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NEW ASPECTS FOR THE APPLICATION AND PERFORMANCE OF LAMROT ATOMIZERS

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ABSTRACT

Rotary atomizers operated in the range of Rayleigh breakup mode are known to generate droplets with a narrow size distribution. However, the bell shaped spray pattern often is a drawback. It can be altered by an axial gas flow into a hollow cone, still allowing for particle size control by the atomizer speed. However, the gas flow velocity also has a significant influence on the drop size distribution when its magnitude is large enough to obtain considerable deflection. This behavior was found with a one row small diameter (32 mm) atomizer with 48 flow (atomizer) channels, high rotational speeds up to 20,000 RPM and deflection air velocities up to 60 m/s.

For high flow rate multi deck wheels comprising a high number of flow channels releasing a multitude of individual threads, a new distributor was developed able to maintain the distribution performance together with practically zero feed pressure. The liquid is introduced into an annular gap between the atomizer axis and the rotating wheel split into equal portions and transported by specially arranged drillings within the distributor to the atomizer channels. The overall non plugging open channel flow concept can be adapted to flow rates even larger then 1000 l/h and drops sizes down to 50µm. The basic design concept is explained and data on the drop size distributions are given in this contribution. At low wheel speed the liquid is spread evenly into the atomizer channels. For high speed operation further improvement of the distribution is ongoing.

1 INTRODUCTION

In case of simplex pressure nozzles, the drop size depends on the liquid pressure, simultaneously giving rise to a specific liquid flow rate. Changing both flow rates and drop size independently is known as fairly difficult.

In case of pneumatic atomizers the mean drop size mainly depends on the liquid to gas mass flow ratio as well as on the gas pressure. The gas pressure thus provides an additional parameter for drop size control even so there is a link between gas flow and gas pressure. However, the size distribution of droplets formed by pneumatic atomizers tends to be fairly broad.

In some applications flow independent control of the drop size is desired as well as narrow drop size distributions. At rotary atomizers, also the speed of rotation provides an additional independent parameter in adjustment of the desired drop size. Standard rotary atomizers are the “working horse” e.g. in spray drying when fine drops d < 100µm are needed. They are able to spray practically any feed no matter what consistence or what viscosity without significant plugging tendency and to generate fine droplets. Standard rotary atomizers however lead to very broad particle size distributions with typical spans $(D_{v.90} - D_{v.10})/d_{v50} \geq 3$. Reason is the discharge of the fluid in shape of thick, mostly turbulent strands detaching from a few channels or ribs with high velocity and the subsequent fragmentation of these thick strands within the stagnant environmental gas atmosphere.

This behavior can be altered by dividing the flow into a multitude of laminar threads then breaking up by the Rayleigh mechanism. For that purpose sometimes rotating baskets with a multitude of small holes are used or decks of grooved bells as also in spraying of paints, see e.g. [1, 2, 3]. Another option are porous rotating rings [4, 5]. The drawback of small holes $d < d_{crit}$ or small pores however is their tendency to plugging. Therefore the so called LAMROT(1) atomizer was developed as described in [6, 7, 8, 9]. It consists of a rotating cylinder with a wall of sufficient thickness. This mantle contains a multitude of bores in rows inclined to the radial direction. This inclination is mandatory in order to collect the fluid within single open channel flows leading to just one thread at each bore outlet. Inclination of the channels in downward direction has the additional advantage of utilizing the flow velocity within the channels to deflect the threads slightly in axial direction and to support the axial transportation of the spray as e.g. desired in spray drying. Special geometries at the channel outlet help to detach the threads from the wall of the cylinder or wheel, as described in [8].

In single row atomizers the liquid can be fed into the gap between the axis and the cylinder completely closed on one side and on the other side is provided with a circumferential weir. See **Fig. 1**. Experiments were performed with such atomizers located within a gas orifice in order to deflect the spray into axial directions and to shape it into a hollow cone pattern. This arrangements may be applied for cases where a targeted spray is needed as e.g. in fluidized bed agglomeration or spaying on to substrates. Significant changes in the drop sizes were found in case of high gas flow velocities compared to stagnant gas conditions [10].

