RECENT RESULTS OF STUDIES ON THE SPRAY BEHAVIOR OF NEWTONIAN AND NON-NEWTONIAN FLUIDS WITH DOUBLET IMPINGING JET INJECTORS

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Abstract

An injector that realizes the required drop size and drop size distribution is one of the conditions for obtaining good performances in a rocket combustor. In this publication results of the basic research activities conducted at DLR in the last few years on the spray behavior of impinging jet injectors are summarized, with particular focus drop size measurements. A modular doublet like-on-like impinging jet injector setup has been used and various Newtonian and non-Newtonian fluids have been investigated under ambient conditions with injection velocities up to 80 m/s. The large amounts of Newtonian liquids tested allowed covering a very wide range of Ohnesorge numbers. In studying non-Newtonian fluids the spray behavior of gels has been compared to that of their corresponding pure solvents. Also the influence of the addition of aluminum particles to gels has been studied. Finally an overview on recent studies focused on the understanding of the formation of thread like structures instead of droplets is given when certain non-Newtonian fluids are used.

1. INTRODUCTION

Impinging jet injectors are often used for the atomization of storable liquid and gelled propellants in rocket engines due to their simplicity, low manufacturing costs, good atomization and mixing characteristics. The atomization behavior of Newtonian fluids through this type of injectors has been studied for more than 50 years, and the vast majority of publications concern doublet impinging jet injectors. Some of the first studies were conducted by Heidmann et al [1, 2]. In these works the first categorization of spray patterns has been introduced. One of the first theoretical studies was conducted by Taylor [3] who formulated a theory, which allows a quite good prediction of the shape of the fluid sheet formed by the impingement of the two jets of a doublet impinging jet injector setup. Significant is also the model proposed by Dombrowski and Hooper [4] that allows to determine the droplet diameter.

Many other studies followed, focusing on various aspects of the breakup characteristics such as breakup length of the sheet (see e.g. Ref. [5]), size of droplets formed (see e.g. Ref. [6]) and the effects of higher ambient pressure (see e.g. Ref. [7]). A very detailed description of physical phenomena underlying the breakup of liquid sheets is given in a series of articles published recently from a group from the University of Provence in France [8, 9]. In particular the nature of the capillary and aerodynamic instabilities leading to the breakup is described in their publications in detail. Also it should be noted here that basic research activities on the breakup of 2-D planar sheets formed by Newtonian or non-Newtonian fluids have been conducted, see e.g. Ref. [10].

Impinging jet injectors have been used in many rocket engines, mainly in the USA. This kind of injector has seen application both in first stage and upper stage engines. In first stage or booster engines impinging jet injectors have been used mainly with the propellant combination LOX-RP1. The injection head of the F-1 engine, the first stage engine of Saturn V, used 714 like-on-like doublets for the atomization of LOX and 702 doublets for the atomization of RP1. Other notable engines using this kind of injector are the booster of Atlas and Titan. In upper stage applications impinging jet injectors have been used with storable propellants, generally with nitrogen tetroxide as oxidizer and different derivatives of hydrazine as fuel. Examples of this kind of engine are the Apollo Lunar Module Ascent (LEMA) Engine and the Viking V engine (Ariane 4 upper stage).

A precious source of information on impinging jet injectors in rocket engine is the monograph "Liquid Rocket Engine Injectors", prepared by NASA in 1976 [11]. It gives a very detailed overview of the state of the art, design criteria and recommended practices to construct injectors for rocket applications.

As mentioned above also for the atomization of gelled fuels and oxidizers impinging jet injectors are interesting. Gelled propellants are of interest for rocket and ramjet propulsion systems, because of their safety and performance benefits. Gels are non-Newtonian fluids, whose shear viscosity decreases with increasing shear rate. High shear rates can be produced both in the taper inside the injector tip and in the region around the intersection point

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of the fluid jets. This leads to a strong decrease of the shear viscosity of these gelled fluids up to an extensive liquefaction. This liquefaction offers the possibility to design engines, which can be throttled similar to engines with liquid fuels, but have simple handling and storage characteristics similar to engines with solid fuels.

At the beginning of the 21st century also at DLR test site at Lampoldshausen research activities on the atomization behavior of non-Newtonian gelled propellants with impinging jet injectors were started. Various fuel/gellant mixtures were investigated. Only some publications are cited here, see e.g. [12-15]. The used experimental setup was modular so that the influence of different impingement angles and internal injector geometries could be investigated [16,17]. Also metallized gels were investigated with focus on the influence of particle size and concentration, see e.g. [18-20].

