Rheological, Optical And Ballistic Investigations Of Paraffin-Based Fuels For Hybrid Rocket Propulsion Using a 2D Slab-Burner

Mario Kobald^{*}, Elena Toson^{**}, Helmut Ciezki^{*}, Stefan Schlechtriem^{*}, Serenella di Betta^{**}, Matteo Coppola^{**} and Luigi De Luca^{**}

> *Institute of Space Propulsion DLR - German Aerospace Center D-74239 Hardthausen, Germany

**Space Propulsion Laboratory Aerospace Engineering Dept. Politecnico di Milano, I-20156 Milan, MI, Italy

Abstract

This paper describes combined rheological, ballistic and optical analyses performed on paraffin-based mixtures that can be used as high regression rate hybrid rocket fuels. Experimental activities have been done at the DLR Institute of Space Propulsion in Lampoldshausen and at Space Propulsion Laboratory (SPLab) of Politecnico di Milano [1]. This paper describes in detail the experiments performed at the DLR. Viscosity, surface tension and regression rate of the fuels have been determined. Furthermore the combustion was evaluated by optical measurements. Data collected so far indicates an increasing regression rate for decreasing viscosity of the liquid paraffin.

1. Introduction and theory

Hybrid rocket engines are said to combine the advantages of solid and liquid propulsion systems: simple and safe storability due to separately stored oxidizers and fuels, straightforward control of mixture ratio by variation of the oxidizer mass flow and the possibility for immediate shut-down by closing the oxidizer's main valve. Compared to solids they offer a higher specific impulse and thus more payload capability. Applications of hybrid rocket engines can be in small and medium sized sounding rockets or also as upper stages. Such programs exist in a large variety at different universities and companies worldwide. The most well-known example clearly shows the advantages and possibilities of hybrid rocket engines: Space Ship One by Scaled Composites achieved the first privately funded suborbital flight in 2004.

In the past hybrid rocket engines have been blamed for their relatively low regression rate compared to solid rocket engines. For high thrust long fuel grains with multiple ports are necessary which results in a low volumetric efficiency [2]. Carrick and Larson evaluated cryogenic solid hybrid rocket fuels [3, 4, 5]. They used cryogenic solid n-pentane and measured regression rates 5-10 times higher than polymeric hybrid fuels. Following these studies tests have been done at Stanford University with hydrocarbons with longer chains that are solid at ambient temperature [6]. These fuels are paraffin-based hydrocarbons and show a regression rate 3 to 4 times higher than with conventional fuels. These high values are achieved by entrainment mass transfer. Normal polymeric fuels need to be fully vaporized or pyrolysed before being burned. Paraffin-based hydrocarbons form a melt layer on the surface on the fuel. From that layer liquid droplets are entrained by liquid layer instabilities. Those are caused by the high velocity gas flow in the combustion chamber [7]. For liquefying hybrids the regression rate \dot{r} is composed of 2 parts, namely the classical regression rate \dot{r}_{vap} consisting of the vaporizing fuel and an additional term \dot{r}_{ent} which accounts for the mass transfer by entrainment.

$$\dot{r} = \dot{r}_{vap} + \dot{r}_{ent} \approx 3:5 \, \dot{r}_{HTPB}.\tag{1}$$

To account for the increased regression rate by entrainment the classical hybrid combustion theory needs to be modified to consider the reduced heating of the entrained fuel, the reduced blocking effect due to two-phase flow and the increased heat transfer due to the increased surface roughness. By the entrainment much more fuel can be transported into the flame zone before being totally vaporized. Scale-up tests have been done confirming that the theory is applicable also for large engines [8].

To quantify the value of entrainment mass transfer Karabeyoglu et al [6] assume an empirical formula from literature for the mass flow by entrainment which includes the dynamic pressure p_{dyn} , the thickness of the melt layer h, the surface tension σ and the melt layer viscosity μ_l :

$$\dot{m}_{ent} \propto \frac{p_{dyn}^{\alpha} h^{\beta}}{\mu_{i}^{\gamma} \sigma^{\pi}}$$
⁽²⁾

Here the upper part of equation 2 contains the operational parameter of the combustion: p_{dyn} and indirectly the oxidizer mass flux. The lower part contains the material properties σ and μ_l of the fuel. Literature values for the exponents of equation 2 are given in table 1.

