Experimental and theoretical investigations of Twin-Jets

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Abstract
High pressure driven "Twin-Jet sprays" were studied by the authors in connection with development work for new injectors employed in combustion engines. For this purpose, a test rig was set up that allowed two liquid jets to be produced which were crossed under a pre-given angle. From the crossing region, controllable sprays emerged and their properties were investigated for different nozzle-diameters, different crossing angles and different supply pressures to the nozzles. The latter value is equivalent to giving the exit velocity of the jets.
The experimental results, obtained with the test rig set-up for the authors' studies, are summarized in this paper. They were compared with corresponding theoretical results using theories of spray formations by Twin-Jets, available in literature. The agreement, regarding the particle size, was very poor and it was therefore decided to develop a new theory to describe the experimentally obtained data. The resulting theory is summarized and predicted results are compared with corresponding experimental data. Good agreement is achieved.

1. INTRODUCTION AND AIMS OF WORK

There are numerous ways to produce sprays. Different atomizers are available to yield sprays with properties needed in a wide range of applications in various fields of engineering, science and medicine. A good summary of methods of liquid atomization is given in the book of Lefebvre [1] where a classification into pressure atomization, air assists and air blast atomization is introduced. Rotational atomizers are also described by Lefebvre [1] and those working with ultrasonic and electrostatic spray generators are briefly discussed. Hence, this book gives a good summary of existing atomizers, the various methods of atomization and applications in practice.

This paper focuses on the production of sprays using two impinging jets, which generate sprays with very fine droplet diameters even at relatively low pressures. The employed spray mechanism is based on two inclined liquid jets that impinge on each other, to produce, in their interaction region, the mentioned spray. At low Re-numbers of the two impinging jets, a liquid lamella is formed as a thin flat plane perpendicular to the plane of the interacting jets and it is this lamella that disintegrates, first into fluid ligaments and further into droplets that form the actual spray. With increasing Re-number the lamella disappears at a critical Re-number. Fine droplets or fluid ligaments are generated directly from the impingement region as can be observed.

Previous experimental and analytical studies of Twin-Jet spray have been extensively carried out to understand the general disintegration mechanism. Most of these studies focused on modeling the shape and thickness of the formed lamella and predicting the droplet sizes at low Re-numbers. Investigations on the thickness of a liquid sheet have been carried out by Taylor 1960 [2], Hasson & Peck 1964 [3] and Ibrahim & Przekwas 1991 [4]. The shape of the lamella has also been treated by Ibrahim & Przekwas 1991 [4], Kang et al. 1995 [5].

The theoretical treatment of the disintegration mechanism of a plane liquid sheet has been forwarded by Dombrowski & Johns [6]. They treated the aerodynamically caused disintegration of the two-dimensional liquid sheet that is stretched by surrounding air flows, present at both sides of a liquid lamella. Corresponding pressure interaction, acting as disturbances of the liquid sheet, is amplified by the stretching action of the air flows and these finally cause the ligament formation when critical disturbance amplitude is reached. These ligaments become rapidly unstable and break up into fine droplets finally under the action of surface tension. The expressions for the thickness of the lamella and the drop size, derived by Dombrowski & Johns [6] read as follows:

$$d_L = 0.9614\left[\frac{K^2\sigma^2}{\rho\rho_L U^4}\right]^{1/6}\left[1+2.6\mu\sqrt[3]{\frac{K\rho^4U^7}{72\rho_L^2\sigma^5}}\right]^{1/5} \quad (1)$$

$$d_T = \left(\frac{3\pi}{\sqrt{2}}\right)^{1/3} d_L\left[1+\frac{3\mu}{(\rho_L\sigma d_L)^{1/2}}\right]^{1/6} \quad \text{with} \quad K = hx \quad (2)$$

μ: Liquid viscosity; ρ_L: Liquid density; ρ: Gas density; σ: Surface tension; U: Jet velocity;
h: Thickness of the liquid sheet; d_L: Diameter of the ligaments; x: Distance in moving direction.