In order to separate influences, which could be caused by non-Newtonian fluid behavior, also detailed investigations with Newtonian fluids were conducted. The viscosity of Newtonian fluids is independent from flow conditions like shear and elongation rates as well as time, so that boundary conditions of the experiments are simpler and the analysis of results and their comparison could significantly easier be conducted. First results of these studies were published in Ref. [21]. This work was extended in [22], using a broader selection of fluids and a broader range of injection velocities (up to 80 m/s), in order to cover a broader range of non-dimensional Reynolds, Weber and Ohnesorge numbers. It was observed that with increasing jet velocity the breakup behavior of the investigated fluids changes in different manner. Seven different main break-up modes could be identified and arranged in a regime diagram in dependence of Reynolds and Weber numbers related to the conducted experiments.

A first attempt for the realization of a regime diagram with several non-Newtonian gel fuels was made by von Kampen et al [15]. They used a generalized Reynolds and Ohnesorge numbers $Re_{gen,PL}$ and $Oh_{gen,PL}$ on the base of the rheological power-law equation for the shear viscosity – shear rate dependence. The presented first results showed that at low $Re_{gen,PL}$ the agreement with the breakup modes of Newtonian fluids is poor, which can be explained by the limited area of validity of the power-law equation.

Average droplet sizes and droplet size distributions have a strong influence on the combustor process influencing the combustion efficiency, local heat release and combustion stability. The current paper presents and compares obtained droplet sizes measures obtained in atomization experiments at DLR Space Propulsion Institute with doublet like-on-like impinging jet injector and different storable Newtonian and non-Newtonian fluids. Both an overview about previous investigations will be given and newer results will be included.

It should be mentioned in this context that many methods have been developed to estimate droplet sizes, see e.g. [4,5,11]. These methods allow to obtain only an estimation of droplet sizes and cannot be applied to non-Newtonian fluids or fluids with very high viscosities. For this reason an experimental study to determine drop diameter is generally required, especially for propellants with a very low data base.

2. EXPERIMENTAL

2.1. Experimental Setup

The experimental setup for the spray investigations under ambient conditions concerning pressure and temperature consists of a cartridge with the fluid to be investigated, a hydraulic driving unit and a modular injector unit (Fig. 1). The injector arms of the injector unit are mounted on movable rotary tables so that the impingement angle as well as the pre-impingement length can be varied easily. The injector tips (nozzles) can easily be changed for the variation of the nozzle exit diameters and the internal injector geometry. For the present work an impingement angle of 90° and a pre-impingement length of 5 mm for the tests presented in section 3.1 and 10 mm for the other here presented tests were chosen. The high length to diameter ratio of the internal injector channel as well as the internal wall inclination angle of 20° were chosen both to reduce influences of separation by the formation of a vena contracta in the intake to the injector channel and to induce a more fully developed velocity profile at the injector exit. The diameter of the injector nozzle used was of 0.7 mm. For the visualization of the spray patterns the shadowgraph-technique was used, together with two CCD cameras, one parallel and one perpendicular to the plane of the injectors, and two Nanolite spark lights as light sources. Generally more than 50 pictures were analyzed to ensure that stationary conditions were obtained for every experiment.

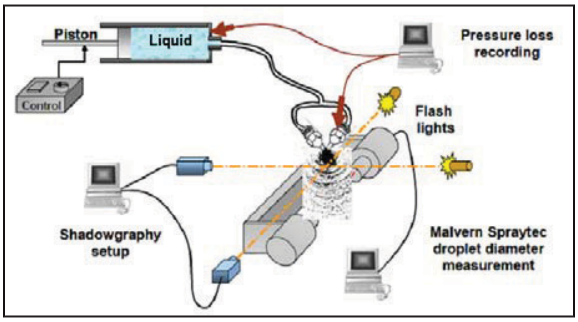

FIG 1. Experimental Setup

The diameter of the droplets was measured using a Malvern Spraytech. This apparatus is based on the Ensemble Laser Diffraction Technique. It is positioned 22 - 23.5 cm downstream from the impingement point. Two plastic tubes have been used to reduce the length of the investigated volume (as showed in figure 2), so that the test volume is the area between the two red discs. The beam diameter of the laser used in the Malvern is 10 mm, and this diameter defines the cross section area of the investigated volume. A slight air flow is injected in the tubes to avoid deposition of droplets on the lenses of the apparatus. In the apparatus a 100 mm lens is used, that allows obtaining results in the drop size range 2.5 – 125 µm.