Table 1: Entrainment exponent values						
Reference	α	β	γ	π		
Gater and L'Ecuyer [9]	1.5	2	1	1		
Nigmatulin et al. [10]	1	1	-	-		
Karabeyoglu [6]	1-1.5	-	$>\pi$	$<\gamma$		

The exponents α and β are believed to be between 1-2 where as γ and π should be almost 1. They also state that the melt layer viscosity should have a greater influence on the regression rate than the surface tension, meaning $\gamma > \pi$. The melt layer thickness *h* can be solved explicitly according to Karabeyoglu et al [6]. Assuming a black propellant that is absorbing all radiative heat transfer on the surface of the liquid melt layer, the melt layer thickness can be calculated as

$$h = \delta_l ln(1 + \frac{C_l \Delta T_1}{h_m}). \tag{3}$$

The characteristic thermal thickness δ_l of the liquid layer is defined as

$$\delta_l = \frac{\kappa_l \rho_l}{\dot{r} \rho_s}.\tag{4}$$

1.1 Optical investigations

Nakagawa and Hikone did an investigation on the dependence of the regression rate on the fuel viscosity [11]. They investigated paraffin and oxygen as propellants in a 2-dimensional slab burner with windows in the side for optical access [12]. They used pure paraffin and the same paraffin blended with different viscosities by adding 10% and 20% of ethylene-vinyl acetate. Tests were run at atmospheric pressure where they could show that droplets are generated during combustion and entrain in the flow. They assume the heat transfer coefficient *h* is

$$h = 0.332kPr^{\frac{1}{3}}\sqrt{\frac{u_{\infty}}{vx}}$$
(5)

where k is the thermal conductivity, Pr the Prandtl number, u_{∞} is the melted fuel general velocity, v is the kinetic viscosity of the fuel and x is the distance from the starting edge of the grain. Substituting the definition of the Pr number

$$Pr = \frac{\mu c_{pl}}{k} \tag{6}$$

in equation 5 one obtains

$$h = 0.332k^{\frac{2}{3}}c_{pl}^{\frac{1}{3}}\sqrt{\frac{\mu_{\infty}\rho_{l}}{x}}\mu^{-\frac{1}{6}}.$$
(7)

Their measured regression rates seemed to be proportional to $\mu^{-1/6}$. This would be a very low dependence on the viscosity of \dot{r}_{ent} . Additionally the mass flux of the tests was very low. The viscosities which were compared with the tests have been done only at one temperature of 120°C. The average melt layer temperature is expected to be much higher [13]. It is very likely that the temperature during combustion might be different and the viscosity depends on the temperature of the fuel.

Chandler et al could also show droplet entrainment [14, 15]. They used a 2 dimensional chamber with two windows at the side and one on top. Tests have been done with pure and blackened paraffin as well as with highdensity polyethylene (HDPE) and HTPB. For paraffin based grains droplet entrainment was visible. For HDPE they report little droplet entrainment was visible. They expected this due to the high viscosity of the liquid HDPE. For HTPB no droplet entrainment could be measured.

De Luca et al also do an optical investigation of the hybrid combustion process with a novel technique. They look inside a pressurized chamber over a mirror setup inside the burning fuel grain and thereby measured the instantaneous regression rate [16].

1.2 Paraffin fuels

Four different waxes are being researched as fuels. They are used in pure form as well as with different additives to modify mechanical and rheological properties. Their properties given from the manufacturer can be seen in table 2. Type 6003 is a pure paraffin wax. While type 0907 is a microcrystalline wax which is used for example in hot glues. Type 6805 has the same application but it is a paraffin wax. The last type 1276 is used for coatings, gloss and sealing. Coatings manufactured with these waxes exhibit higher strength and hence abrasion resistance as well as an improved gloss impression. Its special formulation is based on waxes and a variety of different additives according to the manufacterer Sasol Wax.

Table 2. wax properties given by manufacturer						
Sasol Wax	Congealing point [°C]	Oil content [%]	Penetration at 25°C [1/10mm]	Viscosity at 100° [mm ² /s]		
6003	60-62	0-0.5	17-20	-		
6805	66-70	0-1	16-20	6-8		
0907	83-94	0-1	4-10	14-18		

Table 2: Wax properties given by manufacturer

These paraffin waxes have been tested in pure form and also mixed with 2% carbon black (CB) and 10% stearic acide (SA).

