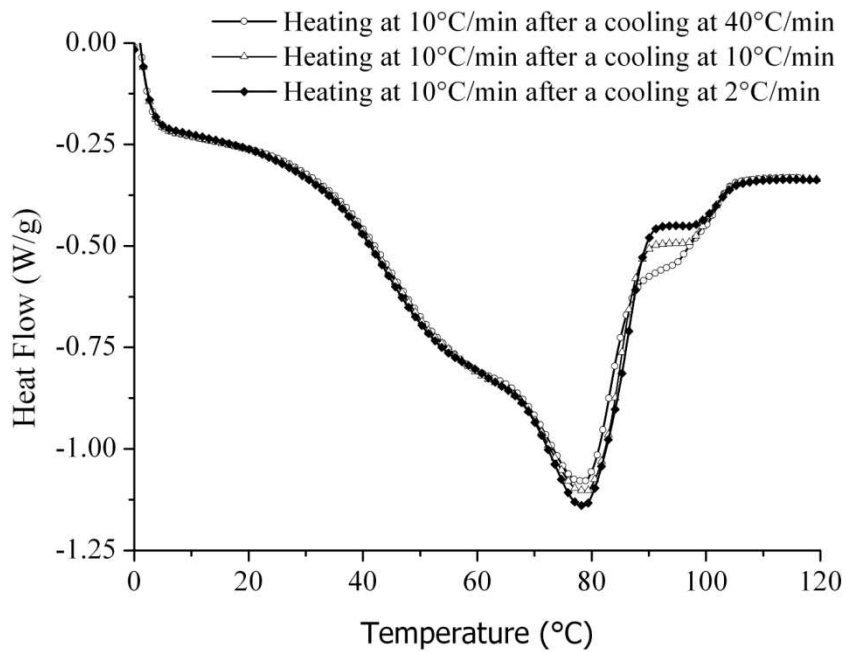


Figure 5: DSC thermograms at 10°C/min of samples cooled at different cooling rates.

3.2 Thermo-Gravimetric Analysis (TGA)

Thermo-Gravimetric Analyses (TGA) was performed using a Discovery TGA by TA Instruments, heating the paraffin wax from 40°C to 700°C at a 10°C/min, in both nitrogen and air controlled atmospheres. Results (Figure 6 and Figure 7) show that weight losses at temperatures less than 120°C are negligible, speaking in favour of the safety workability of this paraffin wax, since volatile elements are almost absent. The thermo-gravimetric analysis performed in nitrogen atmosphere (Figure 6) shows a narrow and well-defined thermal event, which is the boiling point of the paraffin wax. From the analysis performed in air atmosphere (Figure 7) it highlights that, after the main oxidative degradation at about 300°C, there is a significant residual ascribed to the formation of ashes, hard to further oxidize before 550°C, which could affects the re-ignition of the fuel grain.

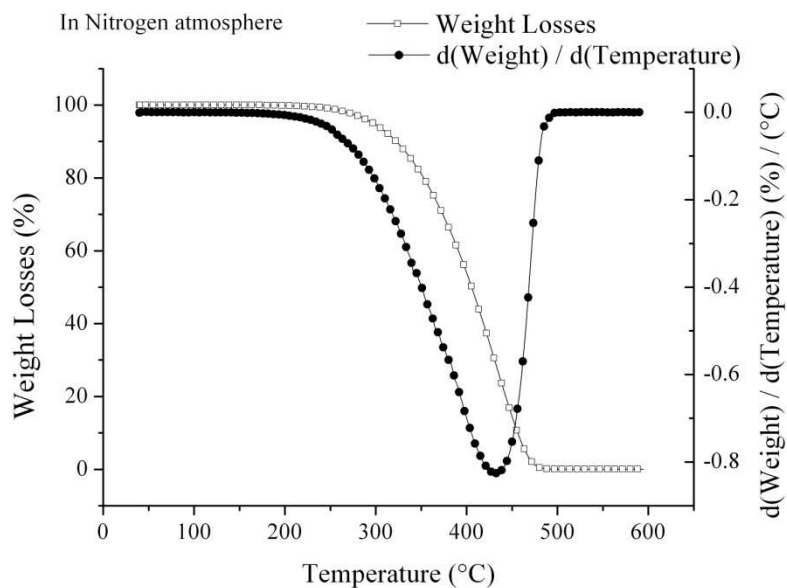


Figure 6: TGA in Nitrogen atmosphere.

