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WATER DROPLET EVAPORATION AT HIGH PRESSURE AND TEMPERATURE LEVELS - PART I: EXPERIMENTAL INVESTIGATIONS OF SPRAY PATTERNS AT VARIED TEST CONDITIONS

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ABSTRACT

Water injection into gas turbines is subject of investigations since decades, due to a high power and efficiency augmentation potential compared to the simple gas turbine cycle. Based on former research at ambient conditions, some technologies have already been realized, e.g. inlet fogging. Further applications of water injection at higher temperature and pressure levels are limited, because of few experimental data. In order to gain fundamental understanding at these boundary conditions, a novel test facility for droplet evaporation investigations has been built up at the University of Duisburg-Essen. The resulting spray patterns are recorded by a laser based measuring technology, Phase Doppler Particle Analyzer (PDPA).

Part I of the paper treats the experimental setup of the test facility; in particular the laser based measuring technology, as well as the measurement results of the spray pattern produced from a nozzle at high pressure and temperature levels. The focus of the investigations is on the droplet evaporation process in dependence on parameter variation of the environmental conditions.

INTRODUCTION

Two-phase flow is a topic of interest in modern gas turbine applications. The injection of water upstream of the first compressor stage, the so called wet compression, has a potential for power augmentation, due to the decreased compressor work and higher mass flow. It is most effective at hot and dry ambient conditions [1], because at these conditions the most water can be absorbed by the air. The influence of wet compression on the engine characteristics has been examined in some studies numerically [2, 3, 4].

However, wet compression supersaturates the inlet air; hence water droplets remain in the flow. The behavior of single water droplets, especially their evaporation, at low pressures and low temperatures, as they can be found in the first stages of the compressor, has been topic of some investigations in the past [5,1]. Several test rigs are conceived to study the two phase flow of fog droplet distribution. Eisfeld *et al*. [6], Bettochi *et al.* [7], Day *et al*. [8] measured the droplet distribution inside a compressor cascade and at the intake of a multistage compressor. Furthermore laser based measuring techniques were used to examine the spray characteristic of different nozzles by Suryan *et al.* [9] at ambient conditions in a wind tunnel or mist cooling in a heated tube by Guo *et al.* [10].

To the authors knowledge, experimental investigations of droplet behavior injected in a hot gas flow at elevated temperature and pressure levels, have not been topic of studies. To investigate this behavior a novel test facility has been built up at the Department of Mechanical Engineering at the University of Duisburg-Essen.

In this paper a brief introduction of the general test facility is given. The installed laser based measurement system as well as the execution of data capturing and evaluation are explained in detail. In the further course first results concerning the realization and visualization of measured data are presented. Finally, the influence of temperature level variations of the environmental airstream on the water spray pattern is examined.

NOMENCLATURE

d	[mm]	Diameter
l	[mm]	Length
$\dot{m}$	[kg/s]	Mass flow
p	[MPa]	Pressure
r	[mm]	Radius
s	[mm]	Thickness
T	[K]	Temperature
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
z	[m]	Cartesian axis direction

Subscripts

i	Inner
max	Maximum
min	Minimum
mp	Meridional plane

EXPERIMENTAL TEST FACILITY

The novel test facility for droplet evaporation investigations at elevated pressure and temperature levels has been built up in the laboratories at the Department of Mechanical Engineering at University of Duisburg-Essen. The scheme of the experimental facility is shown in Figure 1. The setup consists basically of the four stage intercooled compressor, the electric heater, the supply for water injection, the measuring section, and the bypass. A detailed explanation of the single components can be found in [11]. At the test section dry air is provided with a pressure up to $p_{\text{max}} = 1$ MPa, a mass flow rate of $\dot{m}_{\text{max}} = 1.8$ kg/s, and a temperature that can be set in a range between $T_{\text{min}} = 308$ K to $T_{\text{max}} = 688$ K. Through a nozzle demineralized water at ambient temperature and up to $p_{\text{max}} = 25$ MPa is sprayed into the airstream. A PDPA-System, installed on a three-axis traverse system, is used to measure the spray pattern. Figure 2 gives an overview of the measuring section and the implemented measuring devices.

