INVESTIGATION OF THE ATOMIZATION BEHAVIOR OF A DOUBLET LIKE-ON-LIKE IMPINGING JET ATOMIZER IN A WIDE RANGE OF REYNOLDS AND WEBER NUMBERS

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Abstract

The spray characteristics of a doublet like-on-like impinging jet injector in dependence upon Reynolds and Weber numbers have been investigated under ambient pressure and temperature conditions. The breakup behavior has been visualized with the shadowgraph technique. Various fluids have been used to cover a wide range of Reynolds and Weber numbers, i.e. about 60<Re<30,000 and 100<We<30,000. Different atomization regimes could be observed at different Re and We conditions.

1. INTRODUCTION

Impinging jet injectors are often used for the atomization of storable liquid fuels in rocket engines due to their simplicity, low manufacturing costs, good atomization and mixing characteristics, etc. [1,2]. Detailed basic experimental studies about the spray behavior of impinging jet injector systems concerning sheet breakup characteristics, droplet formation, etc. of Newtonian fluids have been published recently, see e.g. Refs. [3-10]. Also for the atomization of gelled fuels, which show a non-Newtonian flow behavior, impinging jet injectors are interesting due to fact that high shear rates are produced both in the taper inside the injector tip and in the region around the intersection point of both liquid jets so that the viscosity is strongly decreased and these gelled fluids can be liquefied. So they can be atomized as has been shown in previous investigations, e.g. [11,12].

In newer experiments it could be observed that distinct fuel/gellator-combinations show unknown breakup modes in distinct Reynolds number regions, whereas e.g. finger-like or ray-shaped structures occur [13]. In order to investigate whether these effects are caused by the non-Newtonian properties or whether they occur also with Newtonian fluids a detailed investigation with Newtonian fluids has been conducted in a wide range of Reynolds and Weber numbers. This publication presents first results of the ongoing investigation.

2. EXPERIMENTAL SETUP

The general features of the experimental set-up for this investigation are presented in the upper sketch of Fig. 1. The setup consists of a cartridge with the fluid to be investigated, a hydraulic driving unit and the injector unit. The feeding of the fluid to the injector is conducted by moving a piston inside the cartridge so that the fluid is pushed through a connecting tube and the injector. The velocity of the fluid jets leaving the injector orifices can be varied by varying the piston velocity so that the average jet exit velocity can be calculated from the piston movement, which is monitored by a piston encoder. The pressure inside the cartridge and the injector unit is observed by pressure gauges. The injector unit is modular and allows to study of the influence of various parameters, as can be seen on the lower sketch of Fig. 1. The movable rotary tables permit to vary the impingement angle 2θ as well as the impingement distance. The injector nozzles can easily be changed for the variation of the nozzle exit diameters and the internal injector geometry. For the present investigation an impingement angle $2\theta=90°$ and equal distances of 10 mm between the impingement point and both nozzle exits have been chosen.

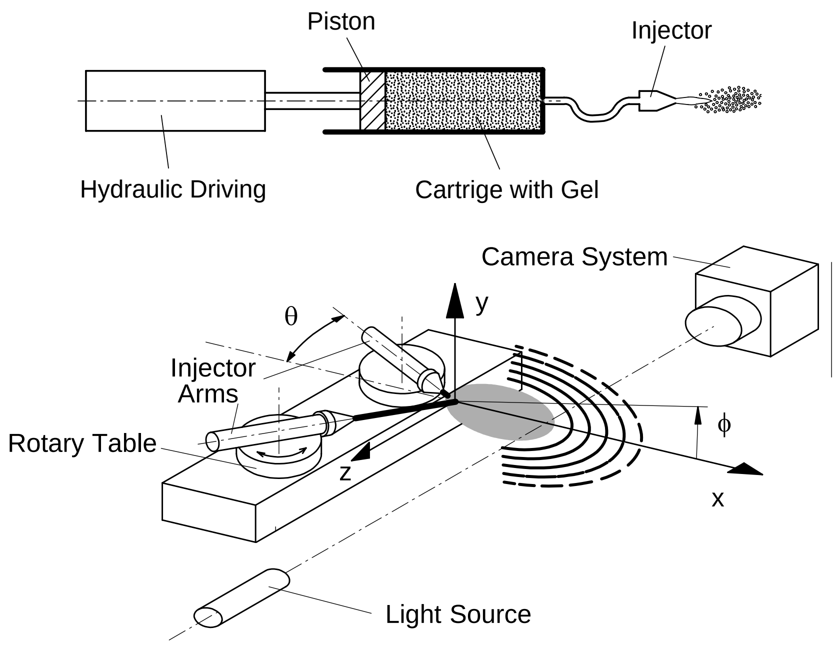


Fig. 1: Schematic sketch of the experimental facility (top) and the modular doublet like-on-like impinging jet injector setup (bottom)

For the visualization of the spray characteristics the shadowgraph-technique has been used with a Nanolite spark light source with a flash duration of 18 ns (FWHM) and a conventional camera. The image plane of all these images is perpendicular oriented to the injection plane, which is spanned by the two impinging gel jets. The obtained images show an area of 26.1 x 17.2 mm².