In multi row systems the distribution of the liquid can be performed e. g. by stationary large fan jet nozzles arranged close to the center of the wheel spraying the liquid outward onto the inner wall of the cylinder. Radial moving large drops either precipitate immediately within the channel or give rise to a film which subsequent flows into the channels. It is obvious that this distribution method must have some drawback as the transient leading during the rotation of the cylinder and a

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limited down ratio. Another approach for a better division of the flow onto rows of atomizers is described in [11]

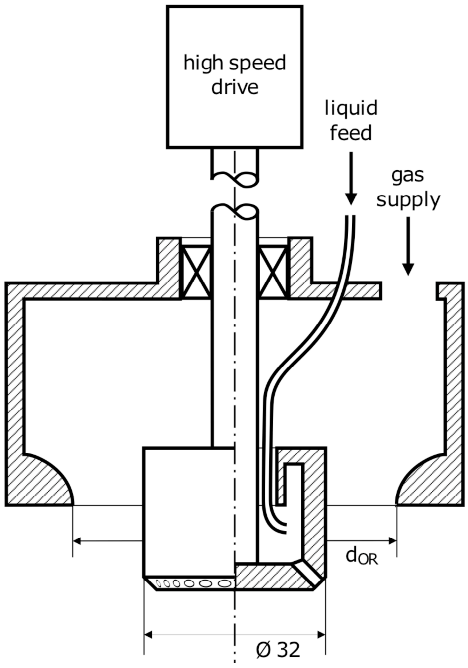

Fig. 1. Single row atomizer arranged within a gas orifice to obtain a hollow conical spray. The liquid feed is supplied through a capillary located between the axis of the wheel and the circumferential weir. The wheel contains 42 atomizer channels, i. e. bores of 1 mm diameter, inclined by α = 45° downward to support the downward deflection of the spray

The distribution now can be greatly improved by a new rotating distributor as described in [12] within the wheel, able to lead the liquid from a position close to the axis continuously outward to axially staged grooves and from there into the atomizer bores arranged in circumferential rows. See **Fig. 2**

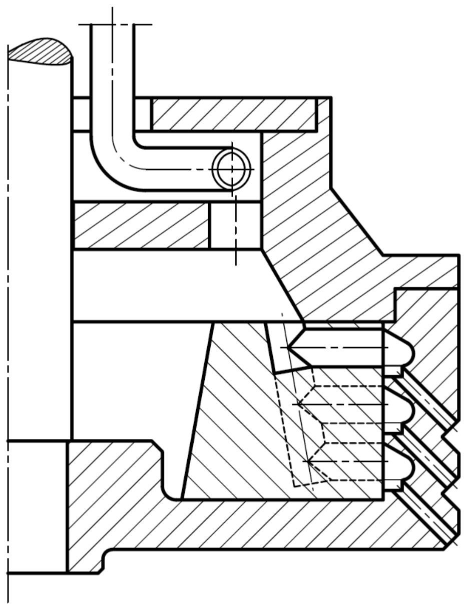

Fig. 2. Principle of the LAMROT-Atomizer with three rows of atomizer-channels supplied by the liquid feed first distributed into circumferential grooves. The feed flow emerges from pipes located within the slot between the wheel and the axis, then follows the contour of the atomizer due to the centrifugal acceleration. The grooves are charged by the distributor drillings without overhead pressure and allow for a very high turndown ratio

2 THEORY

2.1 Open Channel Flow

First, the flow through the cylindrical radial channel with diameters d_a is discussed. Open channel flow will be achieved when the diameter of the opening is larger than the critical one [13], i.e. for low liquid feed rates

$$Bo = d_a^2 \rho a/\gamma \geq 28 \qquad (1)$$

With the centrifugal acceleration $a = r\omega^2$, here $a = R\omega^2$ at the outer circumference of the wheel resp. Under these conditions at low flow rates a film flow through the channel is observed [6]. Only a part of the channel cross section is occupied by the flow. By inclining the channel axis with respect to the radial direction the centrifugal component normal to the channel surface squeezes the film towards the channel surface toward the direction of the radius vector and only a single compact flow strand is formed within the channel emerging as one single jet from the opening. In contrary radial arranged channels are not able to provide well-defined detachment conditions, see e.g. [14].

Within the channel of the radius $r_{ch} = d_{ch}/2$ the flow has an approximately segment shaped cross section with a hydraulic depth of

$$\delta_{hy} = 0.96[\mu_l V/(a\, \rho_l \cos(\alpha)\, r_{ch}^{1/2})]^{2/7}. \qquad (2)$$

V is the flow rate per channel, μ_l is the kinematic viscosity of the fluid, ρ_l is the density of the fluid and a is the local acceleration given by $a = r\omega^2$. The inclination angle between the radial direction and the bore axis is designated with α. The actual depth of the flow is $\delta = 3\delta_{hy}/2$. The mean flow velocity of the liquid layer along the channel is given by

$$v = a \cos(\alpha)\rho_l\, \delta_{hy}^2/3\mu_{\cdot l} \qquad (3)$$

Re being defined with δ_{hy}, the limit to turbulent flow is given by Re ≥ 400, compare also [15, 16]. The Reynolds number for laminar flow conditions is given by

$$Re = a \cos(\alpha)\, \rho_l^2\, \delta_{hy}^3/3\mu_l^2. \qquad (4)$$

After detachment, at r = R, the cross section of the segment shaped film flow is reshaped into a circular ligament or thread by the surface tension with the same cross sectional area when leaving the channel. The diameter of the thread at detachment is

$$d_{thd} = (4V/\pi v)^{1/2}. \qquad (5)$$

Due to the relative motion between the fluid elements and the wheel a further extension of the thread takes place before breakup.