MEASURING SECTION

The measuring section mainly consists of a glass tube and the water injection section. The tube is manufactured of borosilicatglass because of its excellent thermal and optical properties. The glass cylinder has an inner diameter of $d_i = 102$ mm and a length of $l = 1000$ mm. In consequence of high pressure levels a requested wall thickness of $s = 9$ mm has been calculated. The water injection nozzle supply allows a positioning of the nozzle it the center and at the beginning of the glass tube. The fitting is designed to enable the attachment of different kind of nozzles and the alignment of the water injection in different angles in relation to the main air flow direction.

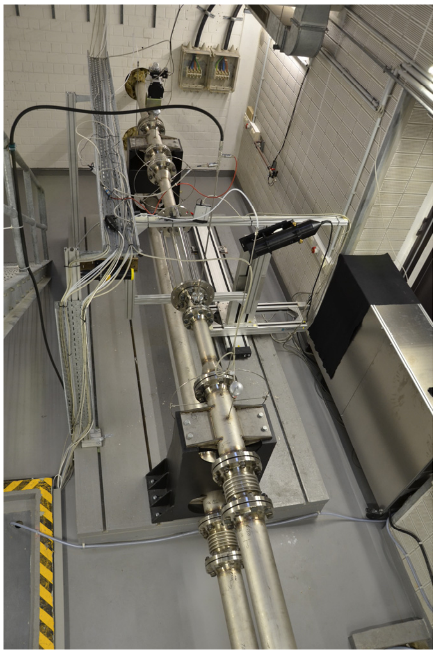

Figure 2 Overview of the measuring section

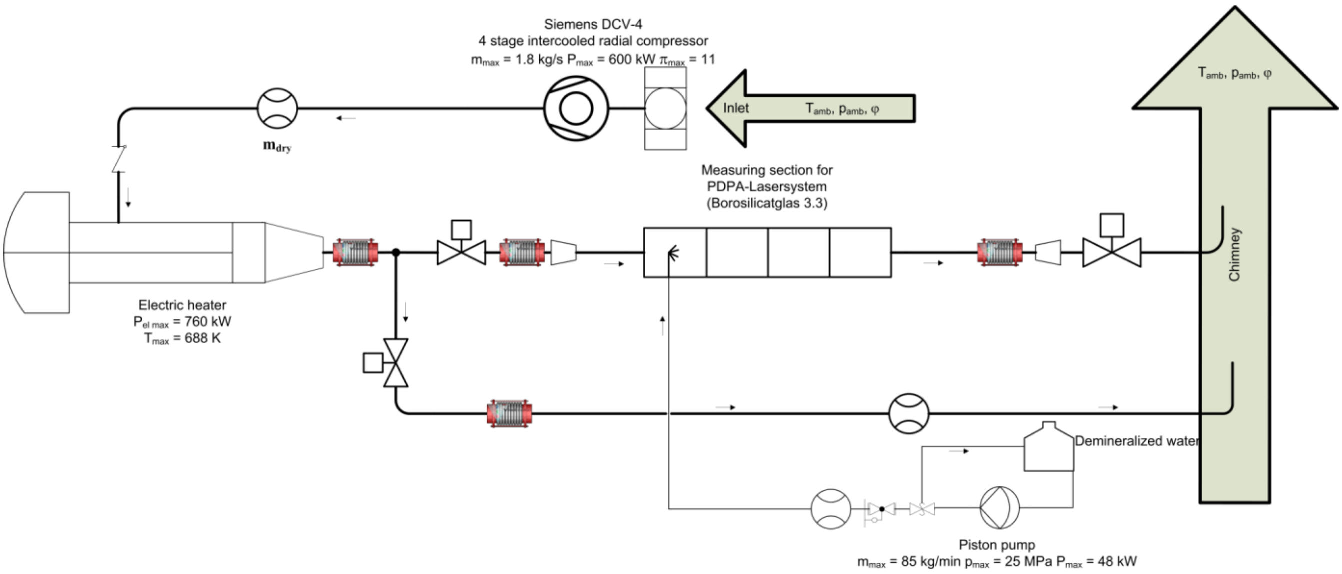

Figure 1 Schematic diagram of the test facility

DROPLET SIZE MEASUREMENT

For the investigations the Phase Doppler Particle Analyzer (PDPA) has been chosen, after several kinds of particle sizing methods were reviewed and compared. The PDPA-System allows the measurement of velocity and the sizing of spherical particles. Similar to the conventional Laser-Doppler-Velocimetry (LDV) the physical principle is based on light-scattering interferometry. Therefore a laser beam is split into two beams of equal intensity. The intersection of the two laser beams results in a fringe pattern (measuring volume). When a particle moves through this measurement volume, it generates a fluctuating pattern of scattered light intensity with a frequency proportional to the particle velocity. By knowing the distance between fringes and the traveling time of the particle from one fringe to the next, the measured temporal signal frequency can be converted to velocity.

