SPRAY AND COMBUSTION CHARACTERISTICS OF ALUMINIZED GELLED FUELS WITH AN IMPINGING JET INJECTOR

J. von Kampen, H.K. Ciezki
German Aerospace Center (DLR), Space Propulsion Institute, Lampoldshausen, Germany

F. Alberio
P Lab, Politecnico di Milano, Milan, Italy

Abstract

The influence of the aluminium (Al) particle content of gelled Jet A-1 based fuels on spray and combustion characteristics as well as on rheological properties has been investigated. A description of the dependence of the viscosity from shear rate and Al content will be given. The atomization behavior of these fuels with a doublet like-on-like impinging jet injector under ambient conditions concerning pressure and temperature is presented. The combustion behavior of gel sprays in air under both elevated pressure and air temperature conditions has been investigated.

Introduction

The addition of energetic particles like carbon, aluminum or boron to liquid fuels is of interest for the realization of throttleable engines with increased flight performances due to the significantly higher energy content of these particles per unit volume in comparison to pure hydrocarbon fuels. Beside more complex combustion phenomena like shell formation on droplets (see e.g. [1-3]) slurry fuels show several severe problems in connection with long-time stability and stability under elevated accelerations due to sedimentation effects, etc., which are also today not yet completely solved.

In gelled fuels with metal particle addition, however, particle sedimentation effects are significantly lower than in slurries and separation effects occur only at very high acceleration levels. This behavior is caused by the internal structure of the gel, where the particles are embedded in the 3D-network of the gellant. Furthermore spillage is significantly reduced in comparison to slurries in cases of leakages and damages due to the “semi-solid” structure of gels under ambient conditions. Due to their shear-rate dependent non-Newtonian flow behavior, they offer the possibility to build throttleable engines, which have additionally similar simple handling characteristics like engines with solid fuels.

Since the 60's efforts have been made continuously to use gelled propellant systems in the United States (e.g. [4]) and later also in other countries. The first reported successful flight demonstration of two test missiles has been conducted in 1999 and 2000 by TRW [5]. More detailed information about these and other investigations are given in the survey of Natan and Rahimi [6] and in [7,8].

The addition of gelling agents to conventional liquid fuels and the conduction of a gellation process changes their rheological properties dramatically. Without any applied shear stress gels are more or less incapable of flow with very high dynamic shear viscosity values and often even a distinct yield stress. Applying high shear rates during the injection process, however, it is possible to reach relative low viscosity values and possibly even liquefaction in the area near the injector exit plane. So an atomization similar to conventional liquid fuels is possible for distinct injection conditions and set-ups as previous experiments have shown, but this process is more difficult to conduct than in the case of pure fuels. Furthermore the vaporization rate of gels is expected to be lower if compared to pure fuels and also the burning behavior of droplets is significantly different [9]. Summarizing these facts, care has to be taken to realize a good atomization and an effective organization of the combustion process in order to reach high combustion efficiencies. The aim of the presented investigation was to show the influence of the aluminium content of Jet A-1 based gels on their spray and combustion behavior.

Experimental Set-ups

The gelled fuels have been produced making use of a Getzmann dissolver stirrer apparatus. The rheological properties (shear viscosity traces and yield stresses) have been obtained with a ThermoHaake RheoStress 1 viscosimeter.

The experimental set-up for the spray behavior investigations is presented in the sketches of Figs. 1 and 2. It consists of a cartridge containing the gelled fuel, a hydraulic driving unit and the injector unit. The feeding of the gel to the injector unit is conducted by moving a piston inside the cartridge and pushing the gel through a tube, which connects the cartridge with the injector unit. The pressure inside the cartridge and the injector unit is monitored by pressure gauges.

For the investigation presented here a doublet like-on-like impinging jet atomizer has been chosen, whose sketch is shown in Fig. 2. This injector type is often used in liquid rocket engines operated with storable Newtonian fuels due to its simplicity and its good atomization and mixing characteristics [10]. All experiments presented here have been conducted with an injector exit diameter d=0.7 mm and an impingement angle of 2θ=90°. The shadowgraph technique has been applied for the visualization of the spray behavior together with a Nanolite spark light source with a flash duration of 18 ns (FWHM). Further information about the set-up and the injector design is given e.g. in Refs. [7,8,11].