8-13

880-920

2. Experiments

1276

2.1 Experimental setup and data aquisition

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The burning rate tests of wax-based fuel formulations were evaluated in terms of regression rate values. The experimental tests have been performed at the Institute of Space Propulsion at the DLR Lampoldshausen at test complex M11 [17]. An already existing modular combustion chamber was adjusted and used for the test campaigns [18, 19]. This chamber has been designed and used in the past to investigate the combustion behavior of solid fuel ramjets. A rearward facing step before the fuel grain was used to provide adequate flame holding and assure combustion stability. A sideview of the whole combustion chamber setup can be seen in figure 1. The oxydizer main flow is entering the combustion chamber from the left after having passed two flow straighteners. Ignition is done via an oxygen/hydrogen torch igniter from the bottom of the chamber. The two windows at each side enable several different optical diagnostics, which have already been performed successfully in the past during ramjet experiments. One measurement was a Color Schlieren setup to visualize the refractice index gradients in the chamber. Particle image velocimetry (PIV) was used to get information about the flowfield and velocity magnitudes. A coherent anti-stokes Raman spectroscopy (CARS) was applied to get information about the temperature distribution. A gas sampling probe system can be used to collect condensed combustion products and analyse them.

A test sequence is programmed before the test and is run automatically by the test bench control system. All tests have been done with the same settings shown in table 3. Each test duration is 5 seconds. For redundancy a separate measurement system is used for data aquisition during the tests. An ADwin measurement system by Jäger Messtechnik



Figure 1: Sideview of combustion chamber setup

is used for this purpose. Data aquisition on this measurement system was programmed by the proprietary software named ADbasic. All raw data is low-pass filtered via Dewetron signal amplifiers before the data aquisition. Depending on the sensor type that is used a gain can be set to the signal if needed. The measured data is then routed from ADwin via Ethernet to a second PC which handles the data saving routines by a Labview program. For video data aquisition a Photron Fastcam 1024 PCI high speed video camera is used with a maximum resolution of 1024x1024 pixel. The frame rate, resolution and shutter time of the camera are adjusted for each test, according to the test conditions and position of the camera.

	Table 3: Automatic test sequence
Time [s]	Action
T-30	Start of sequence
T-29	Commanding control valve
T-15	Set dome regulator pressures
T-03	Start of data aquisition
T-1	Start spark plug
T-0.2	Open ignition valves
T0	Open oxydizer main valve, start High-speed camera
T+0.5	Close ignition valves
T+5	Close oxydizer main valve, start nitrogen purge
T+10	End of sequence

The oxydizer massflow rate is adjusted by a flow control valve. It is measured with a Coriolis flowmeter with an accuracy better than 0.35% and a repeatability better than 0.2% of the flow rate. A mass flow rate measurement of the oxydizer can be seen in figure 2. A steady-state mass flow rate of about 53 g/s is set for all tests. Massflow rate data is aquired in Labview via a digital protocol.

2.2 Viscosity measurements

Viscosity of a fluid defines its resistance to deformation by external forces like shear stress or tensile stress. The viscosity in equation 2 is expected to have the greatest influence on \dot{m}_{ent} . For this reason the viscosity of fuels in these tests is evaluated in detail and will be compared with the regression rate results from the burning rate tests. The relation between the viscosity η and the shear rate $\tau(\dot{\gamma})$ is described by

$$\tau(\dot{\gamma}) = \eta(\dot{\gamma})\dot{\gamma}.\tag{8}$$

The viscosity measurements have been done with a Haake RheoStress 6000 rotational rheometer with a plateplate and cone-plate geometry. The measurement range is between 10^{-7} -1500 min⁻¹ at constant shear and also at constant rotation. The frequency range is between 10^{-5} -100 Hz. A measurement of the viscosity of the pure waxes at different shear rates can be seen in figure 3. Before each test the shear rate versus the viscosity was measured as it can be seen in figure 3. Then a shear rate for the temperature ramp measurement was choosen where the waxes are still in the linear viscoelastic range. In figure 4 the measurement of viscosity depending on the temperature is shown.