To detect the size of a particle a receiver is placed 30 degrees off the plane of the transmitting beams (Figure 3). When a particle moves through the measurement volume the fringe patterns are also captured by detectors in the receiver. Only one detector is required to get the temporal frequency of the scattered light. To measure the spatial frequency, which contains the information about the size of the particle, a minimum of two detectors is required. The spatial frequency is measured as a relative phase shift between the two electrical signals resulting from the scattered light. This phase shift can be related to particle size.

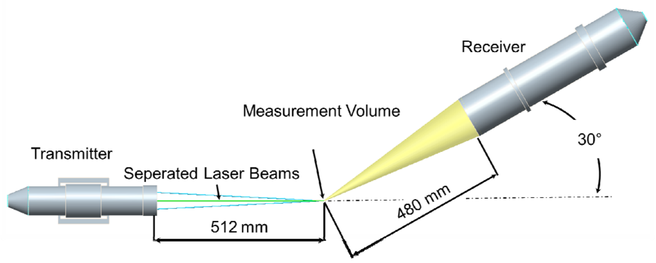

Figure 3 PDPA measurement arrangement

The laser transmitting fiberoptic probe of the applied PDPA-system has a focal length of 512 mm, a beam waist diameter of 115 µm, and the beam spacing for the probe is 50 mm. The receiver focal length of the PDPA-system is 480 mm. A 5W water cooled argon-ion laser is used. The receiver is connected to a photo detector module (PDM) and a signal processor (FSA), which provides the data for an analysis software. This software evaluates the data and generates specific information concerning the investigated spray pattern automatically.

To optimize the measurement process the PDPA-System is mounted on a three dimensional travers system. The travers system allows to determine and define the position of the measurement volume in the test section. Furthermore it enables a fully automated data capturing by following a pre-defined sampling pattern.

DATA CAPTURING

The data acquisition planes, located in the measuring section, are illustrated in Figure The coordinate origin is positioned at the center of the nozzle outlet. The data is captured on half of the meridional *x-y* plane (green) and additionally on three *y-z* planes perpendicular to the flow direction (blue). The perpendicular planes are placed at *the end* (plane 2, x = 850 mm), in *the middle* (plane 3, x = 450 mm), and in *the beginning* (plane 4, x = 14 mm) of the measuring section. Plane 2 and 3 span a surface with a radius of r_{23} = 60 mm. To increase the efficiency of data capturing the surface of plane 4 is adapted to the results of the meridional plane, because the spray pattern seizes only a small part of the tube diameter in the vicinity of the nozzle.

