THE EFFECT OF LIQUID RUNDOWN AND ASPIRATION PRESSURE ON SPRAY QUALITY OF EXTERNAL MIXING ATOMIZERS

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ABSTRACT

Two sets of external mixing atomizers were analyzed experimentally and computationally regarding liquid rundown, aspiration pressure and spray quality. For the cylindrical set of nozzles the gas outlet diameter D, gap width s and tip clearance x have been varied. For the conical set we varied the gas outlet diameter and the tip clearance with gap width following from these parameters. Gas pressure range investigated was 2 to 6 bar.

For the two sets of nozzles, the boundaries of the rundown regime in an operating parameter space spanned by gas pressure and tip clearance have been established experimentally. The occurrence of liquid rundown was found to depend on two dimensionless variables, x_{red}=x/s and s_{red}=s/d with d being the inner gas diameter.

Liquid aspiration pressure regimes (the range of gas pressure and tip clearance where suction takes place) were determined showing a dependence on the same dimensionless parameters.

Spray quality was found to depend primarily on gas pressure for large gas outlet diameters D, while for small D gas pressure has no influence on spray quality. In this case gas-to-liquid ratio seems to be the dominating parameter. The influences of liquid rundown and aspiration pressure on d_{50} could be generalized by introducing a non-dimensional tip clearance x/x_{max}.

INTRODUCTION

External mixing twin fluid atomizers are widely used for atomizing liquids with high viscosity and/or high surface tension. To by-pass the technical inconvenience of pressurizing the liquid reservoir, the liquid to be atomized is commonly feeded vertically or horizontally into the nozzle by a pressure gradient in the liquid delivery tube. This pressure gradient is established by the aspiration, which is induced by the high pressure gas flow surrounding the liquid delivery tube.

As neither gas nor liquid flow phenomena at the nozzle outlet are completely understood, the production of fine droplets or solid particles commonly deals with the following problems:

a) flow disturbances or even freezing at nozzle outlet due to liquid rundown,
b) production continuity problems due to fluctuating aspiration pressure and
c) (in combination with a and b) excessive gas consumption at high gas pressures and therefore high energy dissipation to achieve a sufficient spray quality.

This investigation aims to study the issues of rundown, aspiration pressure and spray quality for atomization at relatively low gas pressures.

EXPERIMENTAL

The Atomization test-rig of the Institute for Process Technology, University of Leoben, is shown in Fig. 1. Liquid flows from the reservoir into the pump (P) generating the feed pressure. Liquid throughput is limited by a valve (V2) and measured by a mass-flowmeter, Danfoss MASS 1100 (FI1), liquid pressure is indicated by a pressure gauge (PI1). Gas is pressurized by a compressor (C) and is feeded into the gas reservoir. Gas throughput is measured by a variable-area-flowmeter, Heinrichs VKN 167 (FI2) (which is calibrated to a pressure (PI2) and adjusted by a valve (V3)). Atomization pressure is adjusted from 2 to 6 bar by a valve (V4) and measured by a pressure gauge (PI3). Dropsize distribution is measured by a Sympatec Helos Vario KF laser diffraction device (QI). Aspiration pressure (suction) can be measured by pressure gauge (PI1) when valve (V2) is locked. Liquid rundown is identified visually: At a given tip clearance x, gas pressure is raised until a shading occurs at the outer surface of the liquid delivery tube and the liquid is seen to flow into that rundown area. Further increasing of gas pressure possibly leads to a disappearance of that rundown area. Gas-to-liquid ratio for spray quality measurements is adjusted by setting liquid throughput with valve (V2).

