Discharge characteristics of the atomization of superheated liquids

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Abstract
The atomization of superheated liquids utilizes the partial evaporation of the induced liquid for the generation of a dispersed spray. In addition to pressure energy, thermal energy is inserted into the system in order to enhance the disintegration ability of the spray. The resulting spray offers moderate droplet velocities and fine resulting particles. In order to gain access to the sum of the occurring incidents, dimensionless quantities, like the cavitation quantity, are applied. Variations of process parameters like the applied temperature are investigated as well as the influence of the nozzle geometry.

Introduction

By inserting thermal energy into the system, a partial evaporation of the process fluid is stimulated. The obtained vapour content is dependent on process parameters like the superheating degree, as well as on the nozzle geometry. When the fluid is discharged into environment a phase inversion, actuated by spray disintegration takes place and the vapour phase inside the nozzle enhances the disintegration. In comparison to pressure atomization a droplet size distribution which is shifted to smaller diameters is resulting. Application of an additive gas phase can be omitted, because a vapour phase is already available due to the evaporation of the process fluid. By observing the massflow as an integral parameter of the spraying process, occurrences inside the nozzle are investigated. The whole process can be regarded as a superposition of a moderate pressure, with a highly efficient two substance atomization. The generation of a dispersed spray can take place in cylinder nozzles with a simple geometry. This is beneficial since the possibility of blocking while spraying suspensions is reduced. Since moderate droplet velocities are obtained, a post-processing, for example particle formulation or drying, is possible.

Materials and Methods

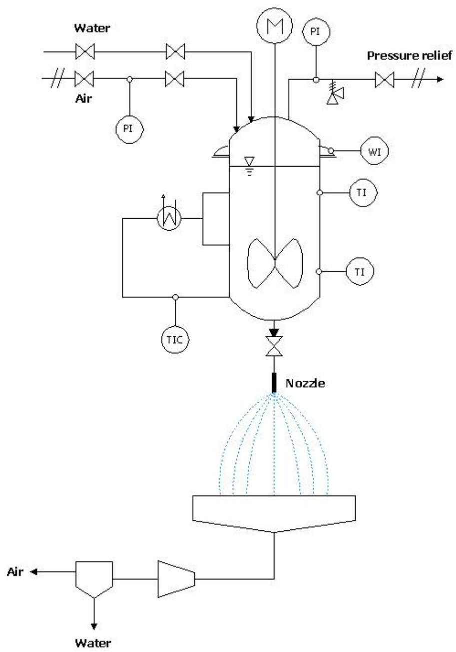

Figure 1. Spraying plant

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The atomization of the media is carried out in a spraying plant which is depicted in Figure 1. Thermal energy is inserted into the system via heating jackets. For the pressure built-up pressurized air is used. The investigated nozzle is located at the lower end of the pressure vessel. By opening an upstream installed valve the atomization is initiated. The massflow is observed by a LabView program. Using a load cell the continuously decreasing weight of the autoclave is measured. The temperature inside the system is monitored by thermocouples. During this work deionised water was applied as process fluid.

An important component of the spraying set up is the applied nozzle. Within the scope are variations of the nozzle geometry. The diameter and length of the applied orifice nozzle are varied as well as the roughness of the inner flow channel by using different fabrication methods and materials. An overview over the applied nozzles is given in Figure 2 with the related abbreviation.