Figure 2 shows the internal geometry of the injector nozzles. The high ratio $l/d=10$ of the internal injector channel length l to nozzle exit diameter d as well as the internal wall inclination angle of $\alpha=20°$ have been chosen both to reduce influences of separation by the formation of a vena contracta, etc. in the intake to the injector channel [14] and to induce a more fully developed velocity profile at the injector exit. For the present investigation 0.7 mm and 1.0 mm orifice diameters have been used. The accuracy of all lengths and angles is better than approximately 5%.

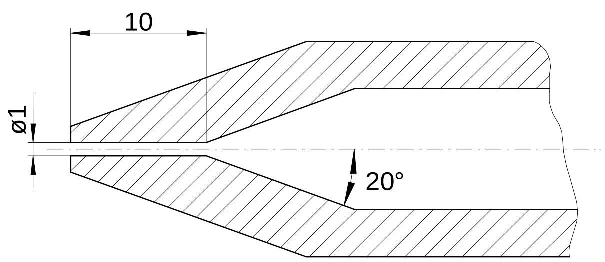
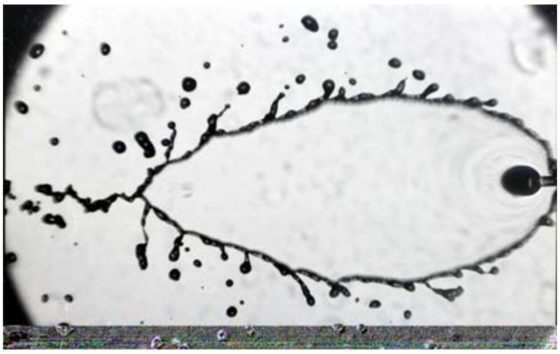


Fig. 2: Sketch of the injector tip with an orifice diameter d=1 mm

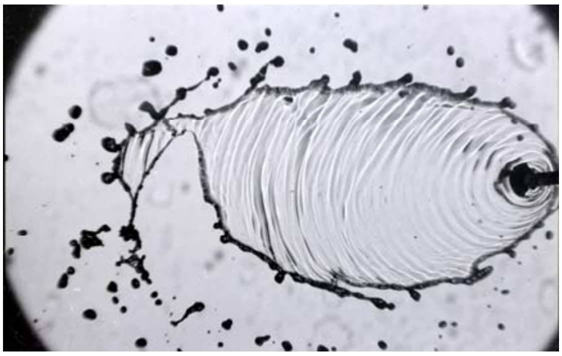
3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 presents shadowgraph images of the atomization behavior of water at various Re and We numbers, whereas the variation has been realized by the variation of the jet exit velocity. At low and medium Re and We numbers the well known liquid sheet can be seen, which is formed at the impingement point. At low Re and We numbers the sheet has a distinct rim from which droplets are peeled of as can be seen in Fig. 3a. At the downstream end of the sheet (on the left side of the image) the sheet becomes smaller and forms a jet, which decays farther downstream. This breakup mode has been described in previous publications as “closed rim with droplet formation”. On the surface of the sheet circular shaped waves can be seen, which are caused by the impact of both jets. These hydraulic waves are damped under laminar flow conditions as Jung at al [10] have reported for water and a different impingement angle $2\theta=60°$. At higher Re and We numbers the circular waves are not damped and are influencing the breakup behavior. At Re=3450 (Fig. 2b) the sheet is ruptured from the sides so that parts of the sheet are separated. These separated parts contracts from the ends and decay farther downstream.