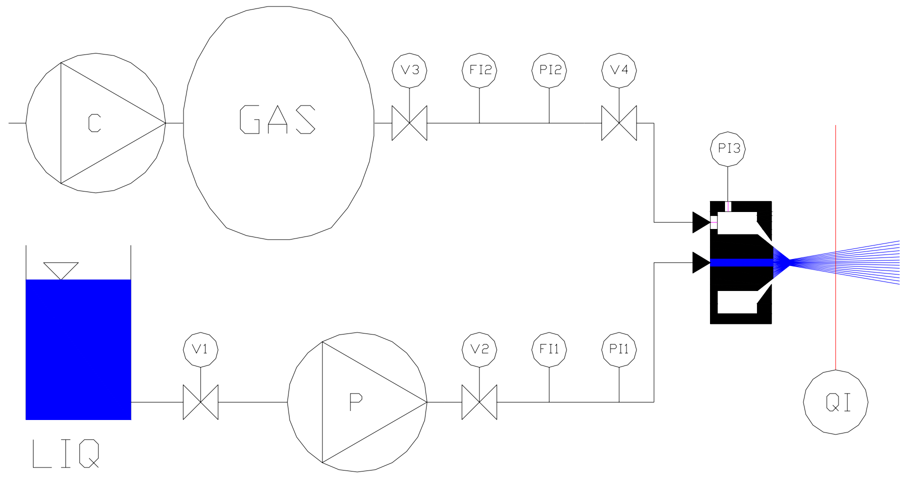

Fig. 1: Atomization test-rig

Investigated sets of nozzles

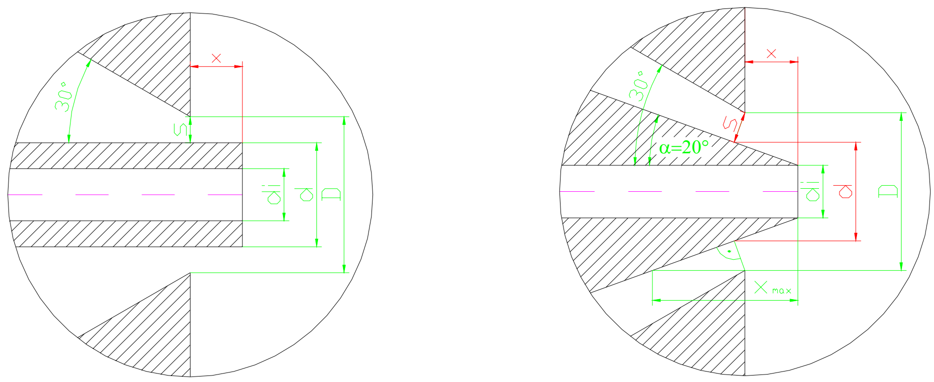

Fig. 2: Geometry of cylindrical (left) and conical (right) set of nozzles; variable parameters lined in red

The two investigated sets of nozzles are shown in Fig. 2. The liquid delivery diameter d_i is kept constant at 2 mm. For cylindrical set of nozzles, inner gas diameter d and gas outlet diameter D were varied (Tab. 1) keeping gap width s constant when changing tip clearance by shifting the liquid delivery tube. For conical nozzles, only the gas outlet diameter was varied. In this design a variation of the tip clearance x from 0 to its maximum value x_{max} concurrently modifies the inner gas diameter d and the gap width s.

Tab. 1: Geometry parameters for cylindrical and conical set of nozzles

Cylindrical	**D**	**d**	**s**	$\mathbf{A_{gas}}$
	[mm]	[mm]	[mm]	[mm²]
#1	12,2	10	1,1	38
#2	12,2	6	3,1	89
#3	9	6	1,5	35
#4	9	4	2,5	51
#5	6	4	1	16
#6	6	3	1,5	21

Conical	**D**	$\mathbf{x_{max}}$
	[mm]	[mm]
#I	19	22
#II	15,5	17
#III	12,2	13
#IV	9	8

LIQUID RUNDOWN

Liquid rundown is a frequent phenomenon accompanying external, close-coupled atomization techniques. It is an important effect which influences both product quality and process reliability due to the liquid prefilming mechanism as well as unwanted freezing phenomena at the liquid delivery tube.

On the contrary to its importance the occurrence of rundown is still not explained satisfactorily and thus is a field of investigation for various researchers.

Ünal [1] investigated liquid rundown at convergent-divergent (c-d) nozzles and proposed a mechanism, which is based on the boundary layer separation due to the interaction with an “incoming” shock wave. The latter is formed at the outer edge of over-expanded operated convergent-divergent (c-d) nozzles and is basically influenced by the nozzle geometry and the ratio of ambient to operating (reservoir) gas pressure. Since the mechanism is associated to flow over-expansion, the application of the proposed model is restricted to c-d nozzles.

Espina [2] carried out numerical investigations of conical convergent nozzles (similar to Fig. 2). He showed numerically that low operating pressure leads to flow separation and explained this by calculating a skin friction coefficient over the surface of the liquid delivery tube. It turned out, that the region of flow separation moves downstream with increasing pressure ratio. Thus, rundown could be avoided, if the tip clearance is chosen within the non-critical region of positive skin friction. The latter effect can be confirmed by visual observation, as shown in Fig. 3.