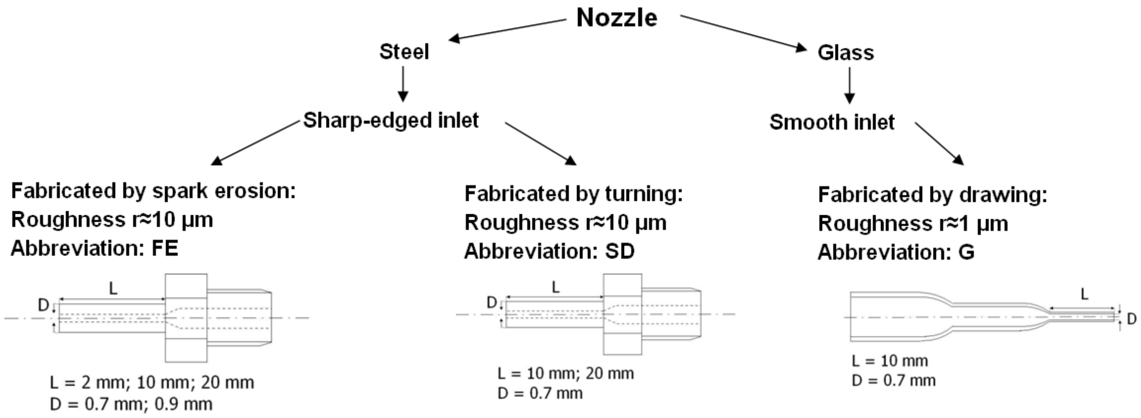

Figure 2. Nozzle Parameters

Theoretical Background

Hydrodynamics of nozzle flow

According to Gebhard [2] the flow pattern inside the nozzle is strongly dependant on the L/D-ratio of the smallest cross-section. Up to a value of L/D-ratio ≈ 3 the nozzle yields an outflow that shows an aperture-like behaviour (Figure 3 a)). The fluid phase is discharged with a minimum fluid jet diameter (Vena Contracta). If the process liquid is heated up to a higher value than boiling temperature, the fluid leaves the nozzle without evaporation, boiling retardation can be observed. In the case of L/D-ratios up to 12 a reattachment of the fluid to the nozzle wall can take place (Figure 3 b)), following the cross section constriction at the inlet of the flow channel. If the local pressure reduction at the Vena Contracta yields a vapour pressure undercut, evaporation can take place and thus a certain vapour content, dependent on the nozzle geometry is possible. If a complete reattachment takes place, a backmixing of the vapour into the flow can occur (Figure 3 c)), according to Gebhard this happens at L/D-ratios with a higher value than 12. The described flow patterns are shown in Figure 3.

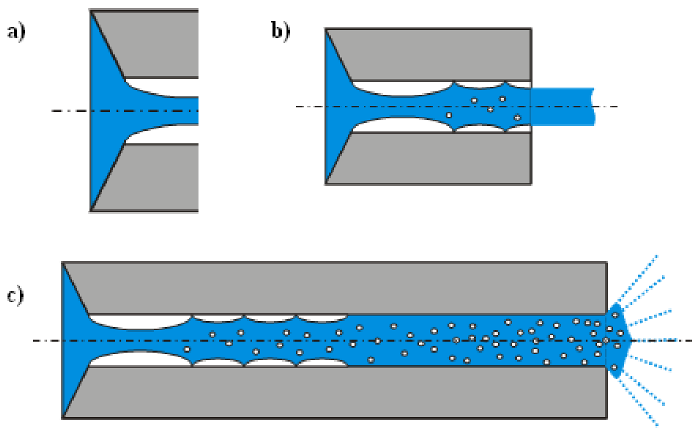

Figure 3. Theoretical flow pattern in the nozzle

Dimensionless Quantities describing the massflow

For the description of the atomization of superheated liquids dimensionless quantities will be applied. A summary of relevant quantities for the atomization adopted in this work is given in Table 1.

Table 1. Summary of the applied dimensionless numbers

Dimensionless Quantity	**Formula**
Cavitation Quantity p*	$p^* = \frac{p_0 - p_s(T_0)}{p_0 - p_\infty}$ (1)
Dimensionless Massflow F	$F = \frac{\dot{m}_{FG}}{\dot{m}_F}$ (2)
L/D-ratio	$\frac{L}{D}$ (3)

The Cavitation Quantity can be regarded as a measure of the cavitation ability of the system. Limiting values are 0 for pure gas flow and 1 for a homogeneous fluid flow. Two phase flow can be observed in between. The smaller the value of the Cavitation Quantity, the larger is the resulting vapour content. In accordance with equation (1) the evaporation tendency increases with enhanced temperature and reduced counter pressure [1].

Results and Discussion

In Chyba: zdroj odkazu nenalezen the massflow is depicted in dependence of the nozzle length. If the pressure difference is enhanced by process pressure-(p_0)-increase, a higher value for the massflow results. It is possible to distinguish two major flow regimes. The upper measurement points show subcooled behaviour at a process temperature of 25°C. There the massflow enhances with nozzle length. This can be explained by the flow pattern directly after the nozzle inlet.