The drop sizes in the present work are expressed in terms of the Sauter mean diameter (D[3][2]) defined as:

(1) $$D[3][2] = \frac{\sum_i n_i \cdot D_i^3}{\sum_i n_i \cdot D_i^2}$$

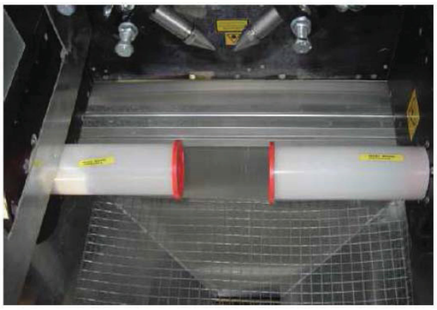

FIG 2. Malvern Spraytech measurement volume

2.2. Fluids Tested

The same Newtonian test fluids from Ref. [22] have been used in the present work. They have been chosen to cover a wide range of Ohnesorge numbers. In Table 1 these fluids are listed together with their properties and calculated *Oh* based on the injector exit diameter d_j = 0.7 mm.

The Ohnesorge number (*Oh*) is a non-dimensional number representing the ratio of viscous force to inertial and surface tension effects. It is defined as:

(2) $$Oh = \frac{\mu}{\sqrt{\rho \cdot \sigma \cdot D_{inj}}}$$

Liquid	μ [mNs/m^2]	σ [mN/m]	ρ [kg/m^3]	*Oh* [-] (*D*=0.7mm)
1-Hexene	0.252	19.00	673.0	0.0027
n-Heptane	0.387	19.65	683.6	0.0040
Water	1.002	74.00	998.0	0.0044
n-Octane	0.508	21.62	700.0	0.0049
n-Decane	0.838	23.83	730.0	0.0076
Ethanol	1.074	21.97	789.4	0.0097
30% Glycerine	2.51	71.50	1072.7	0.0108
1-Propanol	1.945	23.32	803.5	0.0170
1-Butanol	2.544	24.93	809.8	0.0214
1-Pentanol	3.619	25.36	814.4	0.0301
1-Hexanol	4.578	25.81	819.0	0.0376
1-Octanol	7.288	27.60	825.4	0.0577
Ethylene glycol	16.1	47.99	1113.0	0.0833
75% Glycerine	35.5	66.72	1192.0	0.1505
80% Glycerine	60.1	66.41	1208.5	0.2536
90% Glycerine	219	65.17	1235.1	0.9226
Triethanolamine	609	48.40	1124.2	3.1205
98% Glycerine	911	64.17	1256.4	3.8348

TAB 1. Newtonian fluids tested

The drop size measurements for Newtonian and non-Newtonian fluids have been compared by Madlener [24] and are also presented here. To show the influence of adding a gelling agent to a Newtonian fluid these measures have been conducted both with the pure solvent and the gel based on the same solvent. The fluids tested are listed in Table 2.

Solvent		
Jet A1	Paraffin	Ethanol
Gel		
Jet A1 + 7.5% Thixatrol ST + 7.5% MIAK	Paraffin + 7.5% Thixatrol ST + 7.5% MIAK	Ethanol + 10% COK 84
		Ethanol + 3.5% Methocel 311

TAB 2. Pure solvents and gels tested [24]

The influence of the addition of aluminum particles to a gel was also studied by Madlener et al [18]. Different amounts of Al particles varying from 10 to 40 wt.-% were added to a kerosene based gel with the following composition: Jet A-1 + 7.5% Thixatrol ST + 7.5% MIAK. The used Al particles were spherical with an average diameter smaller than 10 µm.

As it will be explained in section 3.4 viscoelasticity may play an important role in controlling the atomization of a non-Newtonian fluid. Thus Boger fluids have been studied to obtain a better understanding of this phenomenon. Boger fluids are very diluted linear polymer solutions. They offer a significant advantage in comparison to more concentrated polymer solutions because they allow to separate elastic effects from viscous effects. More concentrated solutions show typically both shear thinning and extensional thickening behavior. Thus it is difficult to distinguish the influence of these two fluid properties on the flow. Boger fluids, however, have a shear viscosity that does not vary significantly with the shear rate and their extensional behavior is influenced by the molecular weight of the polymer. An increase the molecular weight leads to a more marked extensional thickening behavior as can be seen in the diagram of Fig. 3. Here the Trouton ratio ($Tr = \eta_E / \eta$), which is the ratio of extensional viscosity (η_E) to shear viscosity (η) is shown.

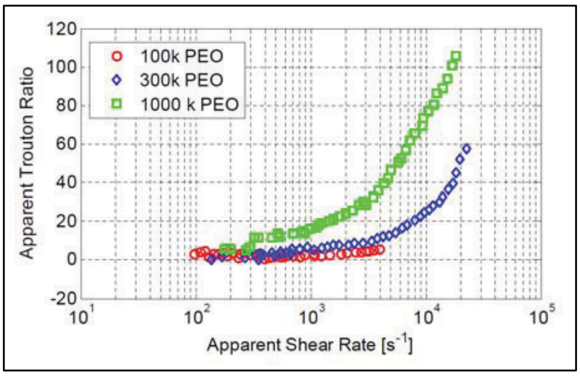

FIG 3. Extensional viscosity values for 3 different Boger fluids (BF1, BF2, and BF3). Data from Ref. [25].