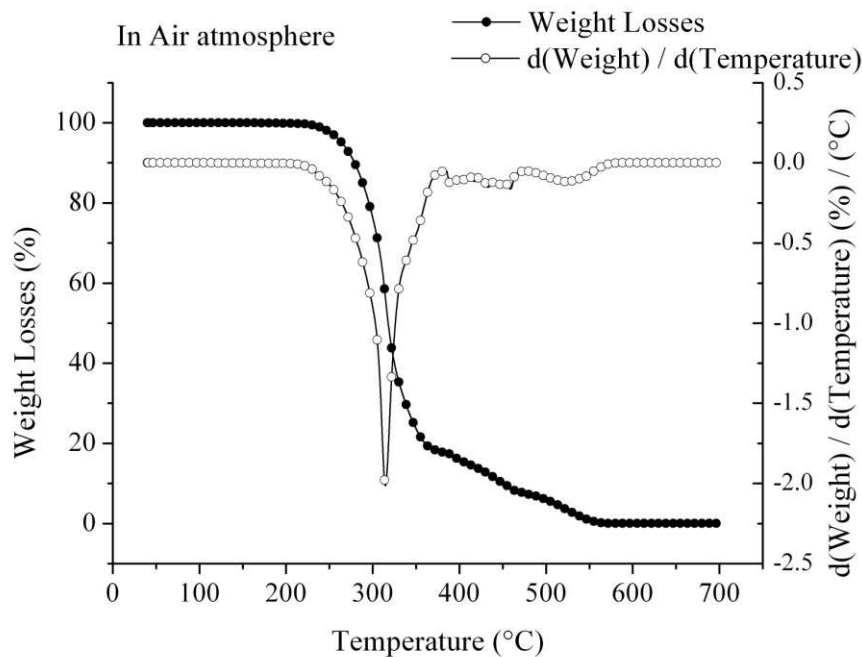


Figure 7: TGA in air atmosphere.

3.3 Rheological and viscosimetric measurements

It has been supposed [2] that the melt layer viscosity should have a greater influence on the regression rate than the surface tension. For this reason, the fuel viscosity has been evaluated in detail. The viscosity measurements were performed using a HR-2 Hybrid Rheometer by TA Instruments. The sample was placed between two parallel plates, with 40mm diameter and 500µm gap distance, one of which was forced to oscillate during heating. The response of the torsion bar and the degree of twist gave the shear stress, while the rotational speed and plate dimensions gave the shear rate. To evaluate the frequency range where the SASOL[®] 0907 highlights a Newtonian behaviour, a preliminary oscillatory shear test was carried out. This test consisted of a sweep frequency between 0.1 and 100 Hz [8] at a fixed temperature of 150°C, temperature at which the SASOL[®] 0907 is completely melted. Results showed a Newtonian behaviour of the paraffin wax over the entire frequency range (data not shown for brevity). The complex viscosity is, then, frequency independent and equal to the Newtonian shear viscosity determined by a continuous flow test. Therefore the melt layer viscosity of the fuel grain is independent of any flow condition inside the rocket combustion chamber. A conventional frequency of 1Hz was then selected for the temperature ramp measurements, with the aim to characterize the viscoelastic properties of paraffin in the solid state before melting. To this end, the paraffin wax was heated from 30°C to 80°C at a heating rate of 2°C/min (Table 4). Results were compared with the calorimetric curve in Figure 8, highlighting that, as expected, the storage modulus falls down in correspondence of the first melting peak at about 70°C, where the maximum value of the loss moduli occurs, meaning that the SASOL[®] 0907 paraffin wax has not capability to preserve its elastic response once softened. In the solid state the paraffin wax has a storage modulus of $1.7 \cdot 10^6$ Pa.