2.2 Drop Size

Suggesting Rayleigh type breakup, the drop size must be narrowly distributed, see e.g. [17]. In case of low viscous fluids, the drop size is 1.88 times the thread diameter at the breakup point. Due to extension of the thread in the centrifugal field the drop size is smaller as expected from the jet diameter immediately after detachment.

Experiments dealing with jet breakup in the field of gravity, $a = g$, exhibit the drop sizes mainly to depend on the flow rate and on the liquid properties [18] and only insignificantly on the shape or size of the channel. The drop size only insignificantly depends on the viscosity even so the breakup length increases strongly with increasing viscosity allowing for higher extension in the latter case due to retarded breakup.

In a simplified description neglecting the gas environment the mean drop size then can be estimated from

$$D = L_c V^{*0.2}. \qquad (6)$$

Compare also [18]. The volumetric flow rate is defined as $V^* = V(a^3\rho_l^5/\gamma^5)^{1/4}$ and the capillary length is given by

$$L_c = (\gamma/a\rho_l)^{1/2}. \qquad (7)$$

It is convenient also for rotary atomizers to choose the capillary length L_c as a primary scaling length for the drop size [19, 20, 21, 22]. The centrifugal acceleration a represents the conditions at the outer circumference of the wheel at $r = R$.

$D^* = D/L_c$ is also designated as a non-dimensional drop size and a is the centrifugal acceleration at $r = R$. The validity of equation 6 is limited to laminar flow and to a minimum flow rate, large enough to generate threads, i. e. $V^* > 0.8$ and to a drop size beyond the "dripping" case, i.e. $D^* \geq 0.8$.

This concept may be applied to cases with relatively low circumferential velocities only as for relatively small wheels and no additional gas flow in the vicinity of the wheel. In case of large wheels, the gas effect is considerably stronger due to the higher circumferential speed at equal centrifugal acceleration.

Experiments with three different wheel diameters where performed in [23] to separate the superimposed effect of the centrifugal acceleration and the circumferential speed or gas impact on the drop size. However, these trials have been performed with a small number of channels (8) on the circumference of the wheels. In general it was found the drop size first to increase at a higher tangential velocity v_t of the wheel corresponding to a higher relative velocity $v_{rel} = v_t$ between the threads and the gas. Thus, the drops became somewhat larger at the larger wheel at equal centrifugal acceleration. This probably is due to premature breakup as the disturbances from the interaction with the gas might trigger the breakup process. The breakup length becomes shorter as the threads are not jet fully stretched compared to the case of gas absence. This behavior could only be observed for fairly small gas Weber numbers

$$We_g = v_{rel}^2\rho_l d_{thd}/\gamma < 3. \qquad (8)$$

Even so the recommended relationships and constants are proposed in a somewhat more complex manner in [23], an average estimate of the drop size can be obtained with the data in [23] from the following relationship

$$D/Lc = V^{*m}[Fr(\rho_g/\rho_l)]^n. \qquad (9)$$

With the Fr number $Fr = v_t^2/(d_{thd}\, a)$. The physical meaning of the term $Fr' = [Fr(\rho_g/\rho_l)]$ is the ratio of the gas dynamic pressure acting on the thread compared to the hydrostatic pressure or extension effect due to the centrifugal acceleration defined with the thread diameter at the detachment point.

No additional gas flow was supplied to the wheel in [23] and the rotational speed was low, i.e. the relative velocities where comparatively small within the range of $2.8 < v_{rel} <$ 28m/s. The specific flow rates per channel also were fairly small as $V^* < 20$. Within the given range, increasing the two parameters V* and Fr' lead to an increase in the drop size and the exponents in equation 9 were where found as $m = 1/3$ and $n = 1/4$. Besides this, also negative exponents of n were found for some trials with low viscous liquids as water.

The gas flow in the vicinity of the wheel forms a boundary layer whose thickness depends on the wheel shape and size. Also the pumping effect of the wheel for the gas phase passing through the distributor has to be considered in order to evaluate the gas flow around the wheel. The liquid threads emerging from the wheel are subject to higher relative velocities with the slower co-rotating gas in a more intensive way when the breakup length increases either due to higher liquid flow rate or higher liquid viscosity.