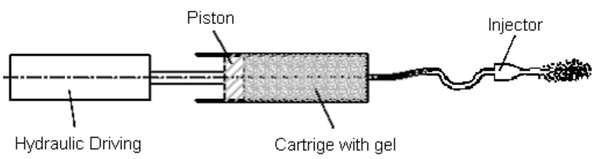


Fig. 1. Sketch of a gel feeding line

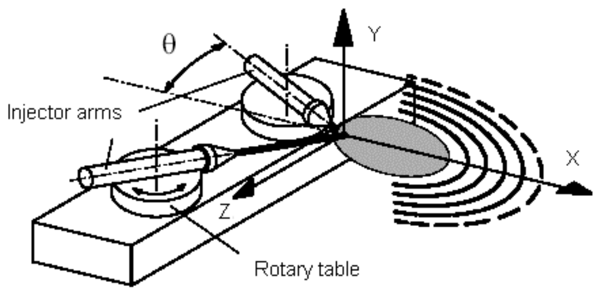


Fig. 2. Sketch of the modular doublet like-on-like impinging jet injector set-up

For the investigation of the combustion behavior of gelled fuels under ramjet relevant conditions concerning pressure and air inlet temperature a pressurized combustion chamber has been used, whose sketch can be seen in Fig. 3. The combustion chamber has a diameter of 0.3 m, a height of 0.9 m and consists of steel rings, which are hold together by a hydraulic system. One of the steel rings contains windows so that a direct access to the occurring processes inside the chamber is given for optical diagnostic tools. The pressure in the chamber can be varied by changing exit nozzles of different diameter located in the lowest ring.

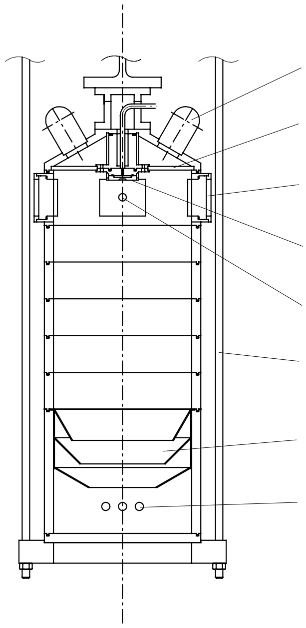


Fig. 3. Sketch of the combustion chamber

The experimental set-up has been designed for maximum air inlet temperatures of 800 K and maximum pressures of 12 bar. Assuming isentropic ramjet air intake conditions flight Mach numbers up to 3.6 can be simulated.

In the present investigation combustion tests have been conducted at 6 and 11 bar with three different temperatures of the incoming air of 300, 550 and 800 K. The gel jet exit velocity u_{gel} has been varied between 12 and 70 m/s. The air to fuel ratio was higher than 45 for an undisturbed observation of the combustion process of a single injector element. A test series, where the air/fuel ratio has been varied, has shown that the combustion efficiency is not influenced so that combustion lengths are significantly lower than the chamber length.

Results and discussion

Rheological properties

Jet A-1 as a commercially and easily available liquid fuel has been chosen for the presented experiments and has been gelled with Thixatrol ST, an organic-based gellant. Thixatrol ST is a castor oil derivative from Rheox, which has been used together with 5-Methyl-2-Hexanone (Miak) for the vehicle/solvent mixture for the gellation process. Al particles with an average diameter of 9 µm (-325 mesh size) and 99.5 % purity are from Alfa Aesar. The chemical composition of the produced gels is presented in Tab. 1.

Table 1

Chemical composition of the produced gels in wt.-%

Test fuel number	Jet A-1	Thixa-trol ST	Miak	Alumi-nium
	[%]	[%]	[%]	[%]
TF1	65	7.5	7.5	20
TF2	60	7.5	7.5	25
TF3	55	7.5	7.5	30
TF4	50	7.5	7.5	35
TF5	45	7.5	7.5	40
TF6	85	7.5	7.5	-

Gel fuels are shear-thinning fluids, which show decreasing shear viscosities η with increasing shear rates $\dot{\gamma}$ as can be seen in the diagram of Fig. 4. Here the shear viscosity curves of the test gel fuels of Tab. 1 are presented together with pure Jet A-1, which is a Newtonian fluid of constant viscosity. It can be seen that the viscosity values of the gels at low and medium shear rates are orders of magnitude higher than of pure Jet A-1.