In order to characterize the viscosity of the paraffin wax in the liquid state and provide a basis for further extrapolation at high temperatures, an oscillatory shear test was performed setting the frequency at usual value of 1 Hz and quickly heating the paraffin wax from 100°C to 200°C at a rate of 20°C/min (see Figure 9). As determined previously, the measured complex viscosity is frequency independent and therefore equal to the Newtonian shear viscosity determined by a continuous flow test. The value of viscosity to introduce in the $\dot{m}_{entr}$ formula should be evaluated at an average temperature ranging between the melting and boiling (about 450°C) temperatures, calculated using equation from Marano and Holder[9],[10]. Since it is not possible to perform the measure at so high temperature, the value of viscosity has to be extrapolated starting from values of complex viscosity obtained in the range 100-200°C, using the asymptotic behaviour correlations (ABC) attributed to Kreglewski and Zwolinski [9], [10]. This is a method which predicts PVT, thermal and transport properties of n-paraffins and n-olefins; nevertheless, it has been demonstrated that it could be successfully applied to branched alkanes if the length of branched chains are limited [9]. The Newtonian behaviour of the liquid SASOL[®] 0907 paraffin suggests that the branched length chains are short enough to not affect the rheological outputs. Indeed, it has been demonstrated that in this case the viscosity errors are limited to 8% [10]. According to the ABC method, the viscosity can be assessed using the following equations:

$$Y = Y_{\infty,0} + \Delta Y_{\infty}(n - n_0) - \Delta Y_0 \exp(-\beta(n - n_0)^{\gamma}) \quad (1)$$

$$\Delta Y = A + B/T + C \ln T + DT^2 + E/T^2 \quad (2)$$

where Y is the property value, namely viscosity, at a carbon number n, Y_0 is the property pseudo-value at $n=0$, Y_{∞} is the limiting property value as n becomes very high, β and γ are adjustable parameters, A, B, C, D, and E, are temperature dependent ABC parameters, listed in [10]. The viscosity was assessed at the temperature of 280°C, assumed as initial combustion chamber temperature, which is the average temperature between the melting and the boiling (i.e., about 450°C) points. In this regards, a melting point equal to 110°C (see Figure 3) has been considered to be sure that all crystals were molten. As reference temperature the highest available experimental value, i.e., 200°C has been used. The value of viscosity at 280°C, calculated using the ABC method, is equal to $0.3747 \cdot 10^{-3}$ Pa s.

Table 4: Rheological test matrix.

Test	$\dot{\gamma}$ [Hz]	$T_{initial}$ [°C]	T_{final} [°C]	Heating rate [°C/min]
1	1	30	80	2
2	1	100	200	20