For thick threads or higher relative velocities corresponding to higher We_g, a smaller drop size is expected as the gas movement will exert further extension to the threads before breakup. Even much higher relative velocities arise when the spray is deliberately deflected by a high velocity gas jet. This happens when the wheel is surrounded by an annular gas slit as frequently found e.g. in spray dryers.

For such cases another approach was chosen to include the relative velocity between the threads and the gas taking into account the gas Weber number $We_g = v_{rel}^2\rho_g d_{thd}/\gamma$ and to implement this parameter into equation 6. Thus one obtains

$$D^* = V^{*m}We_g^{\,n}. \qquad (10)$$

It is expected at least for high gas Weber numbers $We_g > 3$, the threads will be elongated or stretched by the gas flow before breakup and the exponent of We is expected to be negative. Once more it must be stated that equation 10 may have different exponents depending on the geometry and shape of the wheel.

In case the break up process is influenced by the gas, the drop size distribution will be expected to become wider as the breakup process becomes more stochastic. At very high Weber numbers $We_g > 10$ even bag break up may occur due to the interaction of the jets and the gas dynamic pressure as observed in [10, 24, 25].

The flow characteristic through the distributor drillings behaves similar to the flow through the atomizer channels although the specific flow rate in the distributor drillings is much higher. It is therefore necessary to design the drilling diameters accordingly.

3 SIMULATION OF FLOW DISTRIBUTION BY CFD

The simulation of the flow within the whole wheel and its channels could provide considerable insight to the distribution behavior. One major question is, how the flow from the distribution drillings enters into the circumferential grooves and how the flow is equalized there. The flow conditions are actually simulated with ANSYS CFX 10. As the calculation is ongoing we cannot yet present any results but will show them during our lecture in Como.

4 EXPERIMENTS

4.1 One Row Small Atomizer

Trials have been performed with a small single channel row wheel as in **Fig. 1** with additional axial gas supply. This setup is prepared for mutual applications in spray agglomeration, where high jet velocities are required in order to penetrate into the fluidized bed. Due to the special shape of the weir the wheel can also be operated upside down to generate a vertical upward spray as required in spray agglomeration.

The 32 mm diameter brass wheel is driven by a high speed control electrical drive PRECISE SC60/60, Leichlingen, Germany and allows rotational speeds up to 40,000 RPM. The axis was arranged vertically with the drive on top. Water was supplied by means of two 1mm stainless steel capillary tubes into the gap between the weir and the axis. The oxidized brass material provides a more or less perfect wetting condition to water. The total flow rate of water was 30 to 40 l/h., the number of atomizer channels within the 32 mm diameter wheel was N = 48, the hole diameter (atomizer channels) is d_{ch}= 1 mm and the hole length l_{ch} = 5 mm with an inclination angle of $\alpha = 45°$ facing downward in flow direction. The wheel was mounted within a gas orifice of 68 mm and of 76 mm diameter respectively. Through this orifice air could be conveyed with axial velocities within the range of $25 < v_g < 55$ m/s by a high pressure fan.

Fig. 3 shows the deflection of the spray at a rotational speed of the wheel n = 10.000 RPM depending on the gas velocity. The deflection angle is also plotted in **Fig. 4.**

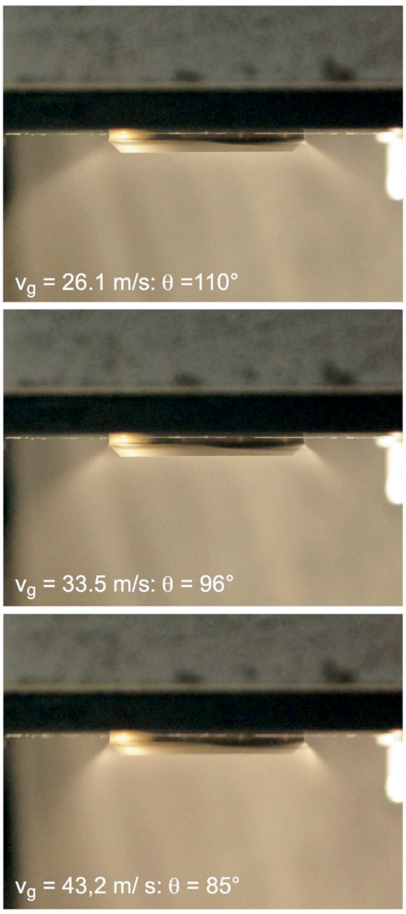

Fig. 3. Deflection of the spray emerging from the single-row rotary atomizer surrounded by a gas orifice. Set up according to Fig. 1.