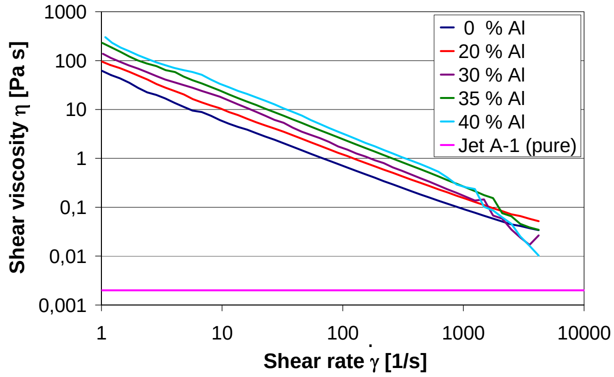


Fig. 4. Shear viscosity vs. shear rate

For gels of the here presented type the η-$\dot{\gamma}$-dependence can be described for low and medium $\dot{\gamma}$ by the Herschel-Bulkley equation

$$\eta = \frac{\tau_0}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \qquad (1)$$

where K is the pre-exponential factor, n the exponential factor and τ_0 the yield stress. These gels are not capable of flow, if applied shear stresses are below the yield stress. It can be seen in Fig. 4 that with increasing Al content increasing viscosities occur.

Table 2

Herschel-Bulkley coefficients and $Re_{gen,krit}$ of gels and properties of Jet A-1

Test fuel number	Y_{Al}	K	n	τ_0	$Re_{gen,krit}$
	[wt.-%]	[Pa·s^n]	[-]	[Pa]	[-]
TF1	20	50	0.12	34.5	1902
TF2	25	63	0.095	52.7	1681
TF3	30	72	0.078	76.1	1482
TF4	35	78	0.067	135.9	1337
TF5	40	81	0.062	225.5	1273
Jet A-1 (pure)	0	0.002	1	-	2300

The related Herschel Bulkley coefficients have been calculated making use of the viscosimeter software and are listed in Table 2. It can be seen that all gels have a distinct yield stress so that they appear “solid” at unstressed ambient conditions. With increasing aluminium content increasing yield stresses, increasing pre-exponential factors K and decreasing exponential factors n occur.

For the characterization of the flow behavior of non-Newtonian fluids of the power-law type ($\eta = K\dot{\gamma}^{n-1}$) through constant area tubes Reed, Metzner and co-workers [12] introduced a generalized Reynolds number

$$Re_{gen} = \frac{\rho u_{gel}^{2-n} d^n}{K\left(0.75 + \frac{0.25}{n}\right)^n 8^{n-1}} \qquad (2)$$

Also for power-law fluids in pipes Ryan and Johnson [13] developed theoretically an equation for the determination of the critical Reynolds number $Re_{gen,krit}$, which separates the laminar from the turbulent flow regime.

$$Re_{gen,krit} = 885\frac{8n}{(1+3n)^n}(2+n)^{\frac{2+n}{1+n}} \qquad (3)$$

Experimental investigations [12] with fluids of exponential factors n between 0.16 and 1 showed that Eq. (3) can be used in this range of values. The exponential factors of the gels of the present investigation, however, are below 0.16. Due to the fact that related relevant data are not available, Eq. (3) has been used for the calculation of $Re_{gen,krit}$ values, presented in Table 2. The higher the Al content the lower is $Re_{gen,krit}$.

Atomization behavior

The impingement of two equal cylindrical coplanar jets produces an expanding sheet in the plane perpendicular to the plane containing their axes as can be seen e.g. in Figs. 1 and 5. This sheet disintegrates in different ways depending on various parameters like jet velocity, impingement angle, fluid properties, etc. Heidmann et al [14] have first identified four different breakup patterns with increasing jet velocities for a Newtonian 70% glycerol solution. For further information concerning impinging jet atomization research up to 1995 please see e.g. the survey in the article of Santoro, Anderson et al [15].

A test campaign has been conducted with the three Jet A-1 based gels TF3, TF4 and TF5 with high Al contents. Three different spray patterns have been identified on the shadowgraph images and typical examples are presented in Fig. 5.

- Rays-shaped pattern (Fig. 5a): At low Re_{gen} a rays-shaped structure, with its origin near the impingement point, occurs on the surface of the sheet. The sheet decays first in a net-like structure and downstream in small ligaments and larger droplets, whereas distinct radial ligaments in direction of the rays can be seen.
- Ligament pattern (Fig. 5b): At medium Re_{gen} circular wave-like structures occur on the surface of the sheet and large bow-shaped ligaments are separated periodically from the rim. These ligaments decay downstream into smaller ones and droplets.
- Fully developed pattern (Fig. 5c): At very high Re_{gen} the shape of the fluid sheet becomes small and irregular. It breaks up directly into very fine droplets without fragmenting into ligaments. These droplets are preferably shed off in a periodic manner as waves from the sheet edge.