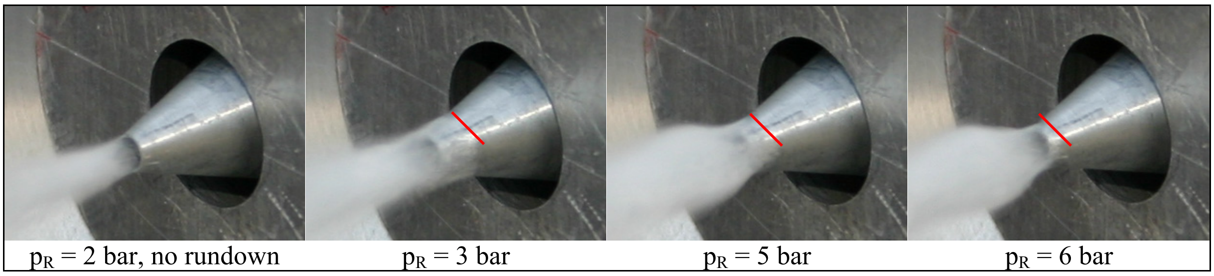

Fig.3: Experimental results of rundown formation at conical nozzle #III at x = 7 mm within an operating pressure range of 2 bar to 6 bar. Rundown, marked with red lines, moves downstream with increasing operating pressure.

The drawback of many explanations for the rundown phenomenon lays in the fact that there is no straight foreward procedure to predict the occurrence of rundown from easily accessible parameters. In the following we introduce some arguments, which intend to provide a rough indication of the rundown phenomenon. Since the expansion process along the liquid delivery tube is crucial in the understanding of the rundown, we adopted a model by Schreithofer [3], which allows a fast characterisation of the under-expanded annular nozzle flow by means of classic one- and two-dimensional gas theory. As a result we obtain a functional dependence, Eq.(1), for the jet expansion, measured by the ratio of the jet´s cross sectional area at position x_{red} to the nozzle exit area. Thereby, the jet expansion is described by two dimensionless geometrical parameters s_{red} and x_{red} and the Prandtl-Meyer jet deflection angle, which itself is dependent on the ratio of ambient pressure to operating pressure.

$$\frac{A_{(xred)}}{A_{gas}} = \frac{\sqrt{4\left(s_{red}^2 + s_{red}\right) + 1} \cdot s_{red} \cdot x_{red} \cdot \tan\vartheta + \left(s_{red} \cdot x_{red} \cdot \tan\vartheta\right)^2}{s_{red}^2 + s_{red}} \tag{1}$$

The model validity is limited by the facts, that 1.) Eq.(1) holds only until full expansion to ambient pressure and 2.) the influence of a potential nozzle inclination is not considered.

The correlation of the independent variables, according to Eq.(1) can be used in the interpretation of the experimental data. In Fig. 4 the empirical determined regions of rundown are shown as function of the dimensionless geometrical parameters and the operating pressure for the set of cylindrical nozzle configurations (Tab. 1).