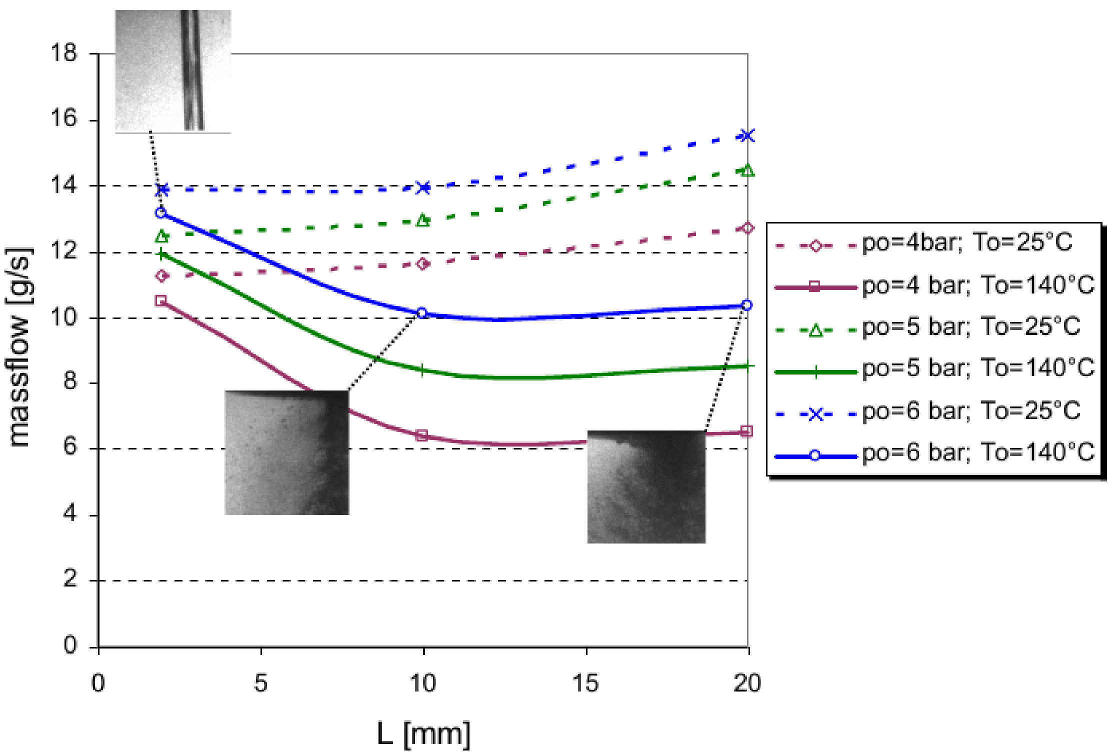

Figure 4. Massflow in dependence of the nozzle length
T_0=25 °C, 140 °C; D = 0.9 mm; p_∞= 1 bar

As has been shown in chapter “Methods and Materials”, the inlet of the steel nozzle can be described as sharp-edged. An inlet of this kind causes a flow detachment from the nozzle inner wall as has been described in chapter "Theory", which yields a massflow reduction if no reattachment occurs. In aperture like nozzles the residence time in the flow channel does not suffice to allow a reattachment. As the nozzle length enhances, the residence time of the fluid in the nozzle is also rising. This in return permits a reattachment of the flow and thus a pressure regain. The longer the nozzle the bigger the pressure regained up to the point where the whole applied pressure difference is again propulsive. This is not the case in the measurements done in this work, since the massflow is still increasing with nozzle length, which would not be the case if a total pressure regain had taken place.

The other flow regime can be achieved if using superheated liquid as flow media. In this case one observes a reduction of massflow in comparison to subcooled outflow. The basic explanation of this occurrence is that by evaporation inside the nozzle, initiated by superheating, the total amount of massflow is reduced. In the first place, concerning the aperture-like nozzle the massflow of superheated and subcooled media nearly coincide. Here the detachment of the flow is the limiting occurrence. In the case of subcooled media the residence time is not long enough to allow a pressure regain, concerning superheated liquids one observes that the media leaves the nozzle superheated still in a thermodynamic unbalance. This phenomenon is called boiling retardation. With enhancement of nozzle length evaporation occurs. Since the propulsive pressure difference is limited by evaporation to the value $\Delta p = p_0 - p_s(T_0)$ no enhancement of massflow can be observed even if elongating the nozzle. Also, it is possible that evaporation does not result exclusively from the local undercut of the vapour pressure at the Vena Contracta. If the flow reattaches to the nozzle wall, evaporation can be generated by germinative boiling initiated by surface roughness in the flow channel. This can lead to a back-mixing of bubbles into the liquid flow. As depicted in Figure 4 the mentioned flow phenomena also can be observed optically. In the case of the aperture-like nozzle a smooth stream is observed indicating boiling retardation. If evaporation can occur a dispersed spray is the result.

Another geometrical parameter with influence on the massflow is the diameter of the nozzle flow channel. In this work two nozzle diameters have been used: 0.7 mm and 0.9 mm. The resulting massflow density, already weighted by the cross section area of the nozzle, is depicted in Figure 5 for short nozzles (L=10 mm).