The three Boger fluids used in the present publication (Table 3) have the same composition as those used by Mun [25]. They are solutions of polyethylene oxide (PEO, Sigma Aldrich) in water and glycerol. They all have shear viscosities around 5 mPa·s. The extensional viscosity of these fluids was measured in Ref. [25] with a Rheometrics RFX opposed jet rheometer. The results of these measures are shown in figure 3. The surface tension of the Boger fluids has been measured at DLR and it was found that the values of the surface tension for each of the fluids are very close.

	Composition	Shear Viscosity	Surface Tension
BF1 Low molecular weight PEO solution M_w= 1x10^5 g/mol	1.1 % PEO M_w 1E5 22.9 % Glycerol 69.875% Water	5.25 mPa s	59 mN/m
BF2 Medium molecular weight PEO solution M_w= 3x10^5 g/mol	0.27 % PEO M_w 3E5 31.23 % Glycerol 68.5 % Water	5.20 mPa s	59 mN/m
BF3 High molecular weight PEO solution M_w= 1x10^6 g/mol	0.125 % PEO M_w 1E6 30% Glycerol 69.875% Water	4.75 mPa s	57 mN/m

TAB 3. Boger fluids tested

3. RESULTS AND DISCUSSION

3.1. Newtonian Fluids

To get a better readability of the results the Sauter mean droplet diameter measurements for the Newtonian fluids have been divided in several groups and presented in separate diagrams. Power law trend-lines were also added for a better visualization.

The results of the tests conducted with hexene and three alcanes, which are the fluids with the lowest *Oh* numbers tested in the present work, are displayed in Fig. 4. It can be seen that the behavior of these fluids is very similar, whereas with heptane slightly smaller droplets can be produced. Moreover the curves representing the diameter vs. mass flow rate are steeper at low velocity and become more flat at higher velocities.

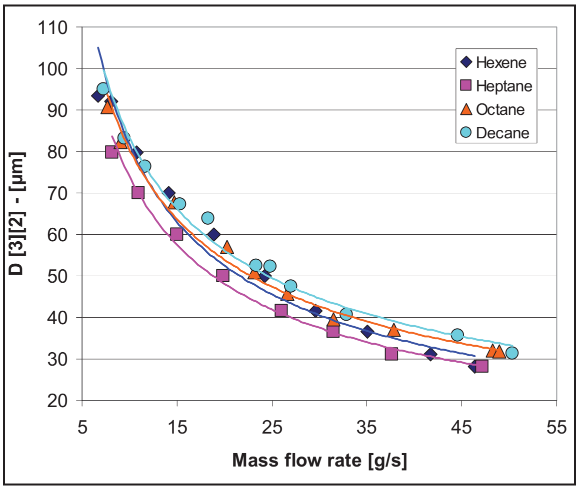

FIG 4. Sauter droplet diameter at increasing mass flow rates for fluids with low *Oh*. Data from Ref. [23].

The behavior of the different kind of alcohols tested is displayed in figure 5. The behavior of these fluids is very similar: the trend-lines for each fluid lie very close to each other. Comparing the fluids in figure 4 and figure 5 very similar results were obtained, whereas the fluids presented in figure 4 (lower *Oh*) show slightly smaller droplets.

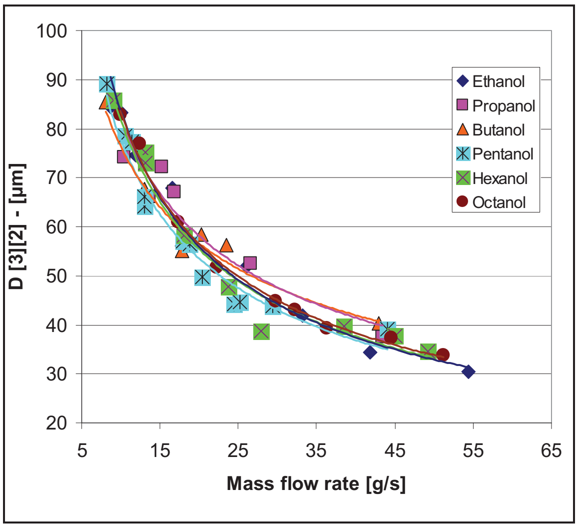

FIG 5. Drop size at increasing mass flow rates for different kind of alcohols. Data from Ref. [23].