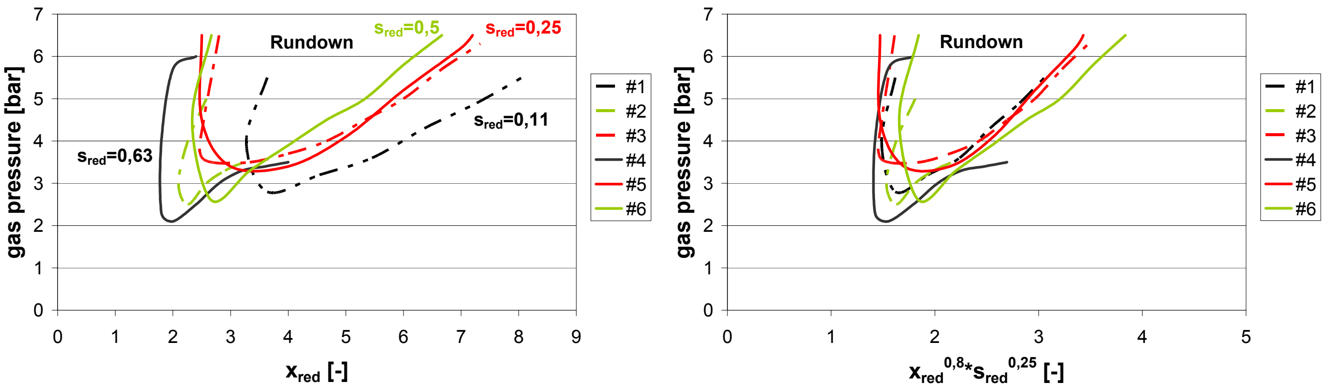

Fig. 4: Liquid rundown occurrence for cylindrical nozzles as function of gas reservoir pressure p_R and dimensionless tip clearance x_{red}, curve parameter s_{red} (left) and alternatively as a function of dimensionless tip clearance and dimensionless gap width (right). Equal colours denote a constant value of s_{red}.

Fig. 4 demonstrates rundown to occur only for operating pressures exceeding 2 bar, which is larger than the critical pressure to obtain supersonic flow at the nozzle exit. This fact may be taken as argument, that supersonic flow is a precondition to obtain rundown and therefore it might be useful to aggregate experimental data with the above deduced dimensionless variables. Furthermore, rundown depends on the dimensionless gap width s_{red}, which is shown as a parameter on the curves in the left diagram of Fig. 4. A pairwise coincidence exists for curves marking nozzle designs with the same value of the parameter s_{red}. Small deviations from this trend are within the experimental uncertainty. Alternatively the rundown domain can be represented almost independently from the nozzle design, with the help of an empirical complex of the geometry parameters, as shown in the right diagram of Fig. 4.

Analogous experiments were carried out with the set of conical nozzles (Tab. 1). Although the proposed isentropic model is not valid exactly in this case, it can be assumed, that the expansion process will be affected by similar dimensionless parameters. Therefore the gap width and its corresponding diameter (see Fig. 2) are adopted as follows in Eqs.(2a,b).

$$s = (x_{\max} - x) \cdot \sin\alpha \tag{2a}$$

$$d = D - 2(x_{\max} - x) \cdot \tan\alpha \tag{2b}$$

As described above, the construction of the conical nozzles allowed variable settings of the tip clearance from x=0 to $x=x_{max}$, but changes simultaneously affected the gap width s and its dimensionless value s_{red}. Therefore an analogous correspondence to Fig. 4 with respect to the dimensionless gap width cannot be established; see left diagram in Fig.5. Note that contrary to the cylindrical nozzles at a given tip clearance x_{red} the occurrence of rundown for conical nozzle configurations with the same value of s_{red} is strongly influenced by the operating gas pressure.

In Eq. 2 the new parameter x_{max} was introduced, which represents the maximum tip clearance for conical nozzles. The parameter x_{max} is specific for a given nozzle geometry, as it is geometrically linked to the gas outlet diameter D and the inclination angle α of the nozzle. In the left diagram of Fig. 5 x_{max} is used to aggregate the empirical data for the boundary of the rundown domain from the conical nozzle experiments.