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Later, Clark and Dombrowski [7] carried out investigations on a fan spray sheet. They made the assumption that the droplets are formed from the rim of the liquid sheet. Based on the experimental data they obtained an expression to predict the drop sizes disintegrated from a liquid sheet of inviscid fluid.
Couto and Bastos-Netto [8] combined the expressions of Dombrowski & Johns [6] and Hasson & Peck [3] to derive an equation for the drop size distribution. They treated the constant K (obtained from Hasson and Peck [3]) as a product of sheet thickness and radial distance from the impingement point and replaced K in eqn. 1 using the flux derived expression.

$$K = hr = \frac{R^2 sin^3\theta}{(1-cos\phi cos\theta)^2} \quad \text{with } r = x \ [6] \qquad (3)$$

Here, θ is half of the impingement angle and ϕ describes the angular position on the liquid sheet. The theory provided by Couto and Bastos-Netto [8] can predict the droplet sizes at any angular position and gives the dependence of the produced drop size on all important parameters. However, the theoretical results failed to produce quantitative agreements with the authors' experiment.
Poulikakos [9] investigated the dense region of a Twin-Jet spray using a novel holographic technique. The effects of several parameters on the atomization process were studied and theoretical predictions were carried out, based on Dombrowski & Johns [6] and Adelberg [10, 11]. The latter author adopted the theory of Weber [12] (eqn. 2), which describes the disintegration mechanism of a liquid jet injected into quiescent air with a movement parallel to the jet axis. Remodeling the break-up of ligaments (eqn.3) using the analysis by Adelberg [10, 11], the obtained prediction represented no improvements to Dombrowski & Johns [6] and Couto & Bastos-Netto [8].
This paper contains the main results of the experimental investigations using water and water – glycerol solutions as test liquids. The effects of jet velocity, orifice diameter and impingement angle are investigated. Based on experimental observations, a theory applicable to high pressure Twin-Jet sprays is provided that is also extended to low pressure Twin-Jets by experimentally based correlations using dimensional analysis, to yield the Sauter-Mean-Diameter and the liquid jet lengths. The effects of several parameters are investigated. The results are generalized by providing them as Oh-Re-correlations and compared with the previous works.

2. TEST RIG FOR THE INVESTIGATIONS

Liquid sheets were formed by the collision of two jets impinging at an angle 2θ. The configuration that we used to measure the Sauter-Mean-Diameter is schematically illustrated in figure 1. This setup is mainly composed of a pump system that supplies controllable pressure to the system, an impinging jet system that forms a liquid sheet or spray, and an optical measurement system that provides the droplets size information.
The liquid from the pump passes through a flow meter and is divided into two identical branches feeding the two individual impinging jets. The pressure is precisely controlled by a bypass valve and monitored using pressure gauges placed just before the inlet of the injectors, while the flow meter shows the instant volume flow rate of the liquid jets.

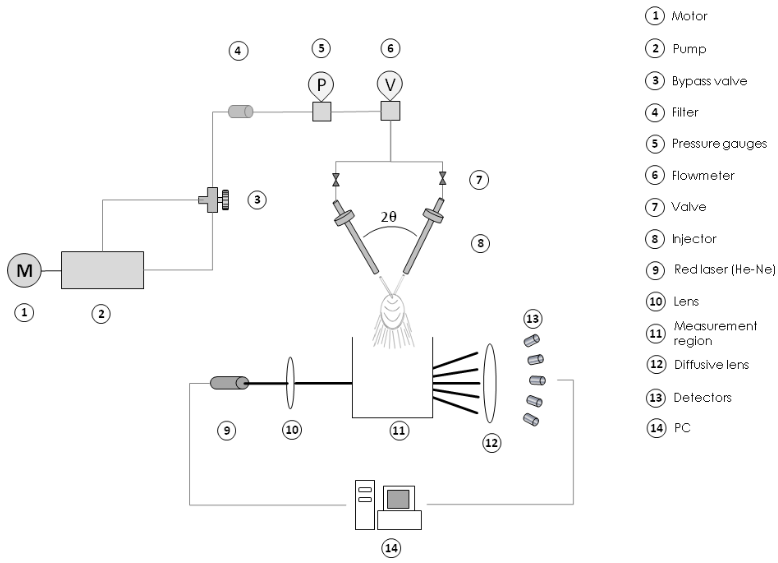

Fig. 1: Schematic of the experimental apparatus.