The results of the tests conducted with 3 different glycerin-water solutions and ethylene glycol are displayed in figure 6. In the same figure also the results from hexene (also displayed in figure 4) and octanol (figure 5) are shown to help in comparing data presented in different diagrams. The results show that the glycerin solutions produce significantly bigger droplets than alcohols or the fluids (alcanes and hexene) with lower *Oh*. Ethylene glycol has a behavior in between octanol and the glycerin solution.

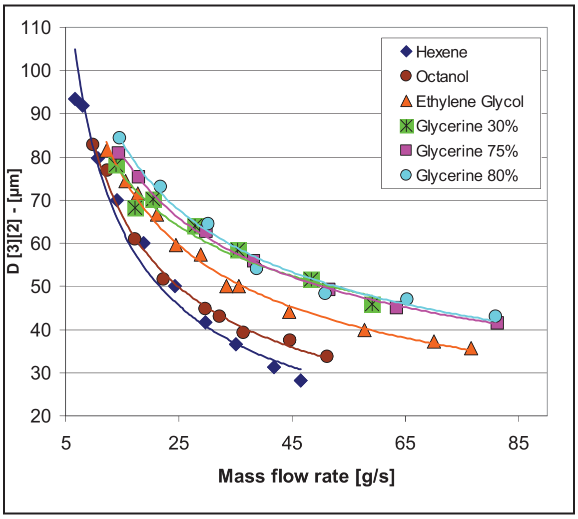

FIG 6. Sauter drop size at increasing mass flow rates for glycerine-water solutions and ethylene glycol. Data from Ref. [23].

Despite the different spray patterns could be arranged in a *Re*-*We* regime diagram with the *Oh* number as additional parameter, it seems that the *Oh* number shows not a clear trend as a controlling factor for droplet diameters. The solution of water with 30% of glycerine has an *Oh* number smaller than most of the alcohols but produces much bigger droplets. The values of the surface tension seem to correlate better with the drop size measurements. The alcohols have relatively similar and low values of surface tension (σ: 22-26.7 mN/m). Also the fluids displayed in Fig. 4 have low and similar surface tensions (σ: 19-23.8 mN/m). These values of surface tension agree well with the drop size measures that show similar results for these fluids. On the other hand the three glycerin solutions have much higher values of the surface tension (σ: 66.4-71.5 mN/m) and produce bigger droplets. The situation of ethylene glycol is in between: both the surface tension (σ: 48 mN/m) and the droplet diameters are in between alcohols and glycerine solutions.

Further investigations are necessary for a better understanding of the parameter influencing drop size.

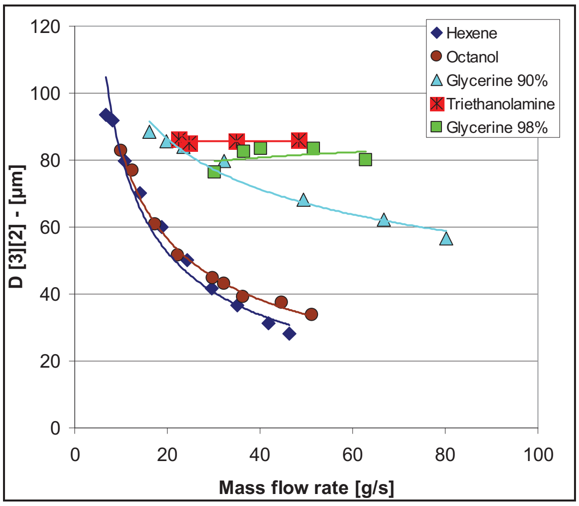

FIG 7. Sauter drop size at increasing mass flow rates for fluids with very high *Oh*. Data from Ref. [23].

The droplet size for the three fluids with the highest *Oh* is displayed in Fig. 7. Also in this case the curves of hexene and octane are included for comparison. The behavior of the measurements obtained with the Malvern is completely different from that of the other fluids, in particular for triethanolamine and 98% glycerine.

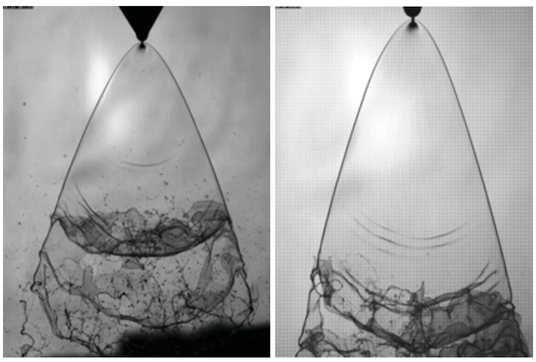

FIG 8. Right: Triethanolamine. Mass flow rate: 24.8 g/s
Left: 98% Glycerine. Mass flow rate: 36.5 g/s

The analysis of shadowgraph images for these two fluids (Fig. 8) shows that these fluids do not breakup into droplets. The calculation of droplet diameters with the Malvern Spraytech considers approximately spherical droplets and this hypothesis is not met by these two fluids. Thus the results delivered by the Malvern analysis software, which are presented in Fig. 7, should be discarded.