Figure 2: Typical oxydizer mass flow rate (Test 107)

Tests have been done from 200°C down to the solidification point of the paraffin samples. The viscosities of each type seem to reach asymptotic values at higher temperatures but the exact value cannot be clearly determined [20]. Thus it is difficult to choose the viscosity at an average temperature between the melting and boiling temperature which could be used for equation 2. The boiling and average temperature can be calculated with equations from Marano and Holder [21], for example.

The pure paraffin samples investigated here show a newtonian behavior over a wide range, which means that the measured viscosity is independent of the applied shear rate. For the mixtures with CB and SA a non-newtonian behavior is measured for percentages of CB greater than 1.5%. This can be seen in figure 5. The influence of the CB percentage to the viscosity is shown in figure 6. Viscosity is increasing with increasing CB percentage.



Figure 3: Comparison shear rate γ of pure paraffin at T=120°C

In table 4 the differences in viscosity are compared. We can see that type 1276 has a viscosity 3 orders of magnitude higher than type 6003. Type 0907 has a 156.72% increase and 6805 a 17.99% increase compared to 6003.

Table 4: Comparison average difference (compared with 6003) between measured viscosity η of pure paraffin

Sasol wax	$\Delta\eta$ [%]
Pure 6003	-
Pure 6805	17.99%
Pure 0907	156.72%
Pure 1276	10707%

Table 5 lists the differences in viscosity of the paraffin mxitures. Due to the non-newtonian behavior we have different viscosities of the same mixture at different shear rate settings.



Figure 4: Comparison viscosity η of pure paraffin



Figure 5: Comparison shear rate γ of 0907+CB+SA with different percentage of CB at T=120°C



Figure 6: Comparison viscosity η of 0907+CB+SA with different percentage of CB (γ =50 1/s)

Sasol wax	Shear rate γ [1/s]	$\Delta\eta$ [%]
6003+CB+SA	300	41.81%
6003+CB+SA	500	44.87%
6003+CB+SA	1000	42.26%
6805+CB+SA	300	37.02%
6805+CB+SA	500	46.72%
6805+CB+SA	1000	33.58%
0907+CB+SA	300	53.81%
0907+CB+SA	500	63.93%
0907+CB+SA	1000	34.37%
1276+CB+SA	300	36.37%
1276+CB+SA	500	30.55%
1276+CB+SA	1000	33.33%

Table 5: Comparison average difference (compared with pure type) between measured viscosity η of paraffin+CB+SA at different shear rates

2.3 Surface tension measurements

Surface tension is the property of a liquid to resist against an external force applied to it. It is caused by the cohesion force of similar molecules. Surface tension depends strongly on the temperature with a linear relation. Empirical correlations like the Eötvös rule use the critical temperature, the molar volume and a molar surface tension to calculate the surface tension of pure liquids at a certain temperature. Another relation that can be used is from Guggenheim-Katayama. For our experiments a Krüss EasyDyne tensiometer was used to measure the interfacial surface tension (IFT) of the waxes. The measurement range is from 1-999 mN/m with an accuracy of ± 0.1 mN/m. Figure 7 on the left side shows the measured points of Sasol 6003 at different temperatures. About 35-40 measurements for each sample have been taken at decreasing temperature. The starting temperature was approximately 130 °C then measurements have been taken while the sample was cooling down until it started to solidify. A best-fit line was calculated to get a linear relation and extrapolate the IFT values at T_{av} in table 6 and 7. T_{av} is the average temperature between the melting temperature ($\approx 60-94$ °C, table 2) and boiling temperature (≈ 450 °C) of the paraffin. Table 6 shows a comparison of the IFT values of the pure substances. The change Δ_{IFT} is calculated by comparison with the value from type 6003.

Figure 7: Sasol 6003 IFT all measurements on the left side and IFT averaged of all samples on the right side



Figure 7 on the right side shows the best-fit lines of all pure Sasol waxes. It can be seen that type 6003 and 6805 have about the same negative slope of the curve and also approximately the same value of IFT with only 2.08 %

Table 0. Comparison IFT of pure paralitie at 100 C					
Sasol wax	IFT	Δ_{IFT}	Δ_{IFT}		
	[mN/m]	[%]	at T_{av} [%]		
Pure 6003	26.32	-	-		
Pure 6805	26.88	2,08	0.87		
Pure 0907	28.28	6,9	-31.89		
Pure 1276	29.09	9,5	28.18		

Table 6: Comparison IFT of pure paraffin at 100°C

difference, see also table 6. Type 0907 has a smaller negative slope as 6003 and therefore the value of IFT at T_{av} in table 6 is -31.89 % lower than that of 6003. At 100 °C the increase in IFT is about 6.9 % compared to 6003. In contrast type 1276 has a slightly bigger negative slope which results in a 28.18 % increase in IFT at T_{av} , compared to a 9.5 % increase at 100 °C. Looking back at equation 2 it should be reminded that an increase in IFT would result in a decrease in \dot{r}_{ent} .