The injectors used precision-bore apertures, which feature a highly accurate inner diameter, to control the jet diameter. In this part, different nozzle diameters of 50 µm, 100 µm, 150 µm and 200 µm were used to set the jet diameters. Two mechanical XY-axis stages (not illustrated in figure 1) for minutely adjusting the position of the

two nozzles relative to the other were applied to enable geometrically right collisions of the two jets. Each injector was mounted on a precision rotary stage, which was, in turn, mounted on the XY-axis stage. That allows a precise control of the position and orientation of each nozzle over a wide range of inclination angles 2θ.
The test liquids in this study were water and two glycerol solutions (with viscosity separately of 0.0058 Pa s and 0.039 Pa s). The working pressure varied from 10 bar to 200 bar, so that we can get the droplet size information in relation to a wide range of jet velocities. The impinging angle was fixed at 2θ = 40°, 60° and 80°. With each impingement angle the jets were injected into air atmosphere (0.101 MPa, 20°C) with a system pressure from 10 bar to 200 bar. The variation of the processing parameters is shown in Tab. 1.

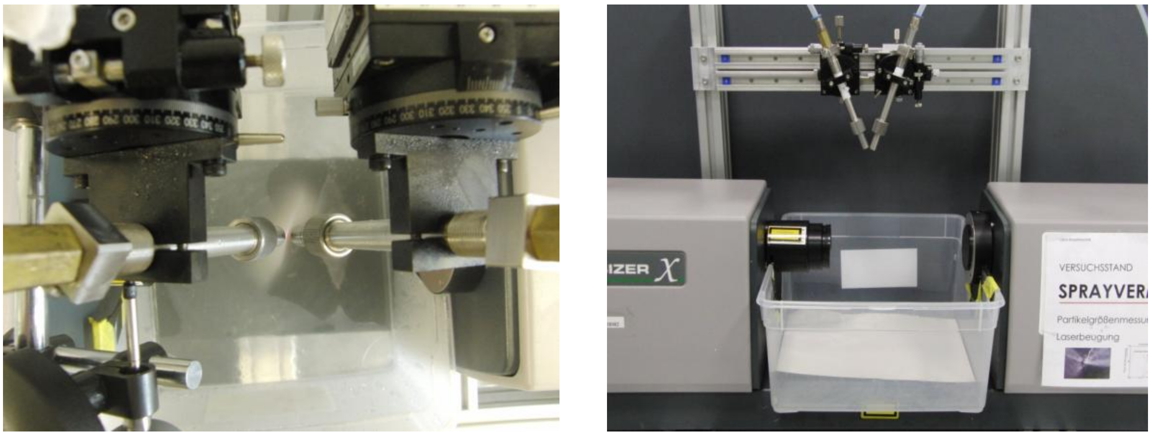

Fig. 2: Photos of the experimental setup.

Outlet velocities were calculated from the measured volume flow rate and can be further used to obtain the Re-numbers of the liquid jets. In order to avoid the existence of non-spherical drops and to ensure a fully developed impinging jet spray, the measurement volume was set at about 100 mm downstream from the impingement point.

Tab.1: Variation of the processing parameters.

D [μm]	2θ [deg.]	Fluid	Pressure [bar]
50	40	water	10 - 200
100	60	water & glycerol A (μ = 0.0058 Pa s)	10 - 200
150	80	water & glycerol B (μ = 0.039 Pa s)	10 - 200

To investigate the various spray properties, two medium speed cameras were available to photograph the sprays up to 10^3 frames per second. The resultant photograph from this camera allowed information on the spray patterns to be obtained. Furthermore, a Malvern Mastersizer X using laser diffraction was employed to measure the mean drop size generated by the impinging jets.