3.2. Comparison of Pure Solvent and Gel

The comparison of the results obtained with pure Jet A-1 and a Jet A-1 based gel is given in figure 9. The behavior of the two fluids is very similar with drops of roughly the same Sauter size for the same mass flow rates.

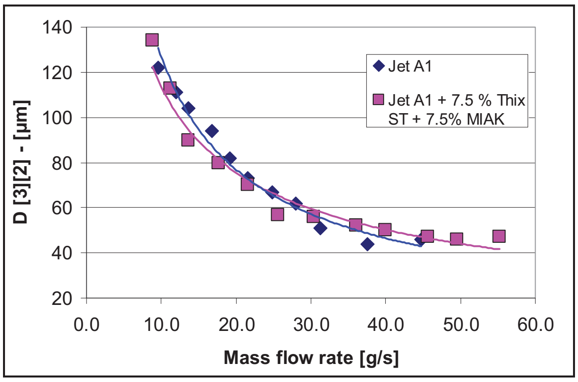

FIG 9. Jet A-1 and Jet A-1 gel. Data from [24]

In Fig. 10 the results of the test conducted with pure paraffin and a paraffin based gel are shown. The differences in the behavior are quite significant. The paraffin gel produces larger droplets for the entire range of used mass flow rates. The diameter of the droplets of pure paraffin decreases rapidly at low mass flow rates for reaching a plateau at the highest rates. On the other hand the curve of the paraffin gel shows a much less marked change in steepness.

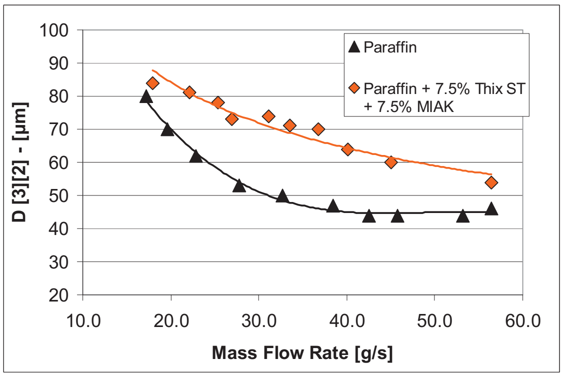

FIG 10. Paraffin and paraffin gel. Data from [24].

The drop size measurements for pure ethanol and an ethanol gel using 10% COK (fumed silica) as gelling agent are shown in figure 11. The behavior of the two fluids is quite similar: slightly larger drops of the gel at high flow rates in comparison to the pure solvent ethanol can be seen. Another ethanol gel, where 3.5 % Methocel 311 was used as gelling agent, produced no droplets and showed a completely different spray behavior. This will be presented later in the section 3.4 in detail.

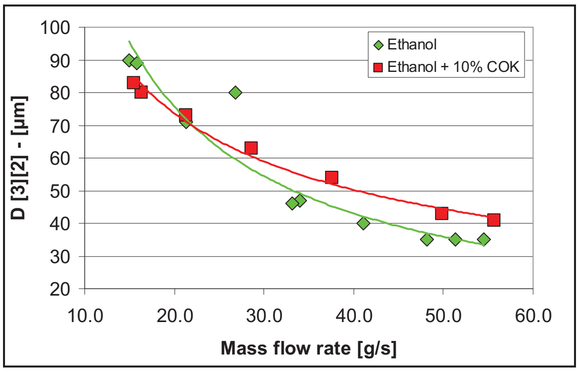

FIG 11. Ethanol and ethanol gel.

3.3. Influence of Particle Loading

In Fig. 12 the Sauter drop sizes for a Jet A-1 based gel with addition of different percentages of aluminum particles are compared. The results show that slightly higher Sauter droplet diameters are obtained with the particle laden gels with aluminum percentages between 10 and 30 wt.-%. No clear trend was observed connecting drop diameter and particle loading: the gel with 10% and 30% aluminum produce slightly smaller droplets than the gel with 20% aluminum. At 40 wt.-% particle content a very irregular behavior can be seen. This could probably be caused by an influence of this high amount of aluminum particles on the shape of the produced droplets. If droplets are not approximately spherical the Malvern could deliver incorrect results.