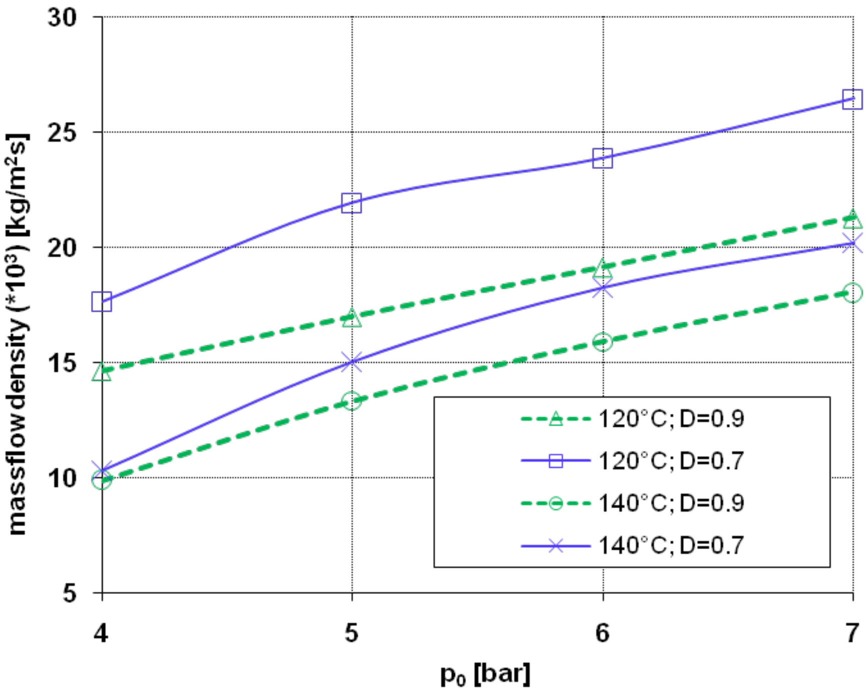

Figure 5. Variation of nozzle diameter - Short nozzle
T_0=120 °C, 140 °C; p_∞= 1 bar; L=10 mm; D=0.7 mm, 0.9 mm

All curves have in common that the massflow density is increasing with rising applied process pressure. Also the usual behaviour of massflow reduction with increasing superheating can be observed. A smaller diameter results in an enhanced massflow density if applying geometrical short nozzles. The detachment of the flow at the nozzle inlet has an influence on the resulting massflow, since a vapour pressure undercut yields evaporation and thus a massflow reduction. If small diameters (0.7 mm) are applied, the detached flow has a shorter distance to cover to reattach, the residence time of vapour after the inlet is low. This means that there is a reduced contact time of vapour and process fluid. In the result there is a minor amount of vapour inserted into the fluid phase, the overall massflow density is enhanced. If a larger cross section is used, the reattachment is retarded, the contact time of fluid and vapour phase is enlarged. Thus there is enhanced vapour insertion into the spray. Abbreviations are also caused by differing superheating degrees. The higher the superheating the smaller is the effect of varying diameter dimension. Concerning higher applied process temperatures the evaporation inside the system is increased. Thus even a temporally short detachment of the flow of the nozzle wall yields intense evaporation and an elongated residence time of vapour phase after the inlet, especially in comparison to a lower superheating degree. The effect of the diameter dependent flow detachment can still be observed but the difference between varying diameters on the massflow density is reduced.

Employing longer nozzles differing results are obtained. The massflow density resulting in geometrical long nozzles using the same diameters as before is depicted in Figure 6.

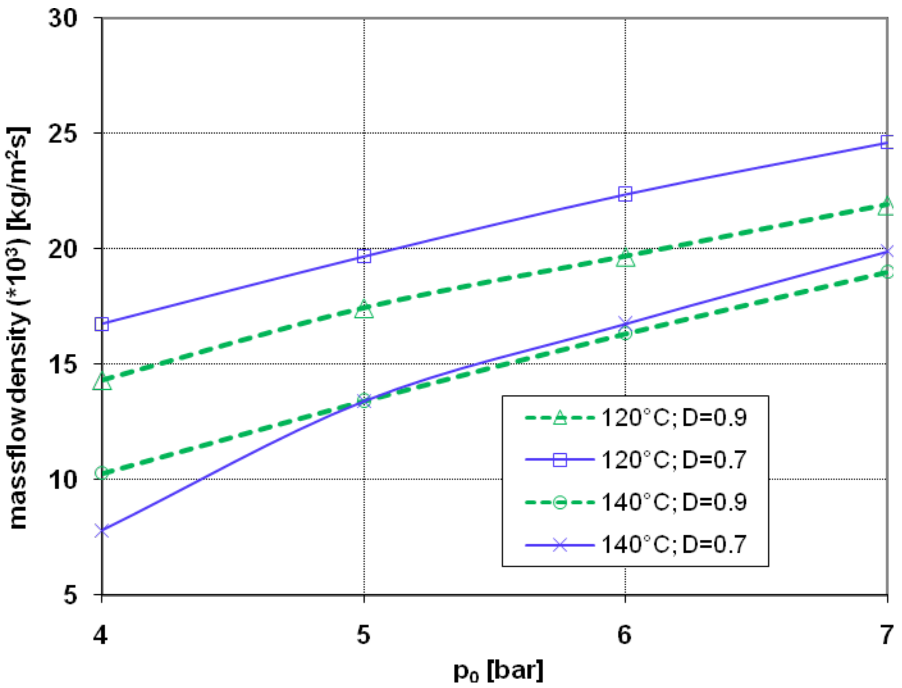

Figure 6. Variation of nozzle diameter - Long nozzle
T_0=120 °C, 140 °C; p_∞= 1 bar; L=20 mm; D=0.7 mm, 0.9 mm