An overview about the measured surface tensions of the paraffin waxes with different additives at 100°C is shown in table 7 [22]. The IFT at the average temperature T_{av} between the melting and boiling temperature of the paraffin is also extrapolated from the measured data and the deviation from the pure formulation is calculated.

Table 7: Measured IFT values at 100 °C						
Formulation	IFT	Δ_{IFT}	Δ_{IFT} at T_{av}			
	[mN/m]	[%]	[%]			
Pure 6003	26.32	-	-			
6003 + 1% CB	26.49	0.65	0.5			
6003 + 10% SA	26.35	0.11	-5.19			
6003 + 10% Al	26.45	0.49	2.84			
Pure 6805	26.88	-	-			
6805 + 1% CB	26.95	0.26	-0.98			
6805 + 10% SA	26.73	-0.56	-15.69			
Pure 0907	28.28	-	-			
0907 + 2% CB	27.71	-2.02	19.51			
0907 + 10% SA	27.82	-1.63	16.42			
0907 + 10% Al	27.69	-2.09	7.17			
Pure 1276	29.09	-	-			
1276 + 1% CB	28.71	-1.31	-2.65			
1276 + 10% SA	28.29	-2.75	-16.63			

Comparing the IFT in table 7 we can see differences smaller than 3 % between the pure formulations and those with additives at 100 °C. At T_{av} the differences are bigger. SA decreases the IFT for 6003, 6805 and 1276 while an increase of 16.42 % is measured for 0907. For CB we have small changes in IFT with 6603, 6805 and 1276 while 0907 has a 19.51 % increase in IFT. 10 % Al addition gives only a 2.84 % increase for 6003 while we get 7.17 % increase for 0907. We can see that for some additives the IFT is significantly changed. This would also result in a change in \dot{r}_{ent} assuming that equation 2 and its exponents from table 1 are valid.

2.4 Regression rate

The reason to use a 2D fuel slab was primarily to get an insight into the combustion process above the fuel surface. The regression rates with this setup have also been measured but they cannot be compared directly with data from cylindrical fuel grains. With the 2D slab the convective and radiative heat fluxes are different. Much more heat is lost to the surroundings like the Quartz glass windows and the upper metallic surface of the combustion chamber. Thus less heat is transfered to the fuel and the regression rates measured are lower than with cylindrical fuel grains.

The fuel mass flow \dot{m}_f from the solid fuel into the combustion zone is defined by the heat of vaporization of the fuel and the total heat transfer by convection and radiation into the fuel. It is proportional to fuel's density ρ_f , its surface area A_S and the regression rate \dot{r}

$$\dot{m}_f = \rho_f A_S \dot{r}.\tag{9}$$

The regression rate \dot{r} in a hybrid rocket engine is described with the oxydizer mass flux G_{ox} by