3. EXPERIMENTAL INVESTIGATIONS OF TWIN-JETS

3.1 Dependence of SMD on Re - number

Using the experimental setup which is described in section 2, experimental studies were carried out and figure 3 – 5 show the measurement results of the mean drop size in relation to Re-number for the three fluids with orifice diameters of 50 μm, 100μm, 150 μm and 200 μm at impingement angles of 40°, 60° and 80°. Drop size here is expressed as dimensionless Sauter-Mean-Diameter d_{32}/D with

$$d_{32} = d_V^3/d_s^2 \quad (4)$$

where d_V is the volume diameter and d_s is the surface diameter. This value indicates the diameter of drops having the same volume/surface ratio as the entire spray. The corresponding Re-numbers were calculated from the jet velocities.

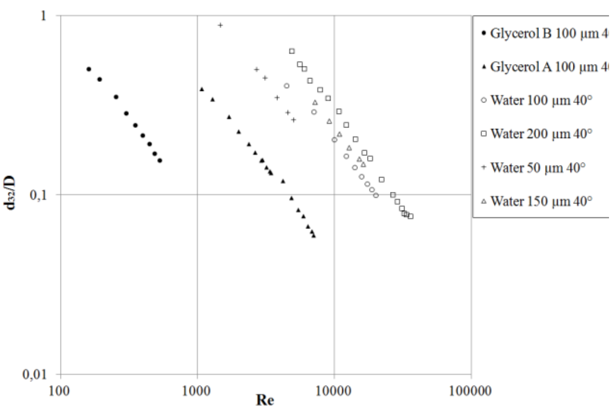

Fig. 3: Dependence of SMD on Re with impingement angle 40°.
Glycerol A (μ = 0.0058 Pa s)
Glycerol B (μ = 0.039 Pa s)

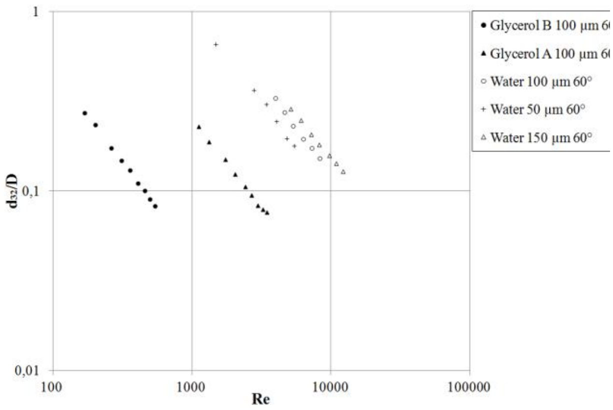

Fig. 4: Dependence of SMD on Re with impingement angle 60°.
Glycerol A (μ = 0.0058 Pa s)
Glycerol B (μ = 0.039 Pa s)

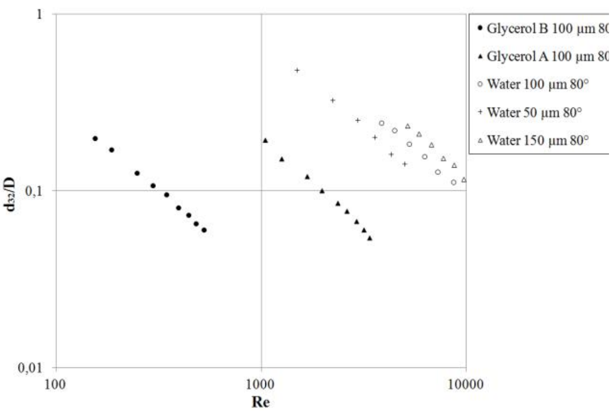

Fig. 5: Dependence of SMD on Re with impingement angle 80°.
Glycerol A (μ = 0.0058 Pa s)
Glycerol B (μ = 0.039 Pa s)