With increasing nozzle length the influence of the nozzle diameter on the massflow density is reduced. In the case of T_0=120°C a difference between the measurement data obtained with differing diameters is at last given, but reduced in comparison to short nozzles. Applying a process temperature of 140°C and thus an increment concerning the superheating degree, yields a near accordance of the resulting curves. As explained before, a longer nozzle increases the possibility of flow reattachments to the nozzle wall and also yield a longer residence time of the liquid inside the nozzle. Thus using longer nozzles two different phenomena have to be distinguished. In the case of short nozzles the detachment of the flow and thus the resulting vapour phase has a short residence time inside the nozzle. A smaller diameter yields a reduced evaporation length induced by detachment, which again yields a smaller propulsive force for evaporation. Concerning longer nozzles one has to mind evaporation at the wall roughness, the so called seed or germinative boiling. Since the flow detachment is not the only cause for evaporation if employing geometrical long nozzles, there is a reduced difference in the resulting massflow density obtained with different diameters. The seeding boiling can be regarded as a kind of attenuation. Since the evaporation tendency of the system increases with superheating the difference initiated by diameter variation is even more reduced in the case of 140°C. At this temperature, evaporation because of seeds has more influence on the system. In the case of the 0.9 mm diameter there is an elongated detachment. Reduction of the diameter to 0.7 mm yields an increase of the S/V-ratio in the flow channel, which enhances the quantity of seeds per fluid element, also resulting in an intensified evaporation.

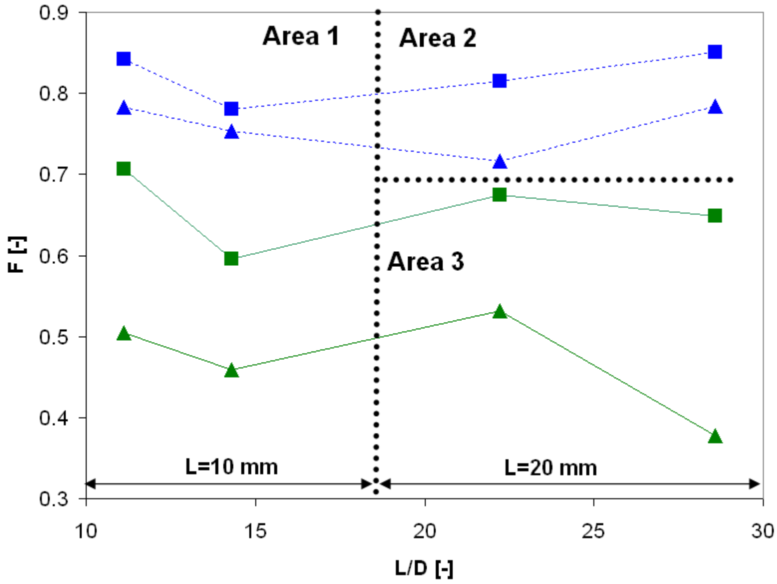

Figure 7. Dimensionless depiction of geometrical influences
T_0=120 °C, 140 °C; p_∞=1 bar ; L= 10 mm, L=20 mm; D=0.7 mm, 0.9 mm

In Figure 7 the dimensionless massflow density F is depicted versus the L/D-ratio of the applied nozzles. No continuous trend of the massflow with L/D enhancement can be observed. Nevertheless it is possible to subdivide the diagram in three different areas.

Area 1:

Short nozzles, varying superheating degrees - In this area the flow detachment at the nozzle inlet is the predominant evaporation initiating occurrence. Thus the influence of the residence time of the vapour phase initiated by that detachment can be regarded as the dominating parameter. Seed boiling can be neglected.

Area 2:

Long nozzles, small superheating - There still is an influence of the detachment of the flow at the nozzle inlet. The seed boiling is initiated since the flow can reattach to the nozzle wall, but is not the predominant initiator of evaporation.

Area 3:

Long nozzles, high superheating - Predominant evaporation because of the seed boiling initiated by flow channel roughness. The detachment of the flow can be regarded as neglectable.

The influence of the seed boiling can especially be observed if the roughness of the inner flow channel of the nozzle is varied as shown in Figure 8 and Figure 9. In the case of a turned steel nozzle (TN) a roughness of 10 micron is given. The nozzle fabricated by spark erosion (SEN) has a medium roughness half the size, 5 micron. Again different phenomena can be achieved by varying nozzle lengths. In Figure 8 the massflow density of short nozzles with a varying roughness is depicted. In this case an enhanced massflow can be achieved by employing a higher roughness. An enhanced roughness is also located at the inlet of the nozzle. At this location the flow is disturbed and the detachment of the flow is thereby reduced. A diminished detachment degrades the evaporation tendency of the system, especially if a relatively low superheating is applied (120°C). Concerning high superheating degrees (140°C) the roughness of the inlet reduces the flow detachment but at the same time is a starting point for seed boiling. Since seed boiling is the major initiator of evaporation in systems with a high superheating, the flow detachment can nearly be neglected, the resulting curves nearly coincide.