Ligament pattern and fully developed pattern are well known from impinging jet investigations with Newtonian fluids, see e.g. [15]. The rays-shaped pattern, however, has first been observed with gel fuels [16] and could be found last year also for Newtonian fluids [17] at Reynolds numbers below 200 and Weber numbers below 2000.

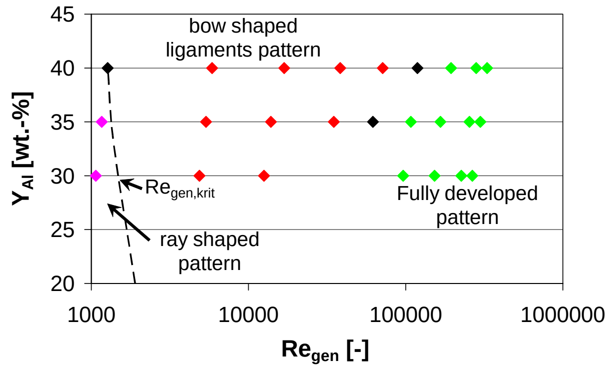
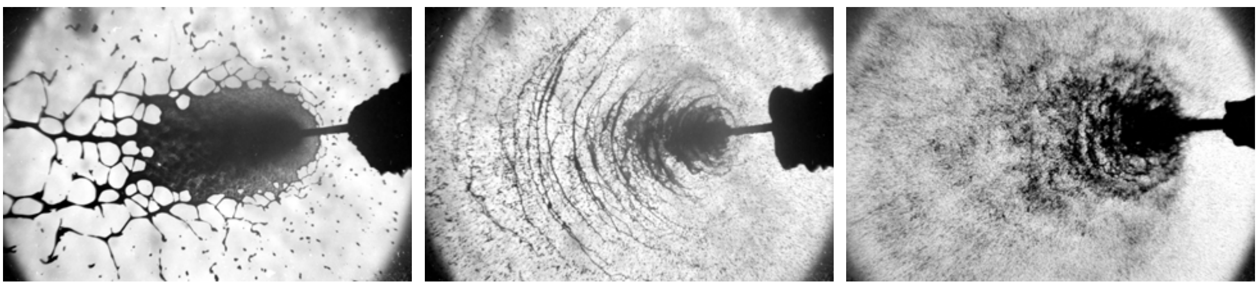


Fig. 6. Spray regimes

Figure 6 shows the different spray regimes for the gelled fuels TF3-TF5 in dependence of Re_{gen}. It can be seen that the rays-shaped pattern (violet symbols) occurs at Reynolds numbers below $Re_{gen,krit}$. This means that the gel jets are leaving the nozzle orifices under laminar conditions. For Y_{Al}=40% and Re_{gen}=1340 a transition between the rays-shaped and the ligament pattern has been observed, whose structure can be seen on the image of Fig. 7.

The transition between the ligament pattern (red symbols) and the fully developed pattern (green symbols) occurs at Re_{gen} of about 100,000, whereas no clear transition point could be identified so that the related



a b c

Fig. 5. Shadowgraph images, 35%Al/Jet-1 gel (TF4)

a: u_{gel}=5.1 m/s, Re_{gen}=1210
b: u_{gel}=18 m/s, Re_{gen}=13890
c: u_{gel}=88 m/s, Re_{gen}=296630

.

experiments in the diagram are presented in black color.

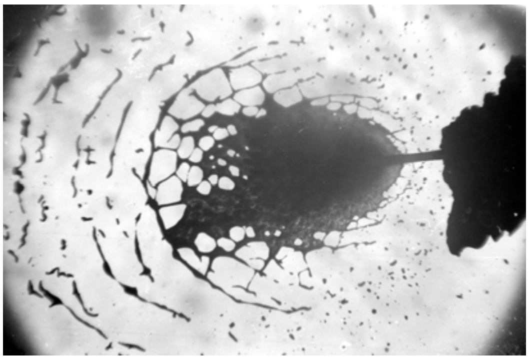


Fig. 7. Shadowgraph image of transition between rays-shaped and ligaments pattern. Y_{Al}=40% (TF5), u_{gel}=5.1 m/s, Re_{gen}=1320, $Re_{gen,krit}$=1273