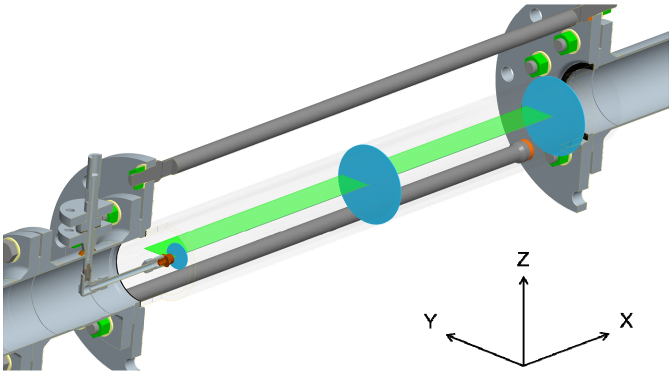

Figure 4 Data acquisition planes in the measuring section

In Figure 5, on the left, the data capture points, applied in the perpendicular planes, are shown. In order of a balanced distribution in the plane a reduction of the spacing in radial direction between the single points is established. To reproduce and compare measurement results a reducing of the plane diameter does not accompany with a variation of spacing or measurement positions. In fact a reduction of diameter only implies a diminution of travel distance. Plane 2 and 3 contain 260 measurement positions, while plane 4 only has 190 points. The distribution of measurement points in the meridional plane matches the radial distribution of the measurement points in the perpendicular plane. In y-direction the spacing between the positions corresponds to the one at the positive axial position of the perpendicular plane (Figure 5). In streamwise direction the measurement positions distribution begins with a very small spacing due to significant changes in the spray pattern at the beginning of the test section. In order of lower gradients, the spacing increases with growing distance downstream from the nozzle outlet. The meridional plane contains 275 measurement positions. At least four hours of operating time is required to capture the data of all exposed measuring points in the four planes without heating up and turn down period of the test rig.

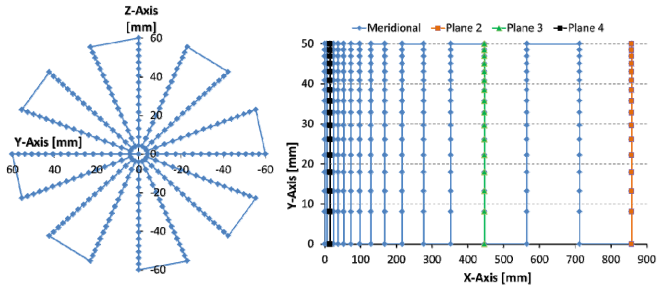

Figure 5 Distribution of the measuring points

MEASUREMENT RESULTS

The following results have been measured with a common hollow cone nozzle. The raw data has been evaluated to calculate the Sauter mean diameter (D_{32}) and the mean droplet velocity distribution of a spray pattern. The boundary conditions of the dry air stream and the injected water are summarized in Table 1.

	Pressure [MPa]	Temperature [K]	Mass/volume flow
Dry air	0.41	480	1.6 [kg/s]
Water	0.80	288	1.7 [l/min]

Table 1 Boundary conditions

In Figure 6 the D_{32} distribution (top) and the mean droplet velocity distribution (bottom) in the half meridional plane (plane 1) are plotted. In the coordinate origin the nozzle outlet is located. The black marks in the picture show the measurement positions. Although data has been measured in the complete plane (r_{mp} = 50 mm), measurements outside r_{mp} = 43 mm were skipped, because of too low data rates for a reliable evaluation.

Due to the outlet angle of the hollow cone nozzle of 45° most water droplets follow the initial direction at first. At a stream wise distance of x = 200 mm from the injection point, the D_{32} values increases from the rotational axis towards the wall of the tube. This is because of the higher momentum of the droplets, due to their size. In order of interaction with the airflow this difference reduces with the growing distance from the nozzle outlet. At 200 mm the maximum difference between the largest and the smallest D_{32} value is 140 µm, at 850 mm only about 40 µm. The visualization of the evaluated measuring data in plane 4 (Figure 7) shows the spray pattern from the nozzle's point of view (looking downstream). The results approve the described behavior of the water droplets at the nozzle outlet. In fact the increasing values of the Sauter mean diameter and the mean droplet velocity from the center to the wall of the glass tube appear here as an annular distribution with a nearly rotational symmetrical shape. The evaluated results of the two perpendicular planes (plane 3 and 2), further downstream the glass tube, are presented in Figure 8 and Figure 9.