Using long nozzles a completely different behaviour is resulting. Án atomizer with a higher roughness of the flow channel yields a lower massflow density. The major driving force for evaporation is not the detachment of the flow but the seed boiling at the channel roughness if employing geometrical long nozzles. A higher value of surface roughness hence results in an enlarged amount of vapour, since more effective seeds are to be found inside the system. With enhanced superheating the seed boiling increases and hence the amount of generated vapour which leads to a reduction of massflow. The output of those diagrams stands in complete accordance to the prior subdividing of flow areas in Figure 7.

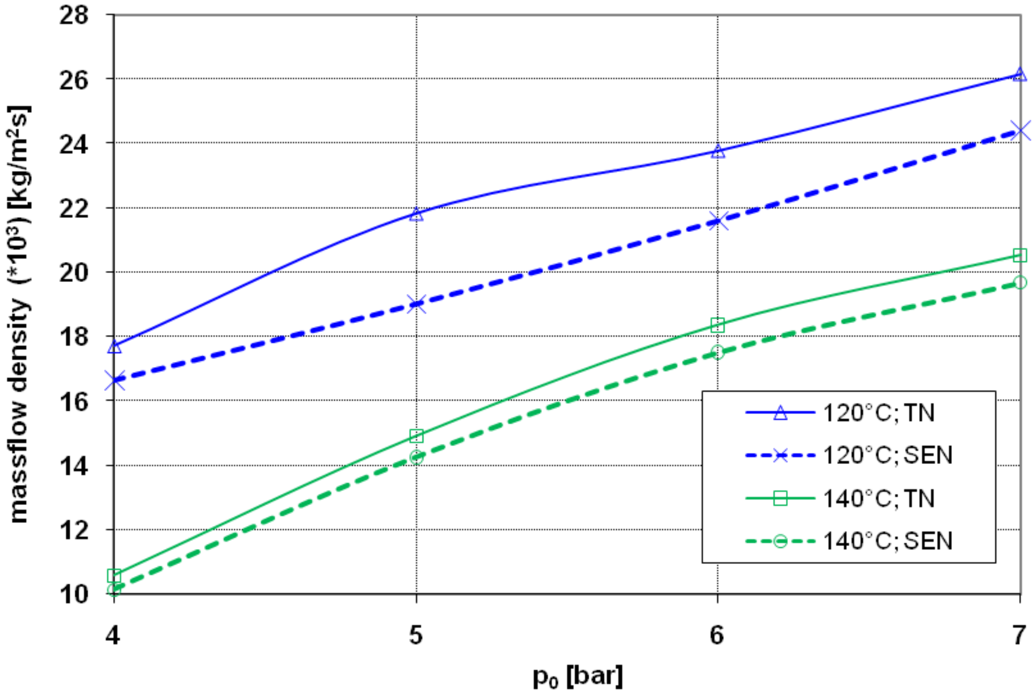

Figure 8. Roughness Variation - Short nozzles
T_0=120 °C, 140 °C; p_∞=1 bar; L= 10 mm; D=0.7 mm; r=5 µm, 10 µm