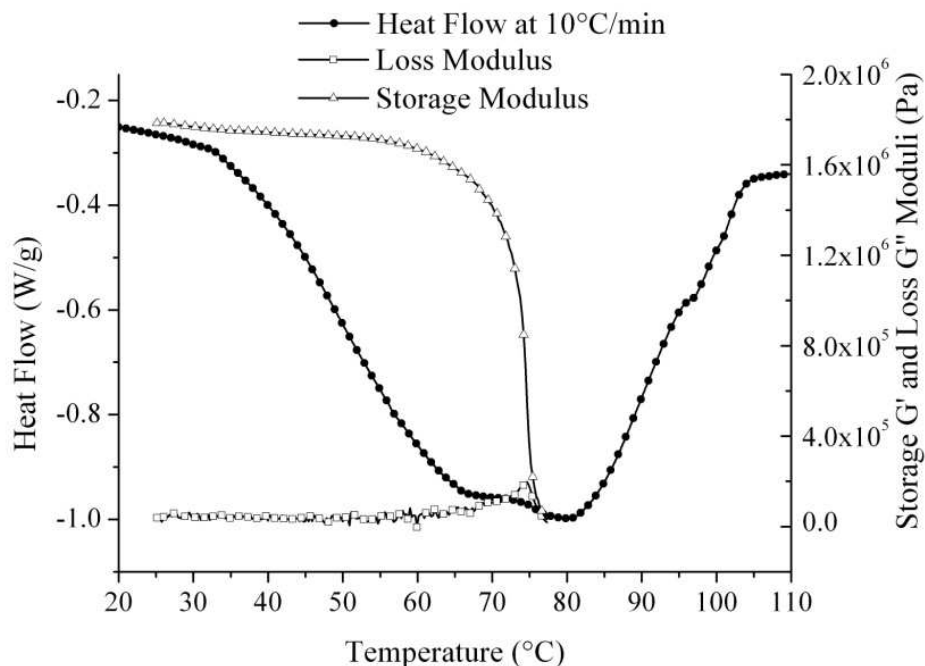


Figure 8: Comparison between rheological and calorimetric behaviour as a function of the temperature.

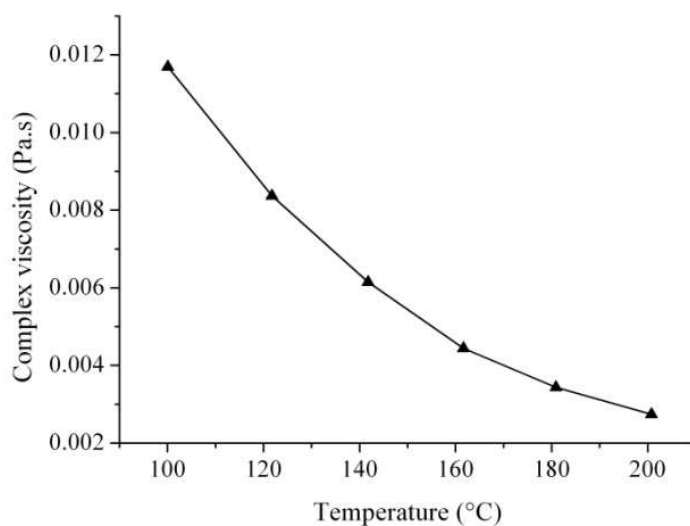


Figure 9: Rheological behaviour of the liquid SASOL® 0907 paraffin wax.

3.4 Surface tension

The surface free energy was calculated according to the Owens-Wendt method [11]. The Owens-Wendt approach is one of the most commonly used methods to calculate the surface free energy of materials [12]. The principal assumption of this method is that the surface free energy is the sum of the two components: the dispersion and the polar components [13]. The Owens-Wendt model is represented by the geometric mean relationship:

$$\frac{1}{2}(1 + \cos\theta)\gamma_L = (\gamma_S^D \cdot \gamma_L^D)^{\frac{1}{2}} + (\gamma_S^P \cdot \gamma_L^P)^{\frac{1}{2}} \quad (3)$$

where θ is the contact angle between the liquid droplet and surface, γ_L the liquid total surface tension, γ_L^D the dispersion component of liquid surface tension, and γ_L^P the polar component of liquid surface tension. The unknown terms in the equation are γ_S^D , which is the dispersion component of the solid surface free energy, and γ_S^P , namely the polar component of the solid surface free energy. The value of total surface free energy of the solid is obtained as $\gamma_S = \gamma_S^D + \gamma_S^P$. Dividing by $(\gamma_L^P)^{\frac{1}{2}}$ the equation (1) can be re-written as:

$$\frac{\frac{1}{2}(1+\cos\theta)\gamma_L}{(\gamma_L^P)^{\frac{1}{2}}} = \left(\frac{\gamma_L^D}{\gamma_L^P}\right)^{\frac{1}{2}} \cdot (\gamma_S^D)^{\frac{1}{2}} + (\gamma_S^P)^{\frac{1}{2}} \quad (4)$$