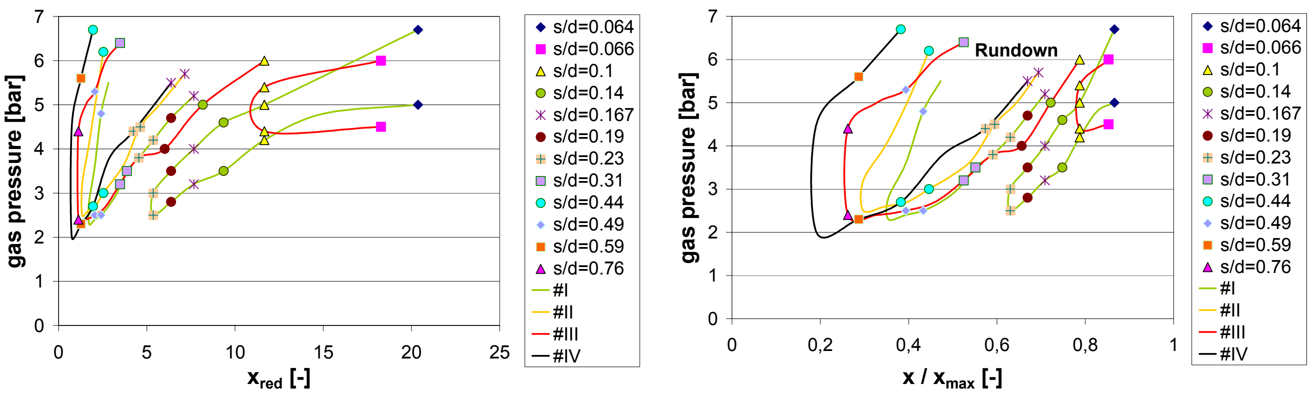

Fig. 5: Liquid rundown occurrence in conical nozzles as function of gas reservoir pressure p_R, dimensionless tip clearance x_{red} and dimensionless gap width s_{red} as a parameter. Line-colours denote nozzle configuration, while the symbols mark data points taken at a constant value of s_{red}.

ASPIRATION PRESSURE

Several studies have investigated liquid aspiration pressure (a summary can be found in [4]) showing complicated interrelationships between suction, gas pressure and the geometrical arrangement (gas outlet diameter D, tip clearance x, gas flow angles α_1 and α_2, liquid delivery tube diameter d_l). All these studies deal with higher gas pressures (> 8 bar) and therefore the findings cannot be applied directly in the low operation pressure range, which is of interest in the current investigation.

Besides other geometrical parameters related to the design of the nozzle tip, aspiration pressure is strongly depending on the configuration of the gas inlet flow. Gas can be introduced into the nozzle tangentially producing a swirl in gas flow or in axial direction (cocurrent to the liquid delivery tube). To achieve a sufficient aspiration pressure, in general gas is introduced into the nozzle tangentially. Preliminary experiments demonstrated the tangential gas inlet design to cause a coarser droplet distribution in the spray. This might be explained by the action of the centrifugal forces reducing the contact intensity between liquid and gas. In the present study, the potential of providing sufficient liquid aspiration pressure in nozzle configurations based on axial gas inlet designs is explored.

As a first step, suction properties for conical nozzles #I-IV were quantified. Thereby the influence of the gas outlet diameter D on suction was of central interest. Suction was measured varying gas pressure and tip clearance. Fig. 6a shows the pressure/tip clearance-field where suction appears (p_{asp}<1 bar). Below a gas pressure p_R=2.8 bar, no suction can be observed. With increasing tip clearance, the gas pressure which starts to induce suction also increases. Introduction of a non-dimensional tip clearance, x/x_{max}, demonstrates the suction for a given nozzle configuration to be nearly independent from the gas outlet diameter D.

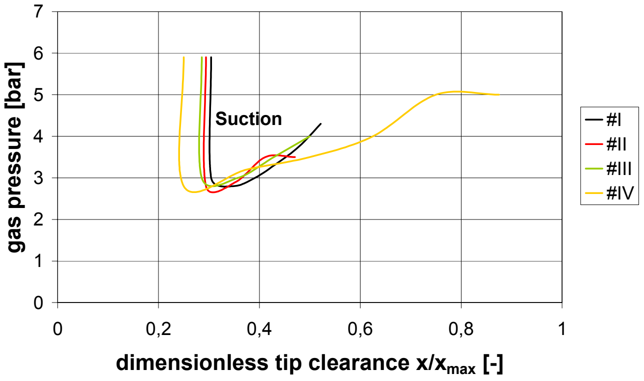

Fig. 6: Suction domain for conical nozzles #I-IV; depending on gas operation pressure and tip clearance.

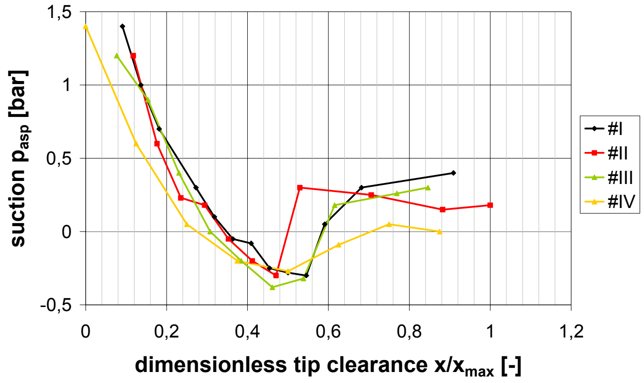

Fig. 7: Suction pressure for conical nozzles #I-IV; depending on tip clearance; gas pressure p_R= 5 bar.