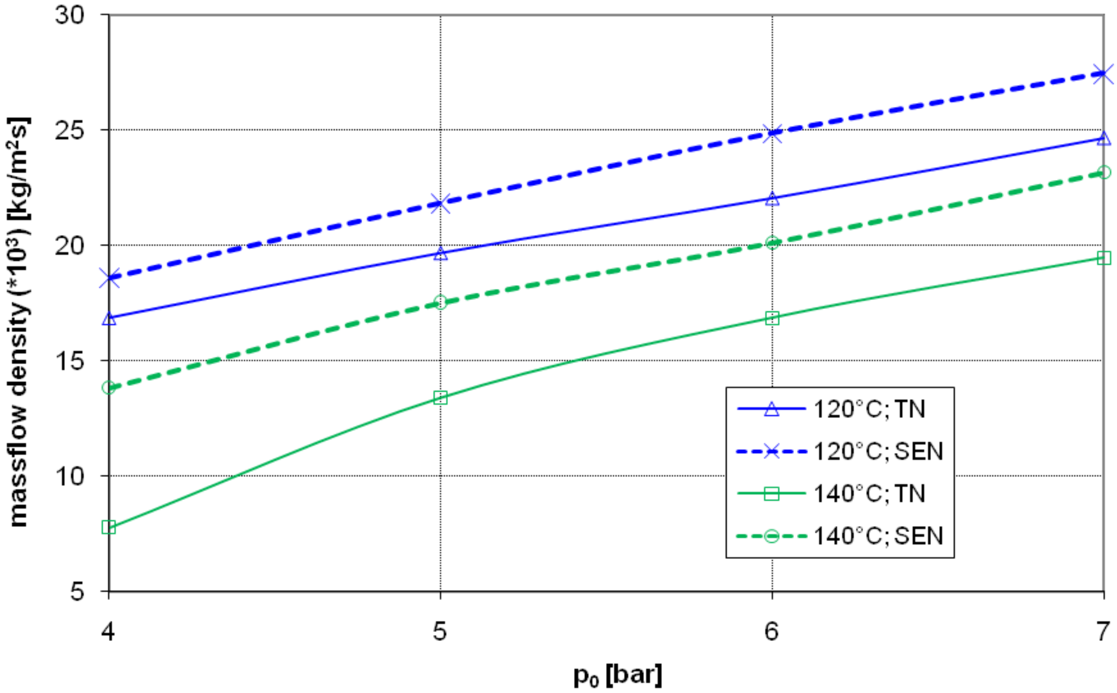

Figure 9. Roughness variation - Long nozzle
T_0=120 °C, 140 °C; p_∞=1 bar; L= 20 mm; D=0.7 mm; r=5µm, 10 µm

An extreme example for the influence of roughness is given by a glass nozzle (GN). In this case one can suppose a roughness of the inner wall of ≈ 1 micron. A comparison of the yielded massflow density is executed in Figure 10.

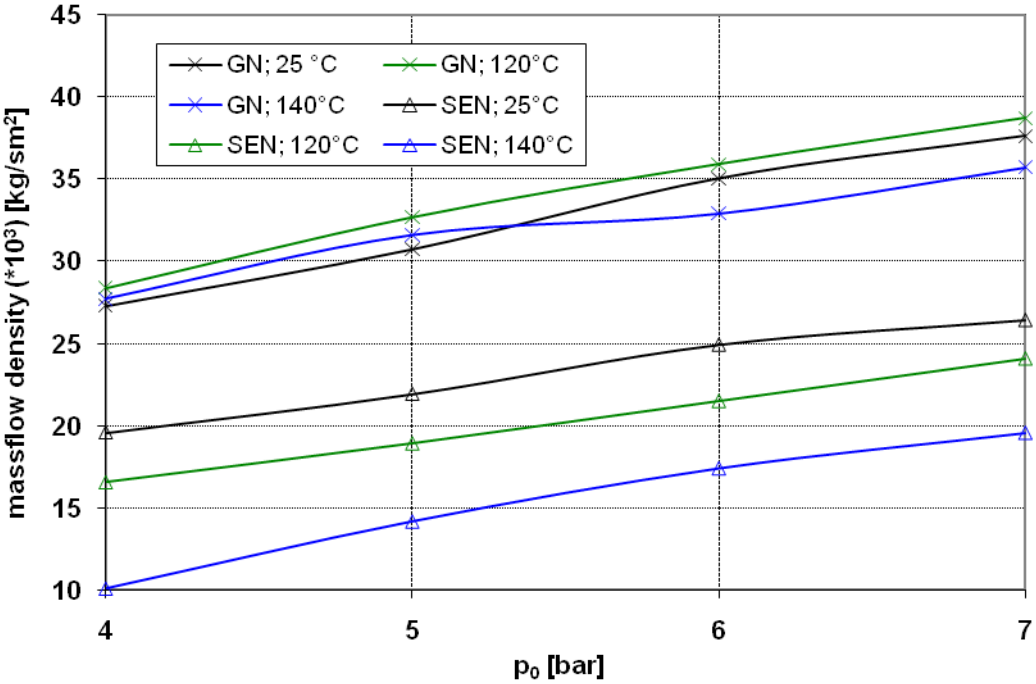

Figure 10. Material Variation – Glass and Steel Nozzle
T_0=25 °C, 120 °C, 140 °C; p_∞=1 bar; L= 10 mm; D=0.7 mm; r=1µm, 5 µm

As one can see in the depicted diagram the glass nozzles does not show a noticeable massflow variation. One reason for this kind of behaviour is that there are no seeds to start seed boiling in the system. To understand the whole course of the measurement curve one has to reconsider the geometry of the glass nozzle. Not only is the roughness of the system, but also the inlet geometry differing in comparison to all steel nozzles. In contrast to the sharp-edged inlet of the steel nozzle, the inlet of the glass nozzle is quite smooth. A smooth inlet inhibits the detachment of flow and hence the other initiating factor for evaporation is liquidated. The result is that the flow leaves the nozzle still superheated, a retardation of boiling takes place. In comparison the steel nozzle shows the typical behaviour dependent on the superheating and hence on the evaporation rate.