The left-hand side of equation (4) contains quantities which are measured experimentally (θ) or which are available in the literature (γ_L^P, γ_L), so that a plot of the left-hand side of equation (4) versus quantity $\left(\frac{\gamma_L^D}{\gamma_L^P}\right)^{\frac{1}{2}}$ gives a straight line with slope $(\gamma_S^D)^{\frac{1}{2}}$ and intercept $(\gamma_S^P)^{\frac{1}{2}}$.

Table 5: Surface tension measurements.

Wettability [°]	87.06±7.4
Surface Free Energy [mJ/m²]	34.77
Dispersion component [mJ/m²]	33.49
Polar component [mJ/m²]	1.27
Work of Adhesion paraffin-water [mJ/m²]	76.58

The surface free energy was measured on solid paraffin sample, realized starting from pellets of SASOL[®] 0907, putting them in a silicone mold and then melted at 100°C. The paraffin sample was solidified very slowly in order to avoid possible macro and micro cracks due to transition. Through this procedure it is possible to realize a paraffin sample with a very smooth surface, therefore the measured surface free energy will depend only on the chemical state of the paraffin, and not on its morphology. In fact, during the melting process, it is evident that a very smooth layer of melted pellets paraffin is obtained due to the surface tension of the liquid paraffin. It is highlighted that the surface tension is related to the liquid paraffin whereas surface free energy is referred to the solid paraffin. In both cases the two performance indexes are the same and they can be compared. The surface free energy is expressed in [J/m²] which is equal to [Nm/m²] whereas the surface tension is measured in [N/m], therefore the two performance indexes can be compared. In order to obtain the surface tension value at high temperature, i.e., corresponding to the liquid state of SASOL[®] 0907 paraffin wax, a measure at 20°C of the surface tension of the solid paraffin wax has been carried out, giving in output a value of 34.78 mN/m. This value is in a good agreement with the corresponding value, i.e., 33.8 mN/m, obtained extrapolating in a linear way (see Figure 10) the surface tension values measured by Kobald et al. [8], meaning that the value of 27.5mN/m at 110°C can be used.

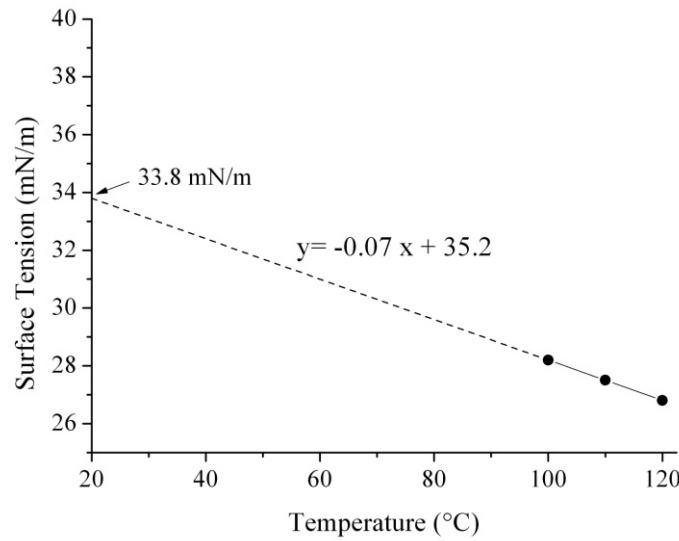


Figure 10: Surface tension as a function of the temperature.