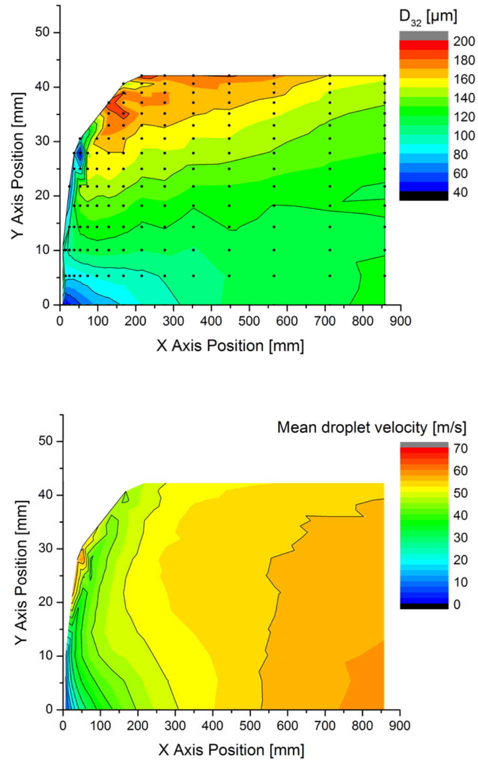

Figure 6 D_{32} and mean velocity distribution in the meridional plane

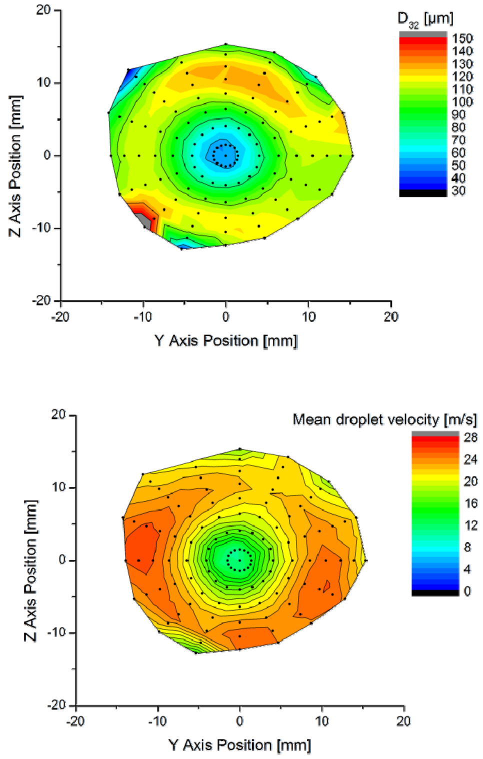

Figure 7 D_{32} and mean velocity distribution in plane 4 (14 mm)

The data evaluation in plane 3 illustrates the intersection of an annular to a homogeneous distribution. Nearly the complete plane shows only a small variation in the D_{32} value (Figure 8 top). Merely few, unequal distributed areas, at the boundary of the measured plane, exhibit a higher Sauter mean diameter value. In plane 2 the D_{32} value distribution is more homogeneous, concerning the maximum value difference, and shifted to a smaller mean value (Figure 9 top). The development of the mean droplet velocity distribution differs slightly from the D_{32} behavior (Figure 9 bottom). In plane 3 and 2 the annular distribution remains, although the velocity declines from the wall to the center of the tube reverses. Furthermore the area of highest mean droplet velocity occurs to the bottom of the tube.