The results of the experiments show a decrease of the dimensionless mean diameter for a constant Oh-number with growing Re-number. With constant impingement angle, all distributions for different orifice diameters and fluids are almost parallel to each other. A least square curve fitting gives a relation between d_{32}/D and *Re* as: $f\left(\frac{d_{32}}{D}\right) \sim \frac{1}{Re^{1.07}}$

3.2 Dependence of SMD on Oh - number

The Oh-number which is defined in eqn. 5, relates the viscous forces to inertial and surface tension forces. It can be characterized as a dimensionless number describing the fluid properties. A larger Oh-number indicates a greater influence of the viscosity, a lower influence of the surface tension or density, or it means that the fluid is injected with a smaller orifice diameter.

$$\mathrm{Oh} = \frac{\mu}{\sqrt{\rho D \sigma}} \tag{5}$$

Here μ is the viscosity, σ is surface tension, ρ is density and D is the orifice diameter. Experimental investigations were carried out with constant Re-number and impingement angles. The variation of Oh is obtained through the combinations of different fluids from different nozzles. Figure 6 – 8 show the double logarithm plots of dimensionless SMD in relation to the Oh-number.

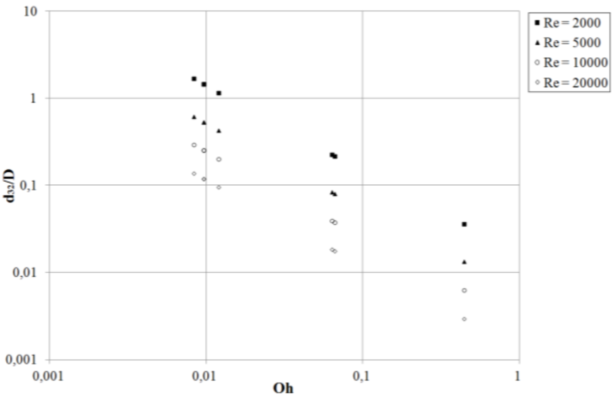

Fig. 6: Dependence of SMD on Oh with impingement angle 40°.

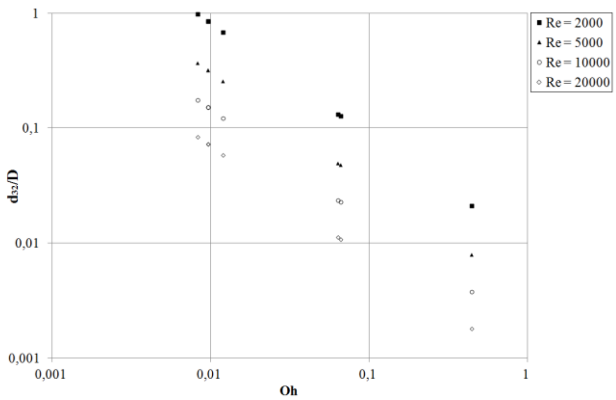

Fig. 7: Dependence of SMD on Oh with impingement angle 60°.

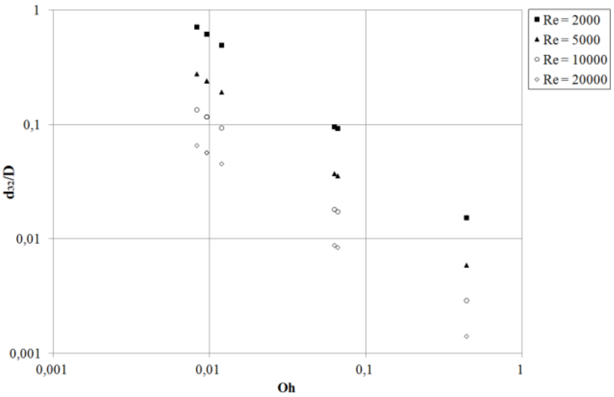

Fig. 8: Dependence of SMD on Oh with impingement angle 80°.