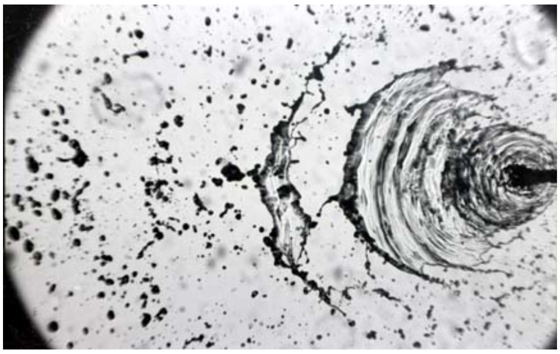
At medium Re numbers the rupturing process starts earlier so that the distinct rim vanishes and the sheet length is shortened as can be seen on Fig. 3c. Parts of the sheet are separated periodically and decay farther downstream so that this atomization mode is called "rimless separation". At high Re numbers (together with high We numbers) the breakup process becomes highly turbulent. The structures on the sheet cannot be identified clearly and also holes occur in the sheet as can be seen on Fig. 3d. Furthermore the end of the sheet cannot be identified anymore as at lower Re numbers. Bow shaped ligaments can be seen behind the "sheet", which decay farther downstream. At the highest Re number (Fig. 3e) a direct decay into droplets can be seen. These droplets are mainly concentrated in wavy structures, which move downstream. This mode is called in literature the "fully developed pattern".



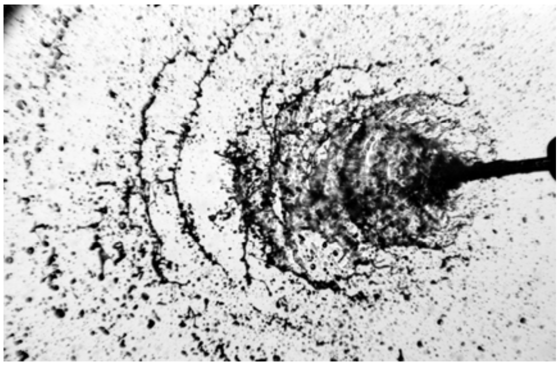
a. Re=2480, We=160, 1178



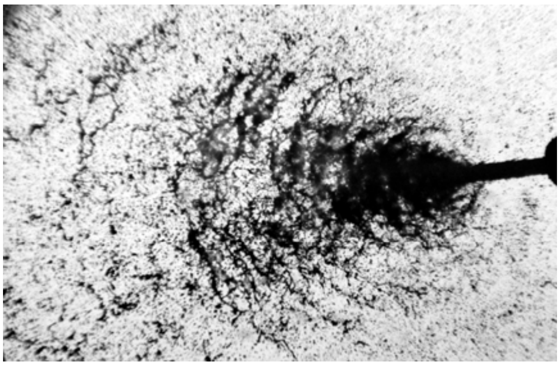
b. Re=3450, We=320, 1177



c. Re=5020, We=670, 1175



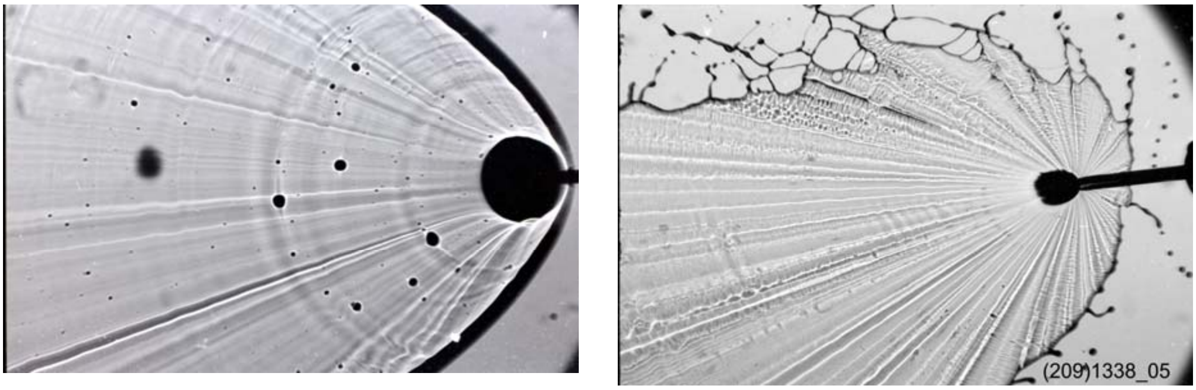
d. Re=10030, We=3420, 1421



e. Re=23740, We=19650, 1427

Fig. 3: Shadowgraph images of the atomization behavior of water at different Re and We numbers

Figure 4 shows the sheet pattern at very low Re numbers. A ray-shaped structure with its origin at the intersection point occurs, which might have an influence on the break-up of the sheet as can be seen on the image of Fig. 4b. Also ray-shaped and wave-shaped could simultaneously under distinct conditions. Further investigations are necessary for the understanding of these phenomena.