It can be seen, the ligaments or drops are deflected immediately at the edge of the wheel. Thus one can assume a very thin boundary layer of the airflow around the wheel.

The distribution of the liquid can be assumed quite uniform onto the atomizer-channels as the wetting conditions with water are quite perfect.

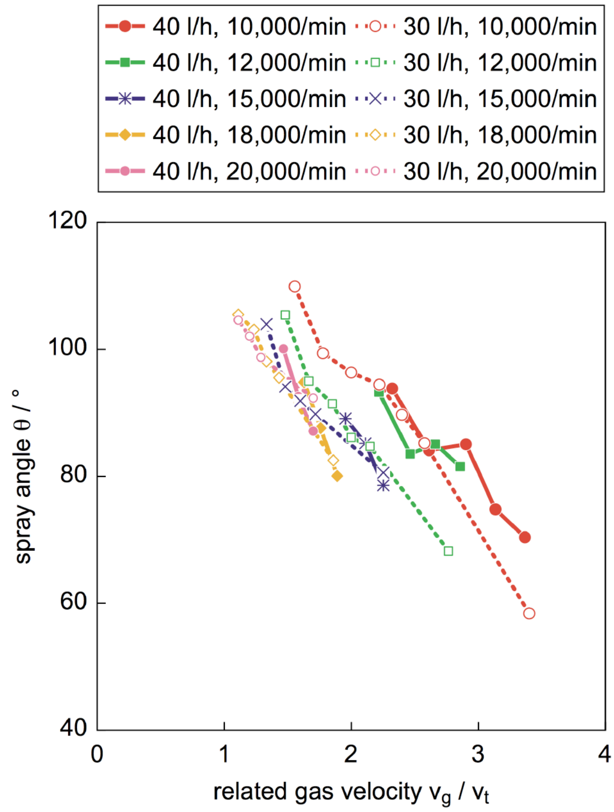

Fig. 4. Deflection angle at different ratios of gas velocity to the tangential velocity of the wheel

Measurements of the drop sizes were performed with a MALVERN 2600 LDS with the center of the laser beam 60 mm below the atomizer and passing through the spray axis. The axis of the laser beam could be moved laterally by an adaptation mechanism and was aligned with the spray axis. Measurements were only possible at deflection angles smaller than $\Theta < 140°$. At larger spray angles droplets hit the laser optics. Therefore no data are available for Θ=180°(no air flow). The received drop size distributions where obtained by setting the independent evaluation mode in order to prevent any bias due to pretended droplet size distribution functions.

The drop size data are presented in **Fig. 5**. Increased gas flow velocities lead to a significant decrease in the mean drop size. This is true for all tested flow rates, i.e. 30 and 40 l/h. corresponding to a maximum flow rate of 0.83 l/h or to $2.3 \cdot 10^{-7}$ m^3/s per cannel respectively. The decrease of the drop size with increasing gas flow velocities is more pronounced at low speeds at 10,000 RPM compared to higher speeds of 20.000 RPM due to higher relative momentum of the gas flow. With increasing gas flow velocities the span value, SP = $(d_{v.90}-d_{v.10})/d_{v.50}$ simultaneously increases from SP = 1.5 to SP = 2.5

Fig. 6. shows the same data presented in terms of the non dimensional parameter D* = f(V*, We_g) as in equation 10. The exponents determined from our data were m = 0,25, n = -0.5. Here, the gas Weber number was determined considering the relative velocity of the gas and the liquid at the detach-

ment points. The magnitude of the relative velocity inserted into the gas Weber number is given by the vector addition

$$v_{rel} = \{v_t^2 + [v_g - v \cdot \sin(\alpha)]^2 + [v \cdot \cos(\alpha)]^2\}^{1/2}. \qquad (10)$$

The value of m = - 0.5 fits quite well to the gas flow influence in pneumatic atomizers [26]. Some gas is also transported through the channels together with the liquid. The influence of this flow for the very small channels is however neglected.

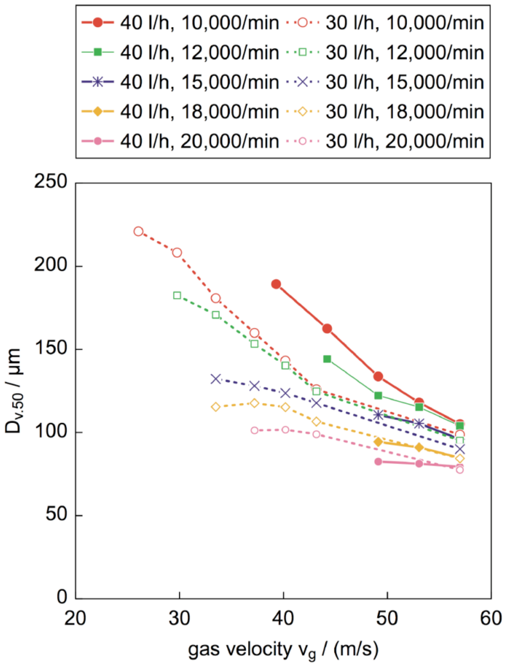

Fig. 5. Original data of drop sizes measured at the single row atomizer with additional gas supply