Aimed to assess the surface free energy of SASOL[®] 0907 paraffin wax, measurements of contact angle using liquid having different polarities, i.e., water, formamide and diiodomethane, have been performed. Results, shown in Figure 11 and summarized in Table 5, highlight the shape of liquid droplets on the paraffin wax surface. It is worth noting that water droplet on the SASOL[®] 0907 paraffin wax surface describes a partially hydrophobic behaviour. This was confirmed also analysing the contact angle measurements on formamide, partially polar liquid with respect to the water, whereas the diiodomethane has a hydrophilic behaviour due to its apolar nature. The angle values are averaged on ten measurements carried out for each liquid.

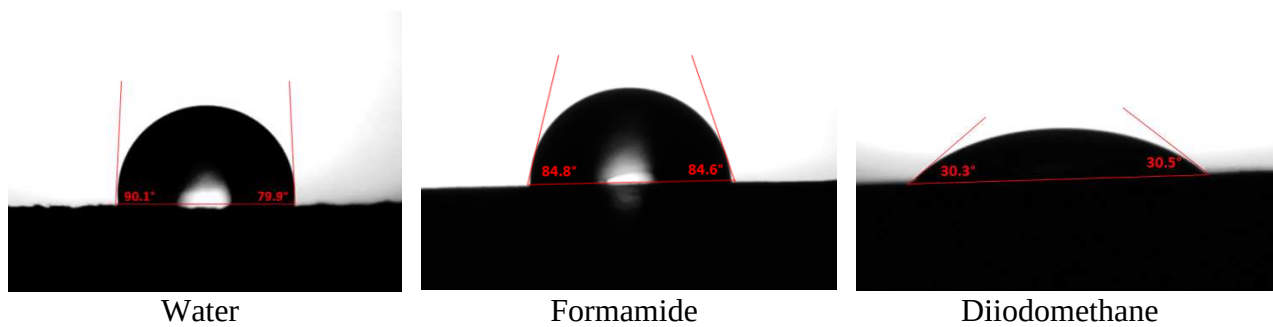


Figure 11: The three different shapes of the liquid droplets (distilled water, formamide and diiodomethane) in contact with the paraffin sample.

3.5 Grain manufacturing

The fabrication of the fuel grain is a critical point of the overall manufacturing process because the possible presence of internal or surface flaws and/or cracks can lead to the catastrophic failure of the motor as a consequence of the strong pressure and temperature loading during combustion. Paraffin wax is particularly sensitive to this kind of problem for three fundamental reasons:

- the intrinsic brittle nature of this thermoplastic material;
- liquefied paraffin wax tends to form internal voids;
- volumetric shrinking of about 15 – 25%, depending on the grade of wax, when transitioning from liquid to solid as reported in literature [14].

Moreover for a grain of large size, possible scale effect can appear mainly due to the increased influence of the thermal gradients inside the grain. To overcome these challenging difficulties, three main solutions could be proposed based on the use of:

- central piston, slipping inside the mould, for keeping the liquid paraffin wax into compression [15];
- suitable insulating mould with only one thermal conductive surface for slowing the cooling and the resulting re-solidification process[1].
- special spin casting machine with a variable rotational speed also useful for the creation of the central port[16].

The best method might be the application of both mechanical and thermal energy, i.e., pressure and heat flux, through a special designed equipment aimed to oppose the effect due to the spontaneous volumetric shrinking occurring during cooling and transition from liquid to solid state. In fact, the use of insulating mould has experimentally demonstrated to be not sufficient to guarantee a homogeneous and dimensionally accurate solid grain without macro-voids, cracks, rips and other surface and internal flaws even detectable by naked eyes, as shown in Figure 12. On the other hand, the centrifugal casting process requires an expensive machine and also a not trivial optimization of the manufacturing process parameters, e.g., spinning rate. Therefore, its use is more justified only in the industry sector for high volume production.



Figure 12: Internal surfaces after sectioning of paraffin wax solid grains manufactured without application of external pressure.