Cyclo Hexanol, Re= Ethylene Glycol, Re=385, We=1025

Fig. 4: Shadowgraph images with ray-shaped structures

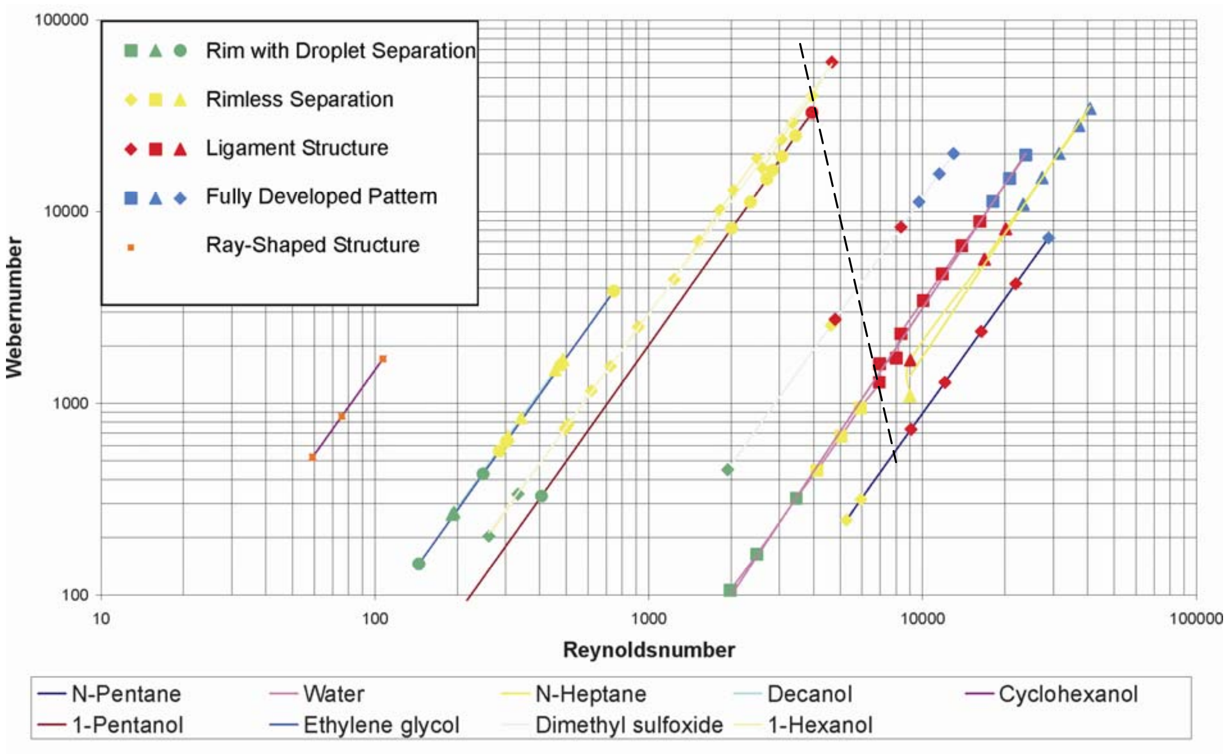


Fig. 5: Regime diagram

An overview about the different breakup and atomization processes is given in a regime diagram, presented in Fig. 5. These diagram presents these regimes in the parameter space of the Reynolds number Re and the liquid Weber number We. Each symbol represents an experiment and the color identifies the breakup regime. The investigated fuels related to these experiments can be identified by the different lines. It can be seen, that the rim with droplet separation regime, to which the experiments of Fig. 3a and b belong, is located below a constant We number of ca. We=400. The transition from the rimless separation regime to the ligament structure regime, however, which is marked by a dashed line, occurs with increasing Re at lower We. The fully developed pattern regime has only been found at the species presented by the four right lines at the highest Re numbers due to the limited velocity. Furthermore ray-shaped structures on the fluid sheet have been found at very low Re numbers, whereas fluid sheets with distinct rims also occur here above We=400.

4. SUMMARY AND CONCLUSION

The atomization behavior of a doublet like-on-like impinging jet injector has been investigated under ambient temperature and pressure conditions. For the visualization the shadowgraph techniques has been used. A variation of Reynolds and Weber number in a wide range has been realized by using various fluids with different shear viscosity, density and surface tension values. Different breakup regimes could be identified and have been presented in a regime diagram as a Re-We-plot. Additionally to the circular shaped waves on the surface of the sheets, ray-shaped structures have been observed at very low Reynolds and medium Weber numbers.

5. NOMENCLATURE

d	orifice diameter, m
l	internal channel length, m
Re	Reynolds number, $Re=\rho ud/\eta$, -
u	jet exit velocity, m/s
We	Weber number, $We=\rho u^2 d/\sigma$, -
x,y,z	Cartesian coordinates, see Fig. 1, m

Greek

α	wall inclination angle, -°
ϕ	position angle (in y-z plane), -°
θ	impingement half angle, -°
η	dynamic shear viscosity, Pa·s
σ	surface tension, N/m

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