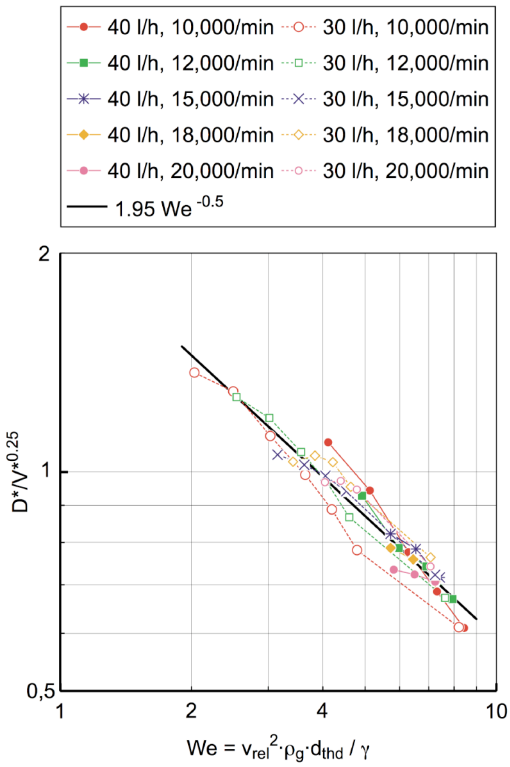

Fig. 6. Non-dimensional mean drop size of deflected sprays. Evaluation according to equation 10 with m = 0,25 and n = -0,5

As the span value increases with increasing flow velocities it is intended in the future to run further trials with larger gas orifices but lower gas velocities. The larger slot would keep the droplets longer within the gas jet as required for a significant deflection but induce lower disturbance to the breakup process. This then may lead to more narrow drop size distributions.

4.2 High Flow Rate Multistage Wheel

For high total flow rates, the number of channels must be increased to maintain laminar flow. As wheel diameters due to practical reasons cannot be increased beyond a certain limit, the only possible designs are staged or rowed wheels. Different attempts are known to distribute the liquid evenly into the channels, see eg.[11]. Instead of spraying the liquid inside the atomizer, a new attempt was made to overcome the drawback of this method.

The new distributor consists of a PMMA insert with drillings whose inlet section is located at the same radius. The drillings are leveled outward in order to conduct the flow from the inlet section into the periphery of the wheel. Every drilling ends at a circumferential groove adjacent to each row of channels. From there the liquid flows into the channels.

The number of drillings ending in one row depends on the number of rows. Typically 6 to 10 drillings are ending in one circumferential groove supplying from there a sector of the groove with an angle of 36° to 60°. The outlet of the drillings is arranged tangentially in order to enable a smooth and inclined entry of the jets emerging from the drillings into the liquid layer rotating within the groove. The liquid transport within the drillings again has the shape of an open channel flow.

The wheel itself was made of PVC and had an outer diameter of 190 mm. The 3 mm circular channels are staged in four rows, instead of three rows as shown in **Fig. 2**, inclined by 45° downward as in the small wheel. Each row has 120 channels along the circumference with 3 mm in diameter giving a total number of channels of 480.

In total 36 drillings where set in the distributor with their centers arranged on the same circle with a radius of 120 mm. The distance between two drillings only was 1.5 mm. Therefore, there are 10 drillings feeding one groove or one channel row. Here, each drilling has to supply a sector of 36° of the groove. The drilling diameter was 8 mm at the inlet and 6 mm at the outlet.

This wheel with the incorporated distributor was also implemented into test rig allowing for measurements of droplets with the MALVERN LDS. For that purpose only a spray sector of about 15° was allowed to penetrate the laser beam of the MALVERN LDS. The other section of the spray was precipitated on a cylindrical metal sheet covered with a rubber foam layer around the atomizer to minimize secondary spray formation on drop impact. The total flow rates were adjusted within the range of 50 to 400 l/h corresponding to a maximum total flow of V_{tot} = 0.11 l/s or $0.11 \cdot 10^{-3}$ m^3/s and a maximum channel flow rate of V = $2.5 \cdot 10^{-7}$ m^3/s. The electrical motor was mounted on the top of the wheel and the speed control was obtained by a frequency transform within the speed range of 1500 to 4000 RPM which is supposed to be the strength limit of the plastic wheel. No gas supply was intended in these trials.