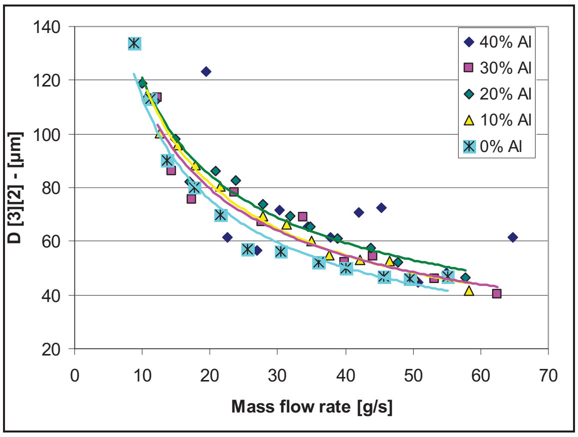

FIG 12. Influence of the addition of aluminum particles on drop size. Base gel: Jet A-1 + 7.5% Thixatrol ST + 7.5% MIAK. Particle size < 10 µm. Data from [18].

3.4. Droplet vs. Thread Formation

A peculiar behavior was observed during the spray tests conducted with several gels. The atomization of these gels did not lead to the formation of droplets, but of threads-like structures. One of these gels is an ethanol gel produced with 3.5 % Methocel 311 as gelling agent. In Fig. 13 a typical shadowgraph image of the spray behavior of this gel is compared with the image of an ethanol gel with 10 wt.-% COK 84 that breaks up into droplets as previously has been presented in chapter 3.2. By comparing the two spray images in figure 13 it can be observed that the specific surface area of threads is much smaller compared to that of a droplet phase. This may lead to lower combustion efficiencies in limited combustor lengths and the accumulation of unburned material on the wall of the combustion chamber.

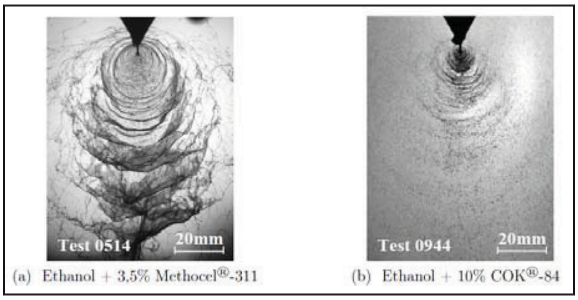

FIG 13. Shadowgraph images of the spray tests conducted with two different ethanol based gels.

A research campaign at DLR Institute of Space Propulsion is ongoing to study the origin of thread formation. The latest results have been published this year in Ref. [26] so that only a short overview will be given here. The results from all tested fluids used in Ref. [26] confirm that a correlation seems to exist between thread formation and the extensional behavior of the fluids, in particular with high values of the Trouton ratio.

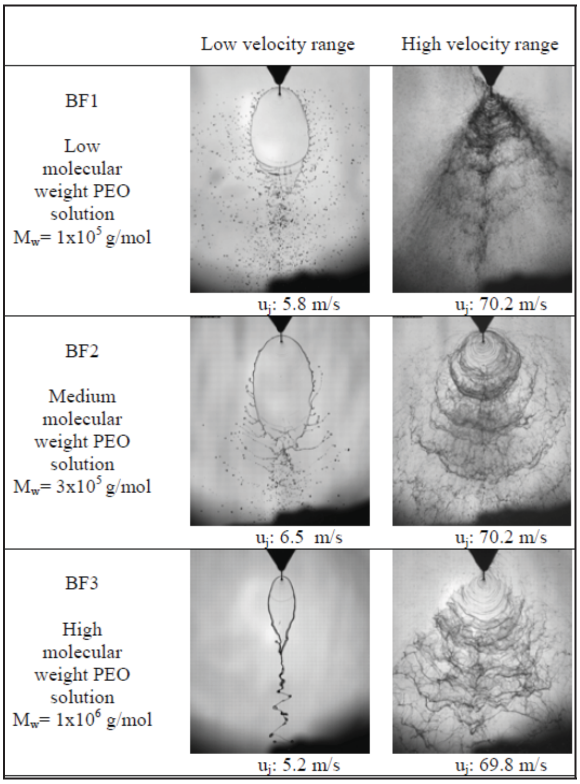

FIG 14. Shadowgraph images of the spray tests conducted with three different Boger fluids.

The tests conducted with Boger fluids were particularly significant to reach this conclusion. Direct measurements of the Trouton ratio of the Boger fluids tested have been conducted in Ref. [25], and the results are also presented in the current paper in figure 3. These measurements show that increasing the molecular weight increases the Trouton ratio. It can be seen on the shadowgraph images of Fig. 14 that the Boger fluid with the highest molecular weight and therewith with the curve with the highest Trouton ratios (in Fig. 3) is the one producing the most marked threads, which breakup less also at high injection velocities.