Therefore, the best method developed in the present work consists in the application of both pressure and thermal flux, following the main steps:

- the starting point is the raw material in the form of commercially available pellets of SASOL® 0907 paraffin wax;
- inserting the pellets inside a cylindrical mould equipped with embedded electrical resistance heating system and temperature measurements through a K type thermocouple;
- heating the raw material up to a temperature of 120°C that, as demonstrated by means of DSC analysis, is sufficient to complete the melting of the solid pellets;
- holding the temperature of 120°C for the time required for liquefying all the paraffin wax pellets;
- stirring the melt;
- switching off of the electrical resistance heating system;
- application of a pressure of about 10 bar by means of cylindrical piston fitted with a load cell for monitoring the applied compression force;
- slow cooling up to room temperature.

This manufacturing method has been accomplished by the use of special designed equipment illustrated in Figure 12 based on the application on a weight lifter of a suitable device for transforming the tensile force component exerted by the crane hook during the lifting phase into a compression force of two opposing plain surfaces. The counter-posed faces of the weight lifter have been adjusted for placing the heated mould and the corresponding piston equipped with the load cell. A load of 300 kg has been set. This value, considering the surface area of the melted paraffin wax, is equivalent to a pressure of about 10 bar, kept constant by means of suitable working of the

hydraulic system. The tight coupling tolerances among the mould components have allowed the outgassing of air entrapped inside the paraffin wax during the heating and stirring steps.



Figure 12: Metallic box, heated through electrical resistance and pressurized with oleo-dynamic piston used to manufacture the paraffin grain.

Satisfactory results have been achieved through this manufacturing method i.e. fabrication of homogeneous, fully densified solid grains without appreciable surface and internal micro-cracks and other geometrical defects as shown in Figure 13.



Figure 13: Picture of the paraffin grain manufactured with the heated and pressurized metallic box.

3.6 Optical microscopy

In order to evaluate the compactness and porosity of the paraffin grain, obtained using the heated-pressurized method, it was broken and the two surfaces of fracture were analyzed. Macro-fractography was performed using a stereo microscope LEICA MZ-12X, whereas the micro-fractography was realized using an optical microscope LEICA DM-RXE in bright field and using an optical magnification of 550X.