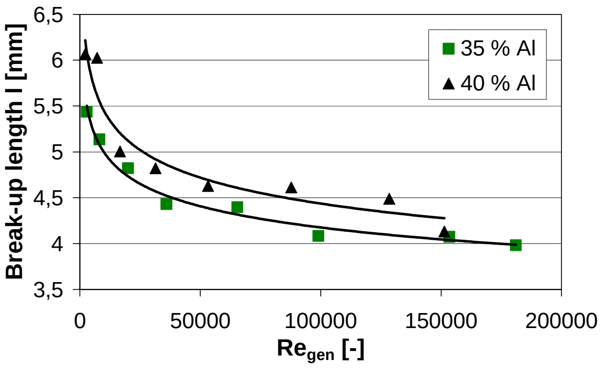


Fig.8. Break-up length vs. Re_{gen}

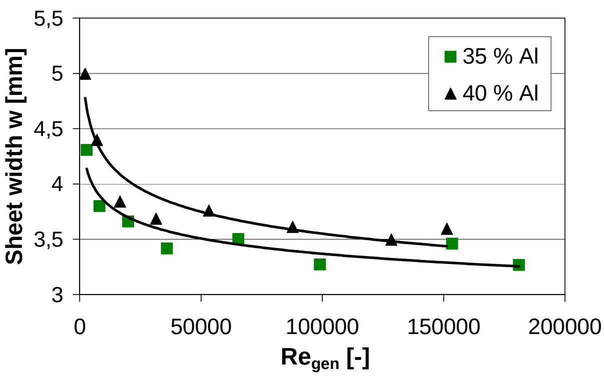


Fig. 9. Sheet width vs. Re_{gen}

The shape of the gel sheet and the position of the break-up point changes with increasing velocity and Reynolds number. Figure 8 presents the break-up length, which is the over a series of images averaged distance from the impingement point to the line where the ligaments are completely separated. With increasing Re_{gen} decreasing break-up lengths have been determined, whereas the trace shows a steep decrease at low Re_{gen} and flattens to higher Re_{gen}. Comparing TF4 and TF5 higher break-up lengths and sheet widths (Fig. 9) have been found for the higher Al content. Also could be found that the distance between the ligaments decreases with increasing Al content.

Combustion behavior

The combustion behavior of gelled fuel sprays in hot air has been investigated under ramjet relevant conditions concerning pressure and temperature of the ambient air. The combustion efficiency ε is defined as the ratio of the "real" heat of combustion ΔH_r to the theoretical heat of combustion ΔH_{th}. ΔH_{th} is calculated making use of the Gordon-McBride CEA program [18] with the mass flow and the state and the species distribution before combustion, whereas adiabatic conditions in the combustor have been assumed. The calculation of the "real" heat of combustion ΔH_r is based on the measured pressure increase due to the combustion, whereas the heat-loss through the chamber walls has also been taken into account.

Figure 10 presents the combustion efficiency of TF4 with 35% Al content in dependence upon the theoretical combustion temperature T_{th}, which has also been calculated with the Gordon-McBride program. It can be seen that the efficiency increases with increasing T_{th} for both chamber pressure levels, whereas higher efficiencies have been obtained for the higher pressure level. For 30% and 40% Al loading, which are not presented here due to limited space, a similar behavior has been found, whereas a maximum of ε could be indicated in the investigated Y_{Al} region, but further investigations are necessary to sustain these results.

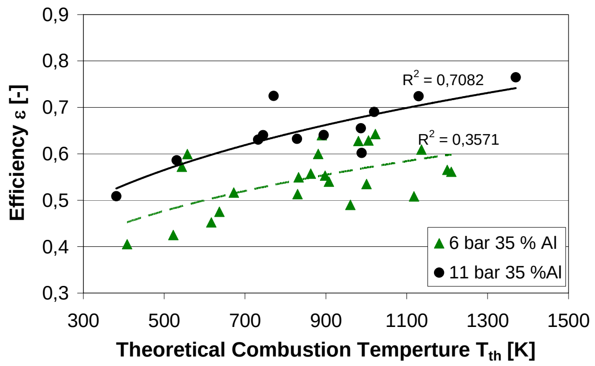


Fig. 10. Combustion efficiency versus theoretical combustion temperature for 35%Al/JetA-1 gel (TF4)

Conclusions

A detailed study concerning rheological, Spray (atomization) and combustion behavior of gelled Jet A-1 based fuels with various aluminum contents has been conducted. The shear viscosity measurements show that with increasing Al content increasing viscosity values and yield stresses occur.