As a detail corresponding to spray quality measurements described below, suction depending on tip clearance is shown in Fig. 7 for a gas pressure of 5 bar, again using non-dimensional tip clearance x/x_{max}. For the investigated conical configurations we find the suction pressure to show a clear minimum at intermediate values in the operable range of tip clearances.

SPRAY QUALITY

Mass median diameter (d_{50}) was analyzed for conical nozzles #I-IV varying gas pressure from 2 to 6 bar and tip clearance from 0 to maximum value.

Fig. 8 shows influences of gas-to-liquid ratio (GLR) and gas pressure (p_R) on d_{50} for nozzle #II and nozzle #IV. For the larger gas outlet diameters D investigated (#I and #II), an increase in GLR and p_R leads to a finer spray. For GLR>5 no improvement of spray quality can be observed. On the contrary, for smaller D (#III and #IV), d_{50} remains constant for $p_R \geq 3$ bar, but decreases with increasing GLR even for values >6 kg gas/kg liq.

In general, improving spray quality is a matter of intensifying phase contact at gas/liquid interface. For larger D, in any case the outer part of the gas will blow by without contact to the liquid. Hence, phase contact can only be enhanced by higher gas pressure while providing higher GLR above a critical gas throughput (in the order GLR≈5 in the left diagram of Fig. 8) will continuously increase the fraction of energy wasted. On the contrary, phase contact is well established for the smaller D design (right diagram of Fig. 8) and this situation can be maintained for increased gas throughput. It may be concluded that for any gas pressure, an optimum gas outlet design can be determined providing best spray quality at minimum energy consumption.

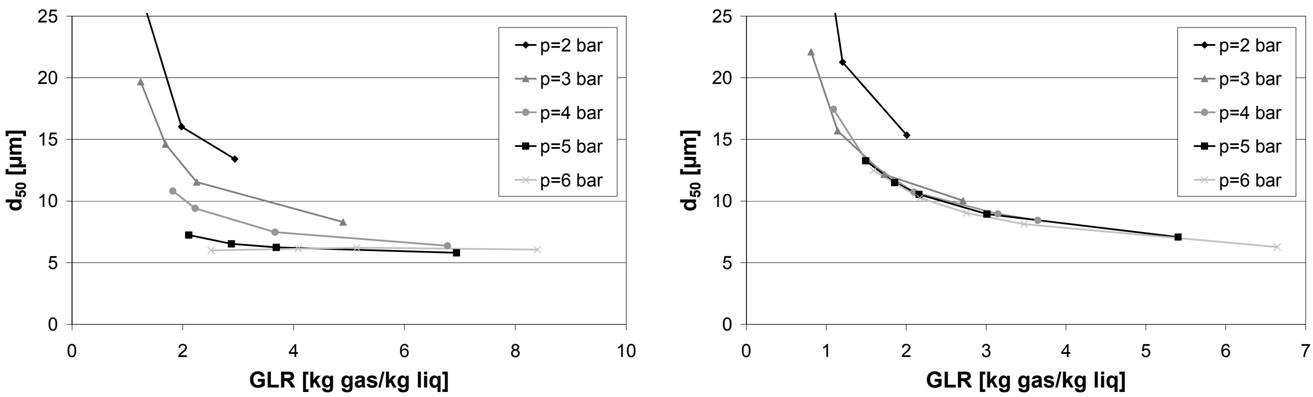

Fig. 8: Spray quality as a function of GLR and p_R for nozzle #II (left) and #IV (right)

Influence of tip clearance x on d_{50} was measured for nozzles #I-IV for a gas pressure of 5 bar from x=0 to maximum value. For any given nozzle configuration, curves of d_{50} versus tip clearance show uniform characteristics: d_{50} is finest at low tip clearances, in the following it raises with increasing tip clearance to a relative maximum, it decreases again and finally grows until the maximum value of tip clearance is reached. Again, non-dimensionalizing of tip clearance x/x_{max} seems an adequate means to generalize these results. As shown in Fig. 9 for nozzles #II and #IV this mapping provides similar positions of minima and maxima for all nozzles.

Fig. 9 also includes the non dimensional zones where aspiration and rundown take place. Liquid aspiration seems to produce a negative influence on spray quality. Definitely the pressure at the gas/liquid interface is higher in case of no aspiration. Consequently, atomization efficiency will be better due to increasing momentum forces at higher gas densities.