The behaviour of the glass nozzle, far away from the thermodynamic equilibrium depicted dimensionless is drawn in Figure 11. The equilibrium curve follows the following dependency:

$$F=\frac{\dot{m}_{FG}}{\dot{m}_F}=\sqrt{\frac{p_0-p_s(T_0)}{p_0-p_\infty}}=\sqrt{p^*} \tag{4}$$

Hence all measurement points located on the equilibrium curve show a good accordance to the ideal case of a developed two phase flow as is the case considering the steel nozzle (SEN). In difference the glass nozzle yields an F-value of around 1 for all Cavitation Quantities. A dimensionless massflow of one is only achieved if there is a pure fluid outflow of the nozzle like in the case of subcooled media. That there is a subcooled behaviour even at a residing superheating in the case of the glass nozzle can only point to boiling retardation.

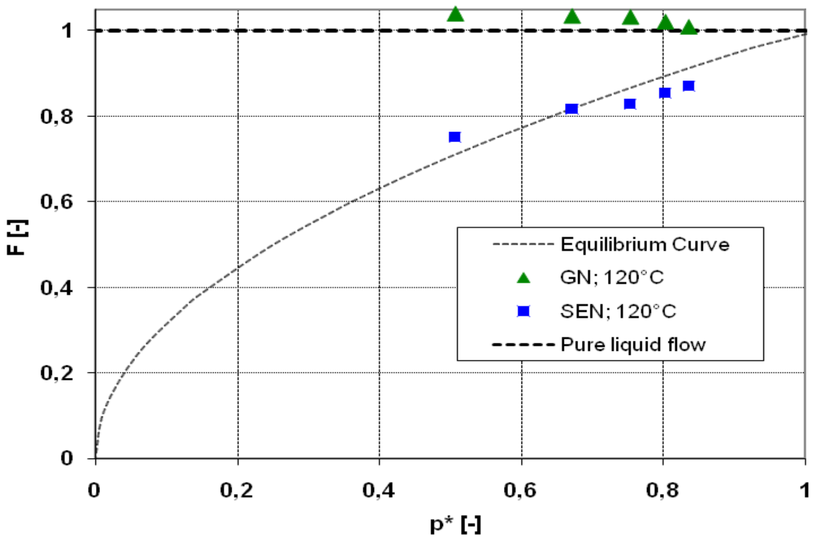

Figure 11. Dimensionless depiction of the massflow of glass and steel nozzle
T_0=120 °C; p_∞=1 bar; L= 10 mm; D=0.7 mm; r=1µm, 5 µm

Summary

The variation of the nozzle geometry has great influence on the resulting massflow. The elongation of nozzles yields enhanced evaporating in the case of superheated liquids. Aperture-like nozzles on the contrary discharge a superheated fluid without vapour content, boiling retardation can be observed. The massflow dependency on the nozzle diameter is more complex. Applying short nozzles the flow detachment at the inlet is the predominant occurrence, hence the mass flow density is reducing with diameter enlargement. If there is a small superheating, but geometrically long nozzles are used, the influence of the flow detachment can still be observed, but it is reduced by seed boiling effects. Employing long nozzles at a high superheating the predominant effect is seed boiling; the flow detachment can be neglected. The roughness of the inner diameter has varying effects on the massflow depending on the nozzle length. If the dimension of the nozzle does not allow a reattachment of the flow a rougher surface yields enhanced massflow. A reversed behaviour is found if elongating the nozzle length. In this case the seed boiling dominates the evaporation. An extreme example for the dependency of the massflow on the geometry is given by the glass nozzle. The nozzle with a smooth inlet and a neglectable surface roughness does not contain an initiating feature for evaporation. The massflow is hence comparable to that of a subcooled media, but located in a thermodynamic unbalance. The discharge can be classified as boiling retardation. The spray morphology can be adjusted by variation of geometrical parameters of the nozzle, varying from a smooth free jet to a dispersed spray.

Acknowledgements

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Nomenclature

D	nozzle diameter [m]
F	dimensionless massflow [-]
GN	glass nozzle
L	nozzle length [m]
p	pressure [bar]
p_∞	counter pressure [bar]
p_0	process pressure [bar]
$p_s(T_0)$	vapour pressure of T0 [bar]
$\dot{m}$	massflow [kg/s]
$\dot{m}_{FG}$	mulit phase mass flow [kg/s]
Δp	pressure difference [bar]
$\dot{m}_F$	fluid massflow [kg/s]
p*	cavitation quantity [-]
T	temperature [°C]

T_0 process temperature [°C]
TN turned steel nozzle
SEN spark erosion nozzle
S surface area [m^2]
V volume [m^3]

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