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Evaporation phenomena in superheated atomization and its impact on the generated spray

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ABSTRACT

Applying the process of superheated atomization (flash atomization) finely dispersed sprays with moderate droplet velocities can be obtained, without the necessity of high pressure or an additional gas phase. In this paper occurring evaporation phenomena inside a nozzle capillary and their impact on the generated spray are analyzed. Evaporation is enhanced for increasing superheating. An intensified evaporation induces a considerably extended spray and smaller droplet sizes are generated. Furthermore a reduced mass flux and decreased velocity of the droplets are to be expected. By increasing the amount of vapor spray pulsation, triggered by bubble bursting, is increased. This is shown in acoustic measurements, which also demonstrate a simple way to monitor, or even control the atomization of superheated liquids.

1. Introduction

In the atomization of superheated liquids thermal energy is used as an additional energy component in order to enhance the disintegration of a spray. Various applications are possible for this thermal spraying process like fuel injection, suspension spraying and desalination [1–3]. Applying this technique, simple nozzle geometries like capillary nozzles, allow the generation of a dispersed spray [4]. In most studies a tube like nozzle geometry [5–7] is used. In other studies more advanced geometries were applied, such as hollow cone nozzles [1,4], fan jet nozzles [8] or nozzles with a premixing chamber [9]. The superheating can be generated by different means: by heating the fluid above the vapor pressure with respect to ambient conditions [6,7,9] or by lowering the pressure of a spraying chamber below the fluid vapor pressure [5]. The initiation of the spraying process allows the fluid to pass through the nozzle. Within the nozzle capillary pressure losses by friction or acceleration can be observed [9]. If the pressure inside the capillary drops below the vapor pressure (corresponding to the applied temperature), evaporation sets in [10,5]. Evaporation is a function of various parameters, including capillary wall roughness, wettability of the nozzle material, L/D-ratio of the nozzle capillary. In addition process parameters like pressure and temperature [4,5] influence the bubble formation. The evaporation itself was analyzed by several authors either experimentally [5], or by modeling [4,11–14].

For an enhanced roughness of the flow capillary a more disintegrated spray has to be expected [6,15]. An increase of the L/D-ratio has the same effect [16]. By increasing the fluid temperature, the driving force for evaporation, vapor pressure p_v, is enhanced. The spray gets more disperse since the evaporation rate is raised [6,7]. The onset of flashing can be described by a material dependent critical process temperature [5,6]. It is described in an empirical correlation by Kitamura [5]. Dependent on the mentioned parameter, evaporation takes place within the nozzle capillary ("internal flashing"), or outside the nozzle ("external flashing") [7,17,18]. Even though the internal flashing is of higher significance for the conducted experiments, the basics for both will be presented in the following. The effect of process conditions on the breakup has been investigated by various authors. Mostly with shadowgraphic methods were applied that allow to relate the flow regime within the nozzle to the actual breakup mechanism of the spray [6,7,19,20]. The internal flashing mode induces mixing of vapor bubbles and fluid phase, yielding a two-phase flow in the nozzle capillary [21,22]. The burst of vapor bubbles ($p_{bubble} > p_\infty$) at the nozzle outlet yields a disintegration of the jet. In the case of external flashing, evaporation starts after the fluid has left the nozzle. Vapor bubbles are formed and disintegrate the jet into ligaments [7,19]. This behavior has to be expected for small superheating, short nozzles and low capillary surface roughness. The transition between the two flashing modes depends on the location of first evaporation. The location of first evaporation is given as a function