$$\dot{r} = a G_{ox}^n. \tag{10}$$

The fuel slabs being used have a length of about 180mm, width of 90mm and height of 18mm. The leading edge upstream has an angle of about 20° with a length of 50mm. Tests have also been done with smaller slabs with dimensions of length of about 100mm, width of 70mm and height of 14mm. The regression rate values shown are space- and time-averaged. A measurement uncertainity during the tests is that some paraffin is flowing down beneath the fuel slab in the chamber. This fuel is not burning and remains in the chamber. Thus this residual is collected after the test and is considered for the mass loss. For Paraffin 0907 and 6805 different tests with both fuel slab sizes can be seen in figure 8. For 0907 the big fuel slabs show about twice the regression rate of the small slabs at similar oxydizer mass flux. For 6805 the difference is almost 3-4 times. The reason for this lies in the different oxydizer to fuel ratios (OF) during the tests with the small and the big slab. For the big slab the OF is between 5-15 whereas for the small slabs the OF ratio is much higher up to 70. When we compute the combustion temperature for 0907 with CEA for different OF ratios we get a graph like in figure 9. There we can see that the maximum temperature is at the stochiometric ratio between 2-3 and the temperature is decreasing rapidly for higher OF ratios. Thus for higher OF ratios less heat can be transfered to the solid fuel and the regression rate decreases. Therefore care must be taken to compare regression rates of the fuels at similar OF ratios. Karabeyoglu proposes a correction for this effect based on the regression rate constants and the OF ratio [8, 23]. The effect of increasing OF ratio can also be seen in figure 8 on the right side for the big slab 6805. The tests with big fuel slab shown have been done one after each other, using the same slab. The highest regression rate 0.24 mm/s corresponds to an OF ratio of about 7. Then the regression rate decreases as OF decreases. At 0.23mm/s we have an OF of 8.2. The smallest value 0.19mm/s had an OF of 13.2.



Figure 8: Comparison between regression rates of big and small fuel slab of 0907 and 6805



Figure 9: Combustion temperature of 0907

An overview about the averaged regression rates of all tests with big fuel slabs and similar OF ratios can be seen in figure 10. Here we can see that the paraffin 6003 with the lowest viscosity shows the highest regression rate. This is

valid for the pure sample and also for the mixture with CB and SA. Furthermore the regression rates are decreasing as the viscosity values of the paraffin samples are increasing, see also table 4 and 5. Type 1276 with its very high viscosity shows regression rate values as low as HTPB values measured at SPLab [1].



Figure 10: Comparison regression rate of pure paraffin (left) and mixtures (right)

The importance of the viscosity gets more clear if we look at table 4. There the average of all regression rate values from figure 10 is computed. We can see that type 6003 with the lowest viscosity achieves the highest regression rates. The difference $\Delta \dot{r}_{pure}$ in regression rate uses the value of pure 6003 for the pure paraffins. For the mixtures, the mixture of 6003+CB+SA is chosen as reference. The same applies for the change in viscosity $\Delta \eta$.

Sasol wax	ŕ	$\Delta \dot{r}_{pure}$	$\Delta \eta$
	[mm/s]	[%]	[%]
6003	0.232	-	-
6805	0.220	-5.55%	17.99%
0907	0.175	-24.61%	156.72%
1276	0.050	-78.61%	10707%
6003+CB+SA	0.204	-	-
6805+CB+SA	0.173	-15.35%	15.41%
0907+CB+SA	0.154	-24.64%	168.76 %
1276+CB+SA	0.070	-65.70%	10188%

Table 8: Comparison average regression rates of pure paraffin and paraffin+CB+SA

Table 9: Comparison average regression rates between pure paraffin and paraffin+CB+SA

Sasol wax	compared with	$\Delta \dot{r}$	$\Delta \eta$
		[%]	[%]
6003	6003+CB+SA	24.9%	41.81%
6805	6805+CB+SA	22.3%	37.02%
0907	0907+CB+SA	11.8%	53.81%
1276	1276+CB+SA	-32.6%	36.37%

2.5 Optical investigations

2.5.1 Ignition delay

From the video data the ignition behavior has also been analysed. Tests with 5000 FPS recording rate and similar shutter settings have been chosen, see table 10. The appearance of the first flame corresponds to the ignition of the oxygen/hydrogen torch igniter. Then the time of the first flame on top of the fuel slab is considered as time when the fuel slab starts to ignite. The time difference between these two is listed as the ignition delay. Finding the ignition time of the fuel is sometimes difficult because the igniter also illuminates the picture and the flame of the paraffin is not

very bright initially. Generally it seems that the pure paraffin samples ignite faster than the mixtures, after about 0.1s to 0.2s. For the mixtures the ignition delay is higher, between 0.22s to about 0.5s. Only the samples 1276 in pure and mixed form seem to ignite after the same delay of only 0.1s. Additionally the flame of type 1276 appeared brighter and thicker compared to the other samples. This might also lead to an earlier visibility of the first flame and thus apparently a shorter ignition delay.