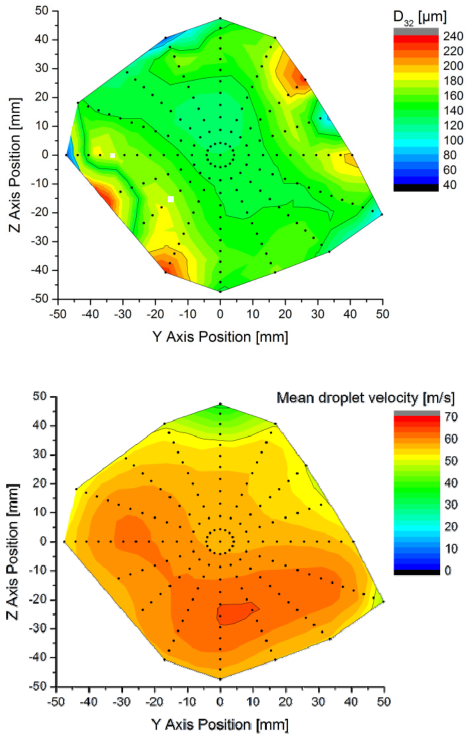

Figure 8 D_{32} and mean velocity distribution in plane 3 (450 mm)

EFFECTS OF TEMPERATURE VARIATIONS ON THE DROPLET SIZE DISTRIBUTION

In Figure 10 and Figure 11 evaluated results are shown, concerning the effect of elevated temperature levels at a constant pressure of the airflow on the droplet evaporation process. In Figure 10 the relative fraction of a droplet size in a plane on the meridional plane over the droplet size is plotted for different distances downstream of the nozzle. The relative fraction gives an impression of each droplet size quantity in relation to all measured droplets in this plane. In Figure 11 the absolute fraction, the number of each droplet size in relation to all measured droplets in the meridional plane, is shown. Every Figure illustrates three fraction distributions plotted over the droplet size in dependence of temperature levels (460 K, 510 K, and 560 K) and position of line in the meridional plane (14 mm, 450 mm, and 850 mm from nozzle outlet). For the investigations the initial boundary conditions are the same as in Figure 10 (blue). In the course of examinations the temperature of the airstream increases, first up to 510 K (green), and finally up to 560 K (red), without changing other boundary parameter. Looking at the first illustration of Figure 10.a the three fraction distributions, based on different temperature, nearly have the same deviation. Merely at higher temperatures the deviation slightly shifts to bigger droplet sizes. With growing distance downstream from the nozzle the influence of the temperature on the spray pattern can be seen. For Temperatures of 510 K and 560 K the relative fractions of medium droplet sizes begin to grow and the fraction of big and especially of small droplet nearly vanishes (Figure 10.c).

For the initial boundary conditions the distribution does not change over the complete measuring section significant. Only a small increase of the relative fraction of medium droplet sizes can be detected. Taking the evaluated results in Figure 11 into account, the change of the relative fraction distribution comes along with a change of the absolute fraction of captured data. The absolute fraction distribution development of the investigation at higher temperature levels indicates that minor temperature elevations effect the development of the spray pattern significantly.

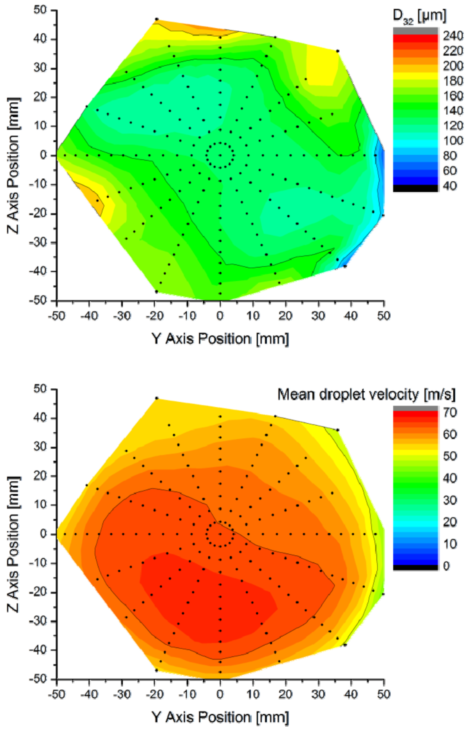

Figure 9 D_{32} and mean velocity distribution in plane 2 (850 mm)