The results clearly show that the dimensionless drop size decreases with increasing Oh-number, which signifies that smaller droplets are generated with smaller surface tension, higher viscosity and smaller orifice diameter at a constant impingement angle and Re-number. The measured data have a linear correlation to the Oh-number and the slops of the distribution for different combinations are almost the same. A least square curve fitting gives the relation between d_{32}/D and *Oh* as: $f\left(\frac{d_{32}}{D}\right) \sim \frac{1}{Oh^{0.97}}$

3.3 Dependence of SMD on the impingement angle

Figure 9 illustrates the measurement results with water at varying impingement angles. Here, θ is half of the impingement angle, the orifice diameter is 100 µm and the Re-number is set at approximately 7000.

Figure 10 shows the measurement results using the same setup but with glycerol – water solution B. The orifice diameter is also 100 µm, density of the fluid is 1181 $\mathrm{kg/m^3}$, surface tension is about 0.066 N/m and the Re-number is set at approximately 440.

The results show a decrease of mean drop size with increasing impingement angle. This phenomenon can be explained using the disintegration theory of Dombrowski & Johns [6], which indicates that the generated drop size relates to the thickness of the lamella and the diameter of the ligaments. An increasing impingement angle leads to a growing of the horizontal momentum of the liquid jet. The increase of the horizontal impact force between two liquid jets results in the decrease of the liquid sheet thickness and the ligament diameter. Therefore, smaller droplets are consequently produced.

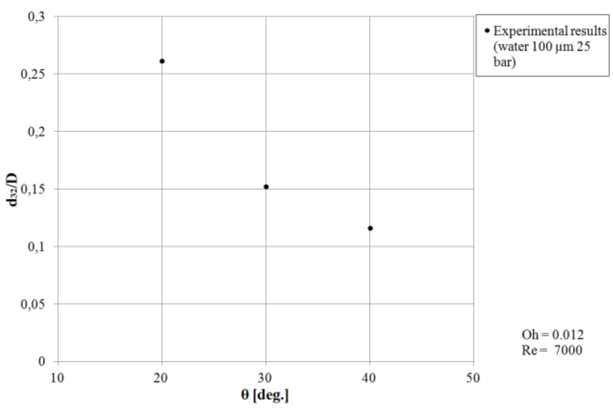

Fig. 9: Dependence of SMD on impingement angle. water (Oh = 0.012, Re = 7000)

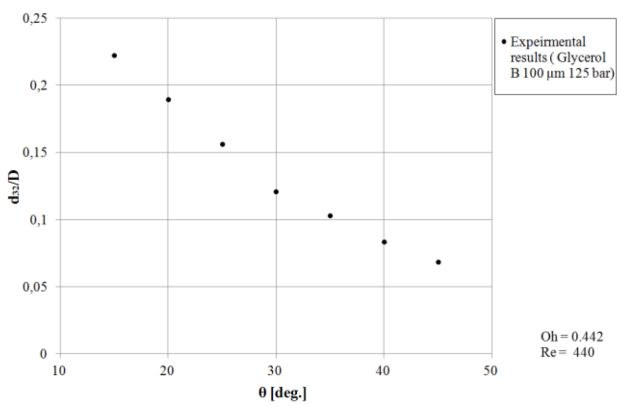

Fig. 10: Dependence of SMD on impingement angle. water – glycerol solution B (Oh = 0.442, Re = 440)

4. THEORETICAL MODELING OF TWIN-JET SPRAYS

The theoretical prediction of the droplet size of Twin-Jet sprays by Couto is based on Dombrowski & Johns [6], but shows no good agreement for the mean drop size with our experimental measurements as shown in Fig. 11. The reason for this might be that only the aerodynamic instabilities are mentioned as the cause of disintegration of the liquid sheet in the later derived equations. The hydrodynamic waves, which produce disturbance at the impinging point of the two jets, are neglected. But this hydrodynamic instability controls the breakdown of the sheet over a wide range of ambient conditions and must therefore be taken into account in the correct theory of liquid sheet disintegration.