Sasol wax	Test no.	Igniter time	Fuel ignition	Ignition delay	Shutter
	[-]	[s]	[s]	[s]	[-]
Pure 6003	075	0.466	0.735	0.269	1/40000
Pure 6003	126	0.460	0.6	0.140	1/40000
Pure 6003	076	0.168	0.3	0.132	1/72000
Pure 6003	128	0.470	0.64	0.170	1/106000
Pure 6805	106	0.176	0.302	0.126	1/41000
Pure 6805	108	0.180	0.3278	0.148	1/41000
Pure 6805	107	0.178	0.316	0.138	1/106000
Pure 0907	081	0.1634	0.3	0.137	1/40000
Pure 0907	089	0.180	0.260	0.080	1/40000
Pure 0907	080	0.168	0.300	0.111	1/75000
Pure 1276	109	0.22	0.340	0.119	1/41000
Pure 1276	112	0.287	0.420	0.133	1/106000
Pure 1276	113	0.140	0.268	0.128	1/106000
6003+CB+SA	096	0.168	0.640	0.472	1/41000
6003+CB+SA	095	0.176	0.640	0.464	1/106000
6805+CB+SA	082	0.188	0.599	0.312	1/40000
6805+CB+SA	084	0.15	0.374	0.224	1/40000
6805+CB+SA	085	0.154	0.380	0.226	1/105000
0907+CB+SA	097	0.190	0.840	0.650	1/41000
0907+CB+SA	098	0.311	0.634	0.323	1/106000
1276+CB+SA	090	0.176	0.280	0.104	1/41000
1276+CB+SA	092	0.222	0.320	0.098	1/106000
1276+CB+SA	093	0.199	0.340	0.141	1/106000

Table 10: Ignition delay of the different paraffin samples

2.5.2 Combustion behavior

The burning rate tests have also been recorded with a high speed camera to get more knowledge about the combustion process. All images are recorded with the oxydizer flow direction from left to right. For all tests a wave like flame structure can be seen in the high speed video data. Figure 11, 12, 13 and 14 show images of the different mixtures during combustion. For all videos we can see the turbulent structure of the flame. The flame is not stationary. We can see a roll up of the flame at start of the fuel grain and then the flame is moving along on top of the fuel. About 2-4 single large scale waves can be seen on top of the fuel at one frame. The rotation of a vortex after the flame holding step can also be seen. The step generates a small flame in front of the fuel which is burning continuously. The appearance of the wave like structures on top of the fuel seems related with the vortex shedding after the step. The lines in the middle of the window are cracks in the glass due to a hard ignition in a previous test.

Due to the high shutter settings droplet formation seems only visible during the ignition transients. When the igniter starts burning and the paraffin is not yet fully ignited many droplets can be seen being released mainly from the area of the fuel where the igniter hits the fuel slab. When the paraffin is fully burning only some brighter, thicker droplets can be seen which are released from near the burning surface.

Figure 15 shows an image of a fuel sample after the combustion test. Here we can also see some residual wave like structure on the surface. These structures appeared on most of the recovered fuel samples, for the mixtures and also the pure samples. It is likely that this structure can be linked to the combustion behavior of the paraffin samples and the wave like flame structure. But we must also consider that N2 purge flow was initiated at the end of the test to end the combustion and purge the pipes. This might have also influenced the surface of the paraffin.



Figure 11: Image of 6003+2%CB+10%SA during test 096 (Shutter 1/41000, 5000 FPS, Frame 11548)



Figure 12: Image of 6805+2%CB+10%SA during test 084 (Shutter 1/41000, 5000 FPS, Frame 12953)



Figure 13: Image of 0907+2%CB+10%SA during test 097 (Shutter 1/41000, 5000 FPS, Frame 15132)



Figure 14: Image of 1276+2%CB+10%SA during test 090 (Shutter 1/41000, 5000 FPS, Frame 19874)



Figure 15: Fuel sample of 0907+2%CB+10%SA after test 097

3. Conclusions

Experimental characterization has been done with paraffin fuels that can be used for high regression rate applications. A wide database concerning viscosity, surface tension, burning rate data and also other measurements has been established. The regression rate data collected so far indicates an increasing regression rate for decreasing viscosity of the liquid paraffin. These results show the same trend as with 2D-radial burning rate tests done at SPLab with the same fuels [1]. Viscosity data shows big differences depending on the paraffin type, type and amount of additives and also on the shear rates of the viscosity measurement. Differences in surface tension between different paraffin samples are smaller and thus might be less influencing on the regression rate.

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