The surface tensions of Boger fluids were measured and it was found that they are very similar, see Table 3. However BF1 lead to formation of droplets, BF2 to the formation of weak threads and BF3 to the formation of marked threads. Therefore for this kind of Boger fluids surface tension does not seem to play a significant role in thread formation. However the influence of surface tension should be studied in future works considering a wider range of fluids. The three Boger fluids tested have also very similar shear viscosities, but behave differently concerning thread formation. From these results it seems that both shear viscosity and surface tension do not play a significant role in thread formation.

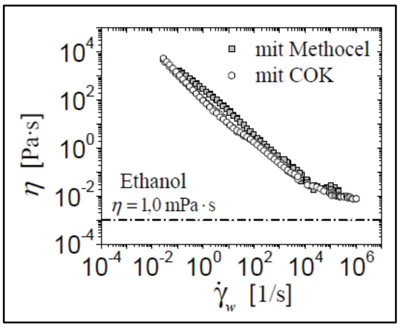

FIG 15. Flow curves (shear viscosity vs. shear rate) of the two different ethanol based gels tested.

It has been shown in Fig. 13 that threads instead of droplets can be produced with one of the presented ethanol based gels. The shear viscosity curves of the two gels in Fig. 15 are very similar in the range of shear rates 0.1 to 10^6 s^{-1}. Trouton ratios have been determined for both gels and presented in Ref. [26]. The results show that the threads producing gel has significantly higher Trouton ratio values. Taking also into account the results from the spray experiments with the Boger fluids, it is obvious that the extensional viscosity and therewith the Trouton ratio influences the spray behavior.

It should be mentioned that it was not possible to conduct measurements with the Malvern Spraytech with the droplets producing fluids in this sub-chapter. This is due to due fact that the Malvern Spraytech gives reliable results only when droplets that are spherical or quasi spherical are measured as has yet been written previously. Anyway due to the problem created by threads to the combustion it should be avoided to use gels in combustors that produce such structures instead of droplets.

4. CONCLUSIONS

Average drop sizes and drop size distributions have a strong influence on combustor processes. In the present publication the results of various spray test campaigns concerning the determination of droplet sizes conducted in the last few years at DLR Space Propulsion Institute at Lampoldshausen with doublet like-on-like impinging jet injectors and various Newtonian and non-Newtonian fluids are summarized. The investigations were conducted under ambient conditions and injector velocities up to 80 m/s have been used. The measurement of the size of the droplets (Sauter mean) has been conducted with a Malvern Spraytech device, based on laser diffraction.

A large number of Newtonian fluids have been chosen to cover a very wide range of Ohnesorge numbers. The results of the tests show that the Sauter diameters of the drops at corresponding mass flow rates are quite similar for all fluids with low surface tension (less than 28 mN/m). In particular all the alcohols tested showed droplets with almost the same diameter. The situation changed significantly when fluids with higher surface tensions have been tested. In particular the droplets produced with three glycerin-water solutions (30-75-85 wt.-% glycerin) are fairly larger. Also ethylene glycol fits into this trend having both surface tension and drop sizes in between alcohols and glycerin. For the fluids with the highest Ohnesorge numbers tested the results are not clear, which may be caused by limitations of the measuring system due to the possible existence of significantly non-spherical droplets.

Different kinds of non-Newtonian fluids have also been tested. A comparison between the spray behavior of pure solvents and of gels based on the same solvents has conducted. Pure Jet A-1 and pure ethanol produce droplets of roughly the same size of their corresponding gels. On the other hand the paraffin gel produces larger droplets compared to pure paraffin.

Also the influence of aluminum particles in a Jet A-1 / Thixatrol ST gel has been studied. The gel without addition of particles shows the smaller droplets, while the gels with percentages of aluminum varying between 10 and 30 wt.-% have slightly larger droplets. The gel with 40 % aluminum loading presents scattered results. This could be caused by the fact that the produced droplets were not spherical and so the Malvern Spraytech cannot give reliable results.

During the tests conducted with non-Newtonian fluids a peculiar behavior has been observed, where the atomization of some gels did not lead to the formation of droplets, but of threads-like structures. To better understanding this phenomenon a research campaign is currently ongoing at DLR. Particularly helpful for the understanding of the governing processes of thread formation have been the spray test conducted with Boger fluids. The results of these tests as well as of tests with other kinds of non-Newtonian fluids suggest that the extensional behavior of the fluid is strongly connected to thread formation. Moreover it seems that other fluid parameters as surface tension and shear viscosity do not correlate significantly with tread formation. Further detailed investigations are necessary to get a better insight in the governing processes which lead to thread instead of droplet formation.

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