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Nomenclature

Roman symbols

A	nozzle cross section area (m^2)
a	radial distance to spray axis (mm)
B	percentage of bubbles filling cross section (%)
CCD	charge coupled device (–)
C_D	discharge coefficient (–)
C_F	correction factor (–)
$c_{p,l}$	heat capacity ($J\,kg^{-1}\,K^{-1}$)
D	nozzle diameter (mm)
$F_{intertia}$	force of inertia (N)
F	dimensionless mass flux (–)
f	frequency (Hz)
Δh_v	heat of vaporization ($J\,kg^{-1}$)
Ja	Jacob number (–)
L	nozzle capillary length mm
L/D	length-to-diameter-ratio (–)
LED	light-emitting diode (–)
$\dot{M}$	mass flux ($kg\,s^{-1}$)
N	number of per image (–)
n	refractive index (–)
Nd:YAG	neodymium-doped yttrium aluminum garnet (–)
p	pressure bar
p^*	Cavitation number (–)
PIV	Particle Image Velocimetry (–)
Q_0	cumulative bubble size distribution (–)
R	radius (mm)
R_D	coefficient of determination (–)
r	roughness (μm)
T	temperature (°C)
t	time (s)
ΔT	temperature difference (°C)
ΔT^*	dimensionless temperature (–)
U	effective stress (–)
V	velocity (ms^{-1})
x	droplet diameter (μm)
x_{32}	droplet Sauter mean diameter (μm)
z	axial distance to nozzle outlet (mm)

Greek symbols

ρ	density ($kg\,m^{-3}$)
σ	surface tension (Nm^{-1})
μ	viscosity (Pas)
τ	residence time (ms)
Δ	difference (–)

Subscripts

b	biphasic
crit	critical
eff	effective
f	fluid
full	filled
i	corresponding to certain process parameter
limit	limiting value
max	maximum
medium	medium value
sat,p_∞	saturated conditions for (p_∞)
sat,p_0	saturated conditions for (p_0)
total	total number
v	vapor
x	at certain location
0	starting condition
∞	at ambient condition
25 °C	at 25 °C

of the L/D-ratio (varying limiting values) by several authors [8,9,24].

The internal flashing mode is favorable for generating small droplet sizes. The measured droplet sizes are in the range of those generated by nozzles with internal mixture of an additive (non-evaporating) gas (e.g. effervescent atomizers). Droplet size distributions in the spray have been investigated by various authors with shadowgraphic methods, laser diffraction or PDA (Phase Doppler Anemometry) [6,7,19,21,24]. Those measurements mostly yield the trend that droplets get smaller with increasing superheating, and larger distance from the spray axis in radial direction. The latter differs from the behavior of a subcooled spray, for which bigger droplets can be expected in the center of the spray [10]. This can be explained by differences in the break-up of the spray itself. For a superheated spray, the breakup is triggered from within by the bursting of bubbles. In the case of a not superheated pressure nozzle the break-up starts at the rim of the fluid jet, based upon interactions with the surrounding. A model to estimate the resulting droplet sizes was developed by Razzaghi [11]. He assumed that the spray breakup is a combination of aerodynamic and thermodynamic fragmentation. The primary breakup is assumed to result from aerodynamic forces. The secondary droplet generation is triggered by thermodynamic breakup due to bubble growth.

Sprays generated with superheated atomization offer wide opening angles at the nozzle outlet, and small penetration depths [9,26]. The spray angle is increased for rising superheating, up to a maximum value which is limited due to entrainment effects [7,19,8,25,26]. The penetration depth is reduced with rising temperature. This can be attributed to the fact that disintegration is induced at an earlier upstream location [27] for higher superheating.

Droplet velocities were analyzed by shadowgraphic methods [6], PIV (Particle Image Velocimetry) [16,17] and PDA [25]. Droplet velocities are lowered towards the spray edges. They are reduced for higher superheating, and rising distance to the nozzle outlet [16,25]. Droplet velocities (20–40 ms^{-1}) are mostly in a moderate range, which facilitates the application of post-processing steps like calcination.

The mass flux exiting the nozzle was measured by various researchers. The results indicated enhanced evaporation with higher superheating [7,23]. Some studies focused on critical mass flux. Critical mass flux is reached, if a further enhancement of the throughput driving force (pressure difference) does not enhance the resulting mass flux any further. This behavior can be observed, if the speed of the fluid equals the sonic speed. Since for two-phase flow the value of sonic speed is reduced in comparison to a pure substance, this can happen for low fluid velocities [9,28–31].

An advantage of superheated atomization is a decrease of coalescence processes of droplets in the downstream area, because of evaporation [32]. Evaporation yields a repulsive force between droplets that can be explained by a flow of steam originating from the droplet surface.

Atomization of superheated liquids is a highly complex topic with regard to the thermodynamic processes involved (see [9,26]). Most studies only give a certain range of measurement data, for example droplet sizes and velocities. In this study a wide set of experimental data is presented, describing the process