The spray experiments have shown that all investigated gels up to Y_{Al}=40 % can be atomized. With increasing generalized Reynolds numbers Re_{gen} decreasing break-up lengths and sheet widths have been found, whereas for higher Y_{Al} higher values have been obtained. Three different spray regimes could be identified and have been presented in a regime diagram in dependence upon Y_{Al} and Re_{gen}. It could be shown that the rays-shaped pattern occurs at laminar conditions of the gel jets.

The combustion efficiency of gel sprays shows increasing values with increasing theroretical combustion temperatures.

Acknowledgments

The authors would like to thank J. Liebl and R. Brändle for the production of the gel fuels and A. Feinauer for his help during the conduction of the experiments. Also the helpful discussions, comments and proposals of Prof. L. DeLuca are gratefully acknowledged.

References

[1] Szekely Jr GA and Faeth GM. Combustion properties of carbon slurry drops. *AIAA Journal*, Vol. 20, No. 3, pp 422-429, 1982.

[2] Lee A and Law CK. Gasification and shell characteristics in slurry droplet burning. *Combustion and Flame*, Vol. 85, pp 85-93, 1991

[3] Mueller DC and Turns SR. Some aspects of secondary atomization of aluminum/hydrocarbon slurry propellants. *J. of Propulsion and Power*, Vol. 9, No. 3, pp 345-352, 1993.

[4] Rapp DC and Zurawski RL. Characterization of aluminum/RP-1 gel propellant properties. AIAA-88-2821, July 1988.

[5] Hodge K, Crofoot T and Nelson S. Gelled propellants for tactical missile applications. *39th Joint Propulsion Conference*, Los Angeles, CA, USA, AIAA-99-2976, 1999.

[6] Natan B and Rahimi S. The status of gel propellants in year 2000. in: *Combustion of energetic materials*, pp 172-194 (Eds.: KK Kuo and LT DeLuca), Begell House, USA, 2002.

[7] Bartels N, von Kampen J, Ciezki HK and Begnini M. The atomization of gelled fuels with a doublet like-on-like impinging jet injector under ambient pressure and temperature conditions. *Novel Energetic Materials, Proc 9th Int. Workshop on Combustion and Propulsion (9-IWCP)*, Lerici, Italy, pp 39-1 – 39-13, September 2003.

[8] Ciezki HK, Robers A and Schneider G. Investigation of the spray behavior of gelled jet A-1 fuels using an air and an impinging jet atomizer. *38th AIAA Joint Propulsion Conference*, Indianapolis, IN, USA, AIAA-2002-3601, July 2002.

[9] Nachmoni G and Natan B. Combustion characteristics of gel fuels. *Combustion Science and Technology*, Vol. 156, pp 139-157, 2000

[10] Sutton GP. *Rocket propulsion elements: an introduction to the engineering of rockets.* John Whiley, New York, USA, 1992, pp 298-311.

[11] Ciezki HK, Bartels N, von Kampen J and Madlener K. Properties of gelled propellants for throttleable propulsion systems. *Proc Symposium on Energy Conversion Fundamental*, Istanbul, Turkey, June 2004.

[12] Dodge DW and Metzner AB. Turbulent flow of non-Newtonian systems. *A.I.Ch.E. Journal*, Vol. 5, No. 2, pp 189-204, 1959.

[13] Ryan NW and Johnson MN. Transition from laminar to turbulent flow in pipes. *A.I.Ch.E. Journal*, Vol. 5, No. 2, pp 433-438, 1959.

[14] Heidmann MF, Priem RJ and Humphrey JC. A study of sprays formed by two impinging jets. *NACA TN 3835*, 1957

[15] Anderson WE, Ryan HM and Santoro RJ. Impinging jet injector atomization. *Liquid Rocket Engine Instability*, Eds.: V Yang and WE Anderson, Progress in Astronautics and Aeronautics, Vol. 169, AIAA, pp 215-246, 1995.

[16] Bartels N, von Kampen J, Ciezki HK and Zanetti N. Investigation of the spray characteristic of an aluminized gelled fuel with an impinging jet injector. *Proc Annual Conference of ICT*, Karlsruhe, Germany, 2004.

[17] Bartels N, Ciezki HK, Tiedt T and von Kampen J. Investigation of the atomization behavior of a doublet like-on-like impinging jet atomizer in a wide range of Reynolds and Weber numbers. *ILASS 2004*, Nottingham, UK, September 2004.

[18] McBride BJ and Gordon S. Computer program for calculation of complex chemical equilibrium compositions and applications, Part II. *NASA Reference Publication 1311*, June 1996.