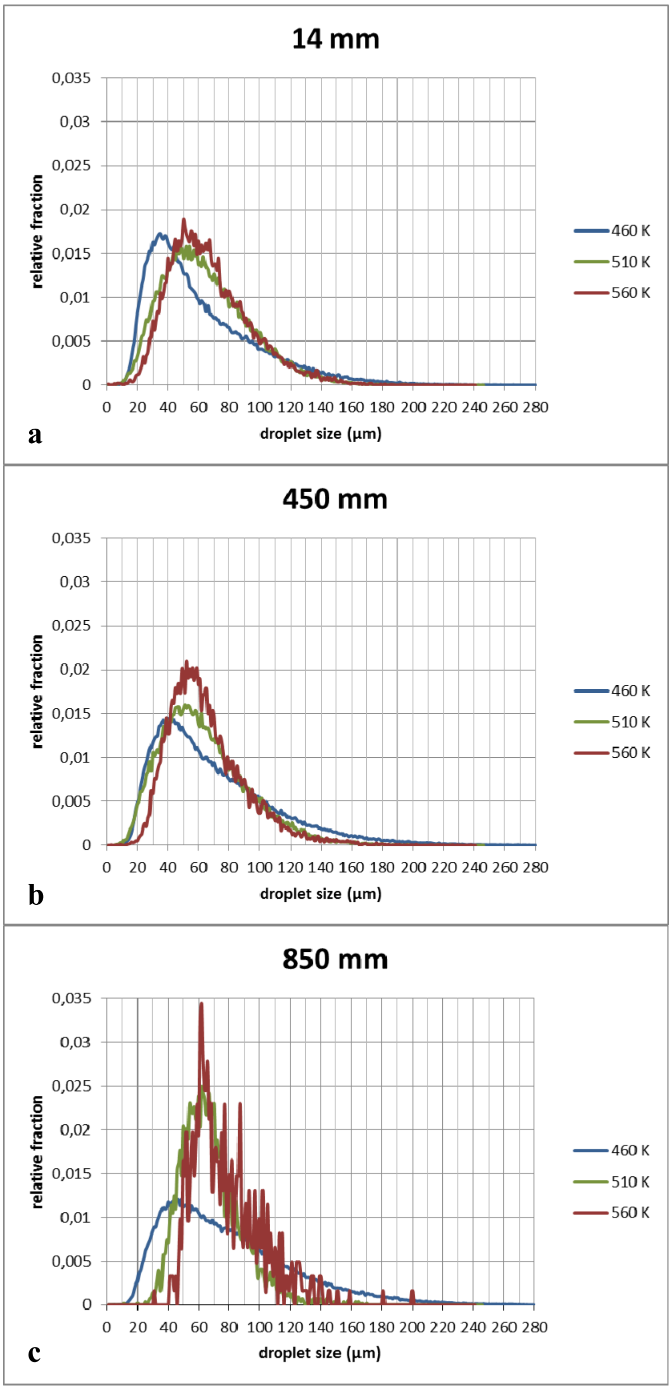

Figure 10 Relative fraction of droplet size

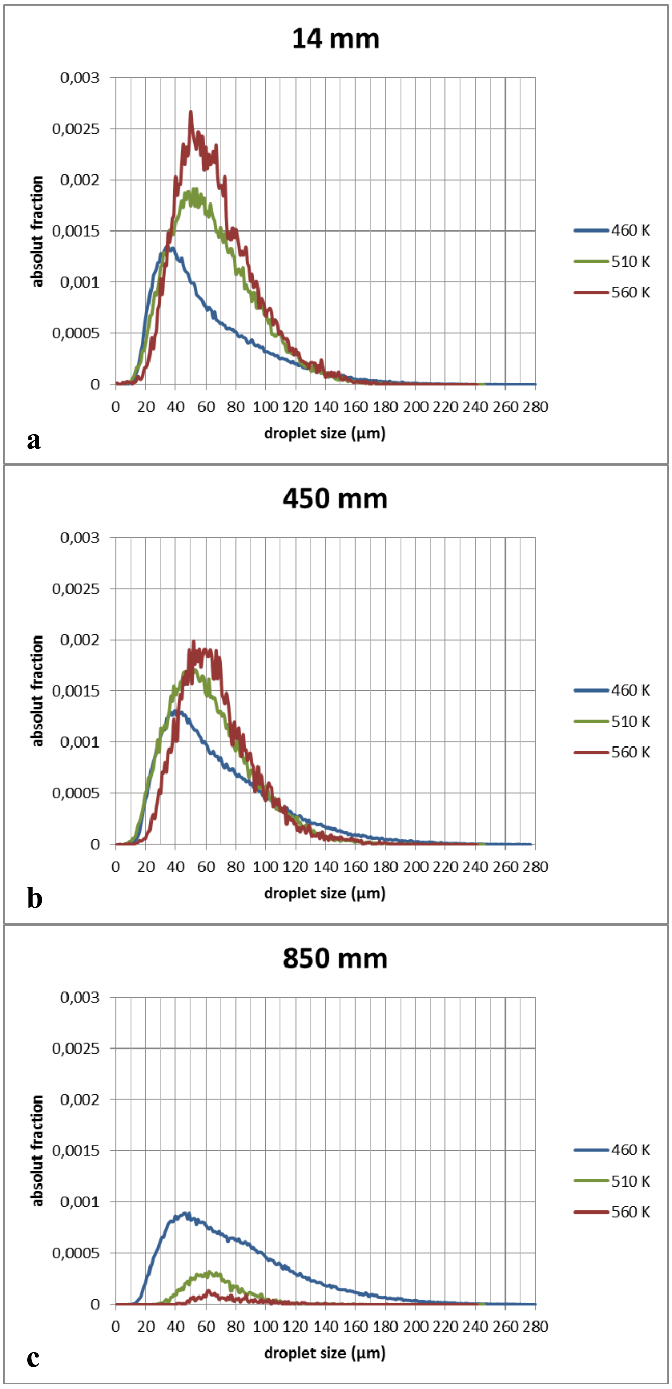

Figure 11 Absolute fraction of droplet size

Corresponding to Figure 10 the distribution of the initial boundary conditions only shows few changes downstream the meridian plane. At least in Figure 11.c a reduction of the absolute fraction of droplet sizes up to 100 µm can be noticed. A temperature increase of 50 K realizes a complete different development of the absolute fraction of the droplet distribution. By the end of the measuring section only a very small data rate is capture, because nearly the complete water has evaporated.

CONCLUSIONS

In this Paper the novel test facility at the Department of Mechanical Engineering at University of Duisburg-Essen for investigations of droplet evaporation processes at high temperature and pressure levels is introduced. The applied laser based measurement system is explained in detail and the execution of data capturing as well as the evaluation of raw data is outlined. Initial measuring results of a spray pattern at boundary conditions of 480 K and 0.41 MPa are presented. The raw data has been evaluated to calculate the Sauter mean diameter and the mean velocity distribution of the water droplets. The generated results present the water droplet development with a high resolution in the meridional plane and three perpendicular planes. Further investigations deal with the effect of temperature variation on the droplet evaporation process. The results point out that the evaporation process of the water droplets is strongly influenced by means of temperature variation. For this reason the effect of boundary condition variation on the droplet evaporation process has to be subject of future investigation.

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