The tip clearance position ($x/x_{max} \sim 0{,}4$) associated with beginning rundown obviously provides worst spray quality. At the left boundary of the rundown regime, droplets again become finer.

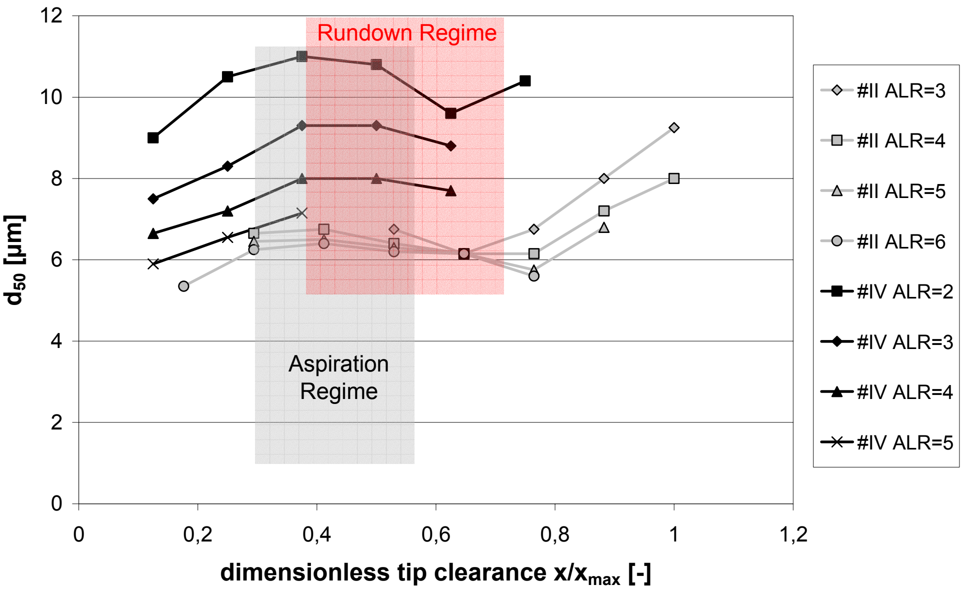

Fig. 9: Spray quality as a function of dimensionless tip clearance x/x_{max} and GLR; (conical nozzles)

CONCLUSION

The influence of liquid rundown and aspiration pressure on spray quality was investigated experimentally and analytically for a cylindrical and a conical set of nozzles. Both rundown and aspiration pressure were found to mainly depend on two parameters, the dimensionless gas gap width $s_{red}=s/d$ (with d as inner gas diameter) and the dimensionless tip clearance $x_{red}=x/s$.

Spray quality turned out to mainly depend on gas pressure for larger gas outlet diameters D and on gas-to-liquid ratio for smaller D. By non-dimensionalizing tip-clearance, a generalization of the combined influences of suction, rundown and tip clearance on mass median diameter was achieved. The experimental fact that increased liquid suction produces a diminished spray quality, may be explained by the suction induced lowering of the gas density at the gas/liquid interface. Although in general higher tip clearance degrades spray quality due to decreased gas momentum forces distant from the nozzle exit, the liquid rundown is demonstrated to counterbalance this effect to a certain extend. In the conical nozzle experiments within the liquid rundown regime, the mass median diameter of the spray could be decreased for a given GLR while increasing the tip clearance.

NOMENCLATURE

x............ tip clearance [mm]
s... .... gas gap width [mm]
d_i........... inner diameter of liquid delivery tube [mm]
d............ inner gas diameter (corresponding to s) [mm]
D........... gas outlet diameter [mm]
α .... nozzle inclination angle [deg]
x_{max} .... maximum tip clearance [mm]
A_{gas} .... nozzle exit area [mm²]
p_R........... gas operating (reservoir) pressure [bar_{abs}]
s_{red}.......... dimensionless gas gap width ($s_{red}=s/d$) [-]
x_{red} .... dimensionless tip clearance ($x_{red}=x/s$) [-]
$A_{(xred)}$ ..... cross sectional area of gas jet at position x_{red} from nozzle exit [mm²]
ϑ .... Prandtl-Meyer jet expansion angle [°]
p_{asp} .... suction [bar_{rel}]
d_{50}.......... mass median diameter of the spray [µm]
GLR....... gas-to liquid ratio [kg gas/kg liq]

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