The derivation of our theoretical model of Twin-Jet spray is based on the analyses of Dombrowski & Johns [6] and R. P. Fraser, P. Eisenklam, N. Dombrowski & D. Hasson [19]. The following breakup mechanism will be assumed. The most rapidly growing wave is detached at the leading edge of the liquid sheet in the form of a ribbon with a width of half a wave length. This ribbon immediately forms an unstable ligament with a diameter of d_L. The ligament moves transversely through the atmosphere and breaks down into drops of equal diameter d_T under the interaction of surrounding air, as mentioned by Weber [12].

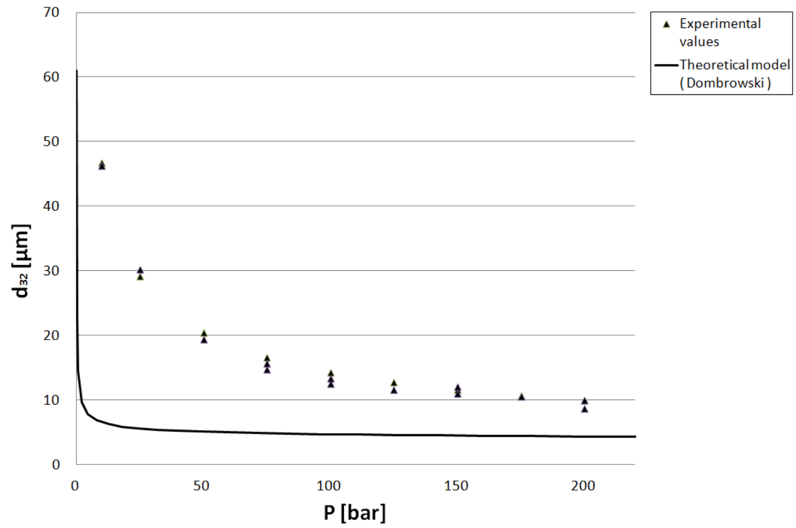

Fig. 11: Comparison of experimental results with the Dombrowski model.

The wave length with the maximum growth for a modeled liquid sheet as:

$$\lambda_m = C_1 \cdot \frac{1}{Re^2 Oh^{2\cdot}} \cdot \frac{K}{D} \quad (6)$$

Here $K = hr$ has the same meaning in the work of Dombrowski's [6] and C_1 is constant. From the mass conservation of the ligament formation, d_L can be obtained as:

$$d_L = const\sqrt{\lambda_m h} = C_2 \cdot \frac{1}{Re \cdot Oh} \cdot \frac{K}{D} \quad (7)$$

From the relationship of Weber [12], similar to Dombrowski & Jones [6], one obtains:

$$d_T = \left(\frac{3\pi}{\sqrt{2}}\right)^{1/3} d_L \left[1 + \frac{3\mu}{(\rho\sigma D)^{1/2}}\right]^{1/6} \quad (8)$$

Using the eqn. 3 of Hasson & Peck [3] and ignoring the influence of angular position, the drop size in eqn. 8 can be then modeled as the mean drop diameter. So eqn. 8 can be rewritten as:

$$\frac{\mathrm{d}_{32}}{\mathrm{D}} = C \cdot f_1(\theta) \cdot f_2(Oh, Re) \quad (9)$$

The constant C should be preferably obtained from the experimental result. θ is half of the impingement angle. Re and Oh are the Reynolds number and Ohnersorge number of the liquid jet. The two functions $f_1(\theta)$ and $f_2(Oh, Re)$ are dimensionless functions which can be derived as indicated above.