The liquid feed flow was conveyed by a circular pump, first passing through a flow-meter and then split into two 10 mm internal diameter tubes extended into the slot between the axis and the wheel. The fluid then passed through vertical holes in the pre-chamber and followed the conical internal contour of the wheel until it entered into the drillings of the distributor. The flow-meter was calibrated according to the fluid properties. Besides water, glycerol-water mixtures with two viscosities and densities were used, i.e. μ_l = 3.8 mPas, ρ_l = 1088 kg/m3 and μ_l = 60 mPas, ρ_l = 1210kg/m^3. **Fig. 7**. Shows original data of the mean drop sizes for different flow rates and the three different liquids.

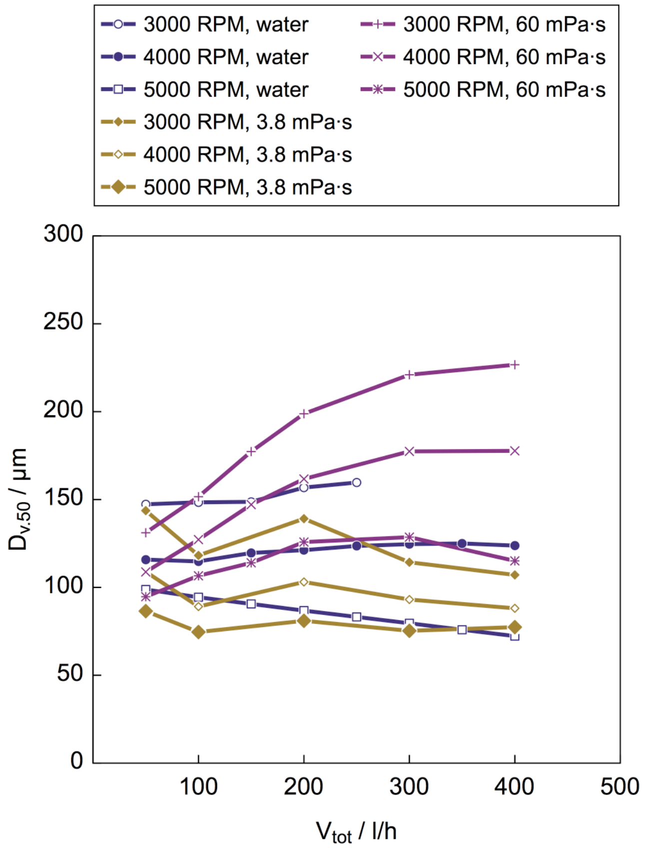

Fig. 7. Original data of the drop size measurement under imperfect wetting conditions in non dimensional terms.

Besides fairly good span values, sometimes even less than SP = 1, unfortunately just after the drop size measurements the observation revealed a poor distribution performance onto the atomizer channels mainly at high speeds, i.e. above 2500 RPM. This behavior sometimes also had been observed earlier in the past. Reason was the poor wetting condition within the wheel. It may be caused e.g. by oily substances in the experimental fluid or from the dismantling and mounting procedure when there is some contact of the plastic surfaces with oil or grease.

The data from **Fig. 7** are presented in non dimensional terms in **Fig. 8**. The drop size data for water and for the low viscous liquid lie close together with related drop sizes in the range of 1.2 < D* < 1.9. The otherwise [8] observed typical increase in the drop size with increasing flow rate only is visible at low speed with water and with the 60 mPas mixture. At given operation parameters the span was in the range of 0.8 < SP < 1.4.

After treatment with surfactant already significant improvement of the distribution was visible during observation with a strobe light. Therefore no attempt was made to evaluate the available data from **Fig. 7** and **Fig. 8** in accordance with the theory. The influence of the flow rate seems to be low and surprisingly negative at least for the low viscous liquids. Reason may be the successive onset of the flow in a larger number of holes during the higher flow rate condition under high speed.

Regrettably there was no more time to repeat the measurements with some amendments in the distributor and surface treatment of the wheel before finishing this paper. Within the next months we intend to repeat our drop size measurement again with some minor modifications on the distributor and with the MALVERN LDS as well as with PDA and to present these data at our lecture in Como.