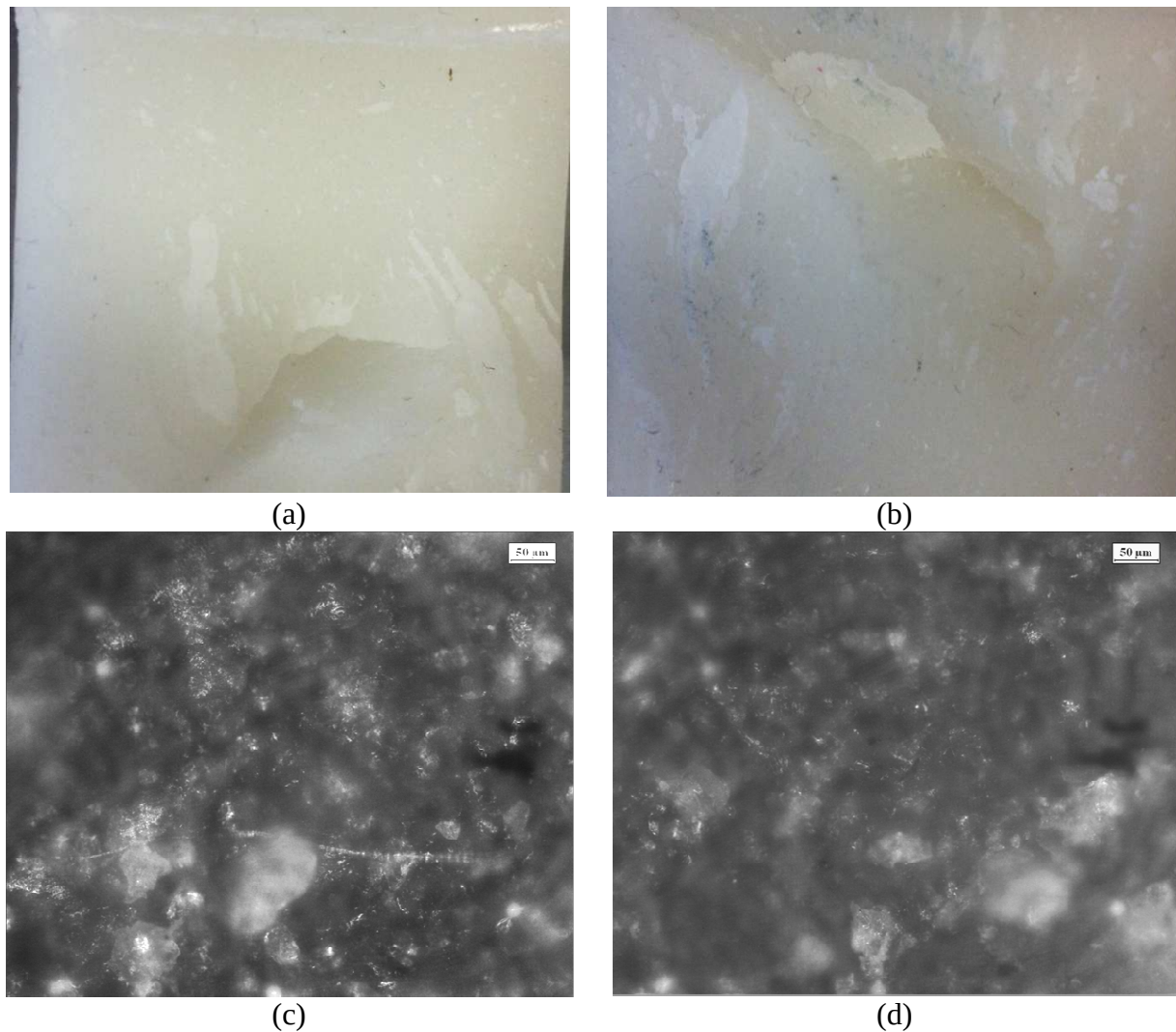


Figure 14: (a) Surface fracture of the broken concave paraffin sample, magnification 20X. (b) Surface fracture of the broken convex paraffin sample, magnification 20X. (c) Surface fracture of the broken concave paraffin sample, magnification 550X. (d) Surface fracture of the broken convex paraffin sample, magnification 550X.

Analyzing the surface fracture of the two half parts of paraffin grain (see Figure 14(a) and (b)), the absence of porosity is evident, since they seem compact and uniform. A further confirmation of this last statement could be done analyzing the images at highest magnification in Figure 14 (c) and (d). In fact no defects, inclusion or shrinkage phenomena are present within the material of the two half parts. This confirms the high quality obtained during the manufacturing of the paraffin grain.

4. Conclusions

Among the available paraffin waxes the SASOL[®] 0907 was selected due to its capacity to form micro-crystals which guarantee high fracture toughness and then a better workability. To achieve a better comprehension of the selected paraffin wax a wide thermal and rheological characterization was carried out. In details, thermal analyses, i.e., DSC and TGA, gave information about the phase transitions and thermal and thermo-oxidative stabilities. Results show that at atmospheric pressure the paraffin pellets are completely melted at 110°C, independently from the heating rate, and that the thermal treatment used to manufacture the fuel grain once melted slightly affect the crystals structure. This information has been used to manufacture the fuel grain. Among the explored methods, that which combines the effect of temperature and pressure allows to avoid the formation of voids and cracks. Surface tension and viscosity measurements have been carried out with the aim to assess the $\dot{m}_{entr}$ -contribution to the overall regression rate of the paraffin fuel grain.

5. References

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