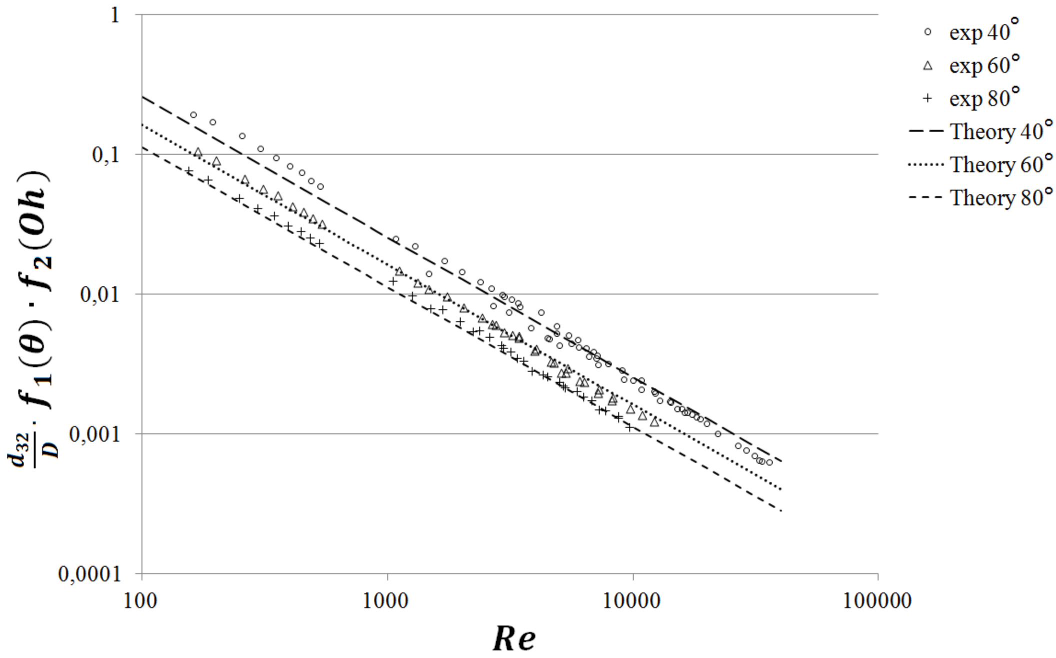

Fig. 12: Comparison of experimental data with theoretical prediction.

Fig. 12 shows the comparison of the theoretical prediction with the experimental data. The dotted lines are the theoretical prediction according to eqn. 9 with 2θ = 40°, 60° and 80°. Each point represents the mean value of 10 to 20 measurement results at the same operating conditions. 120 points were used for the fitting to obtain the correlation.
The result shows an excellent agreement of the extended theory with our experiments for all three impingement angles and over a wide range of Re- and Oh-numbers.

5. CONCLUSIONS, FINAL REMARKS AND OUTLOOK

The present paper underlines that Twin-Jet sprays possess excellent properties for their application in combustion engines. In this application, high supply pressures need to be applied in order to yield the spray properties needed for the combustion. The existing experimental results needed required extensions and for this reason, the authors set up a test rig that allowed them to carry out investigations up to supply pressures of 200 bar. A second test rig is on its way that allows measurements up to $\Delta P = 450$ bar. With this latter test rig, Twin-Jet sprays for Diesel engines will be investigated in detail. The work in this report concentrated on sprays for Otto engines, with supply pressures up to 200 bar.

The experimental results showed that the Sauter-mean-diameter is linearly proportional to the jet diameter and is dependent on the square root of the supply pressure. Hence, at high supply pressures, only a weak dependence on pressure is observed. The dependence on the fluid properties was well captured by the Oh-Re-relation derived in this paper. The dependence of the Sauter-mean-diameter on the impingement angle was also investigated. The theoretical considerations of Hasson & Peck [3] were implemented and verified by experiments with different Twin-Jet parameters. Finally, a complete description of the Sauter-mean-diameter properties of Twin-Jet sprays has become available through the authors' work.

The authors will continue their research in the field of Otto engines. Currently extended measurements are performed for the developed Twin-Jets in a single stroke Otto engine. For this purpose Otto injectors have been modified with Twin-Jet nozzles to use the excellent controllable spray properties in combustion engines. Additionally the experimental investigations of Twin-Jet sprays for Diesel engines will be forwarded up to a supply pressure of 450bar with the aim to demonstrate that future system pressure of 400bar for Diesel engines is sufficient to meet the requirements.

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