A proper operation of the wheel with the 60 mPa s mixture at moderate speed is shown in **Fig. 9.**

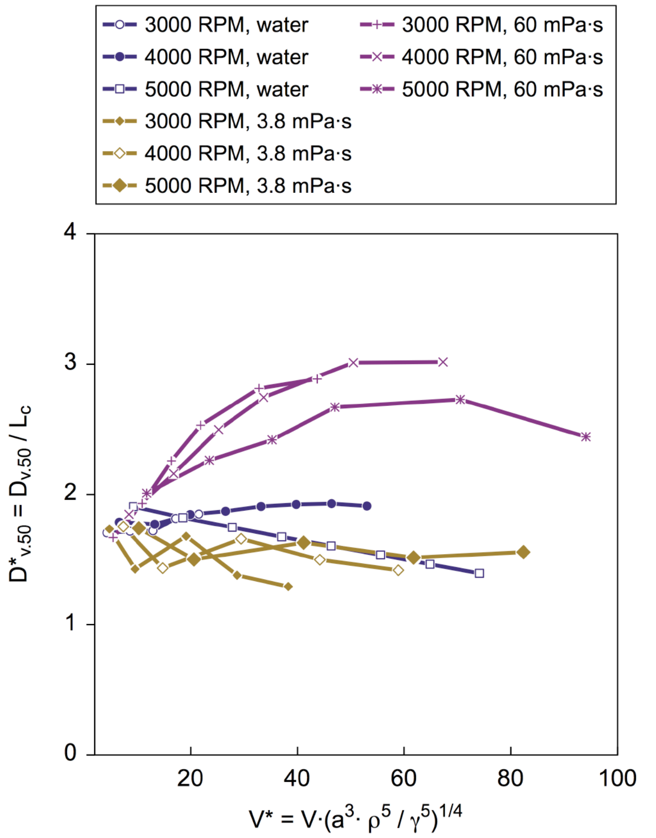

Fig. 8. Related mean drop size for three liquids of different viscosities depending on the non dimensional flow rate per thread

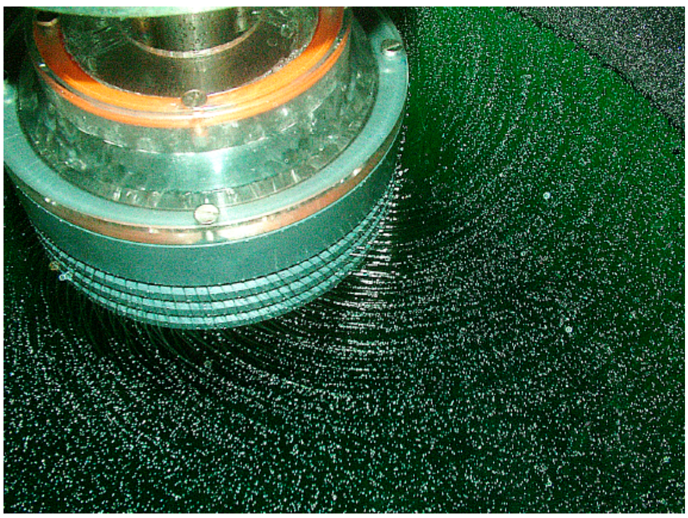

Fig. 9. Operation of a four-row wheel under proper wetting conditions. In order to provide a good visibility the speed only was 1800 RPM. The total flow rate was 200l/h.

NOMENCLATURE

Symbol	Quantity	SI Unit
$a = R\omega^2$	centrifugal acceleration	m/s^2
d_{th}	thread diameter	m
d_{thd}	thread diameter at detachment	m
$D^*=D/L_c$	nondimensional drop size	-
d_{ch}	channel diameter	m
Dv.50	volumetric mean drop size	m
L_c	capillarly length	m
n	Rotational speed of wheel	RPM, 1/s
n, m	exponents	-
r	radius within the atomizer	m
r_{ch}	atomizer channel radius	m
R	outer radius of atomizer	m
V	volumetric flow rate per channel	m^3/s
V_{tot}	total flow rate	m^3/s
v	average flow velocity in the channel	m/s
$v_t = R\omega$	tangential velocity of the threads	m/s
α	Angle between radial direction and bore axis	-
δ_{hy}	hydraulic thickness of flow	m
δ	thickness of open channel flow	m
μ_l	cinematic viscosity of the liquid	kg/sm
γ	surface tension	kg/s^2
ρ_l	density of the liquid	kg/m^3
ρ_g	density of the gas	kg/m^3

Charcteristic π numbers

$Bo = d_a^2\rho a/\gamma$	Bond number
$Fr = v_t^2/(d_{thd}\, a)$	Froude number
$Fr' = Fr\,(\rho_g/\rho_l)]$	modified Froude number
$V^* = V(a^3\rho^5/\gamma^5)^{1/4}$	nondimensional flowrate of threads
$Re = v\rho\delta_{hy}/\mu$	Reynolds number of channel flow
$We = v_{rel}{}^2\rho_g d_{thd}/\gamma$	gas Weber number
$D^* = D/L_c$	non dimensional drop diameter

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