Evaporation of nearly monosized droplets of hexane, heptane, decane and their mixtures in hot air and an air/steam mixture

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ABSTRACT
This paper describes experiments on evaporating initially nearly monosized droplet chains with diameter $230 \pm 15 \, \mu m$ under atmospheric conditions in a grid generated upward turbulent flow with initial liquid temperatures in the range 320 to 350 K and air temperatures in the range 365 to 455 K. The mean air velocity was 5 m/s and the initial droplet velocities were 17 m/s, resulting in a Reynolds number for the flow around the droplets of 100. The turbulent Stokes number was around 10. The liquids used were n-hexane, n-heptane, n-decane and mixtures thereof. A single chain and, for a reduced data set, a spray of 5 parallel chains, to study the influence of increased mass loading, have been investigated. Additionally, the influence of steam with mass fraction 15\% on the evaporation rates has been investigated. The size of the droplets was measured by back light illumination and recording by a digital camera with macro optics. Digital image processing was applied to deduce the size of the droplets and their positions. Laser Doppler measurements delivered the droplet velocities. Besides the generation of a data set for validation of evaporation models the main findings were that turbulence of the surrounding air could increase evaporation for decane and that mixtures evaporated preferentially, indicating mixing inside the droplets being larger than pure diffusion limited. For heptane as evaporating liquid it was found that for elevated droplet loading at air temperature below the boiling point the evaporation rate decreased, while at higher temperatures the droplet loading hardly showed any influence on the evaporation rates. Adding steam led to increased evaporation rates for all liquids, most likely due to condensation on the droplets surfaces.

NOMENCLATURE
$D$ \hspace{1cm} Droplet diameter [\mu m]
$D_0$ \hspace{1cm} Exit droplet diameter [\mu m]
1. INTRODUCTION

The main purpose of this work was to study droplet evaporation and to generate a data base in a simple grid-generated turbulent flow. This is useful for validation of droplet evaporation models and computations, since they rely on several empirical correlations for heat and mass transfer. Additionally, a spray with a size distribution in a more complex flow like a turbulent jet may experience even more difficulties for numerical calculations. Uncertainties exist for dispersion modelling, the contribution of the different droplet sizes and collisions, which may change the size distribution due to coalescence or separation with or without satellite droplets. Sommerfeld [1] and Rüger et al. [2] performed measurements of sizes of evaporating droplets in sprays generated by pressure nozzles and validated their Euler/Lagrange calculations by these data sets. It has been shown in [1] that droplet coalescence has to be modelled to obtain correctly the size distribution of the droplets. Measurements of evaporating suspended droplets at room temperature have been performed by Wu et al. [3], [4] and the authors focused on the influence of turbulence intensity of the flow passing the droplets. They found that turbulence increases evaporation rates compared to the case of laminar convection and they suggested a correlation based on the Damköhler number $Da$, defined as the ratio of the timescale of turbulent eddies to the evaporation time scale (boundary layer thickness divided by blowing velocity), which could quantitatively describe this effect.

A recent review on turbulence effects on droplet evaporation was published by Birouk & Gökalp [5] and finally they suggested that more measurements also in hot environments are needed to test the correlations which include turbulence effects.

Combined measurements of droplet sizes and velocities are difficult in dense regions close to the exit of any atomizer. However, combined information of initial droplet sizes and velocities are required to evaluate empirical correlations for droplet evaporation. Hence, this
work presents evaporation measurements of nearly monosized droplets in a simple grid-generated turbulent flow, which allows to identify collided droplets based on their size.

To avoid the necessity of measurements in the dense spray region to obtain inlet conditions for spray simulations, Chen et al. [6] conducted measurements using a confined air assisted atomizer and reported the streamwise development of the mean and Sauter mean diameter of the droplets for different gas and liquid flow rates and gas temperatures. They employed a Phase Doppler interferometer to measure droplet quantities and planar laser-induced fluorescence imaging to separately obtain acetone vapour data. This flow has been calculated satisfactorily by De & Lakshmisha [7] and the effects of increasing the gas flow rate in the experiments have been captured. However, the measurements of Chen et al. [6] close to the nozzle exit at $x/D = 0.5$ showed (see their fig. 4) that droplets hit the wall and formed large droplets downstream of the edge of the confinement, which increased the Sauter mean diameter by approximately 30% compared to the value on the centre line. For their case, with temperature differences of injected liquid and carrier gas being small, this might have only a negligible effect on the evaporation rates. However, if the droplets were injected in a hot gas, their temperature might change in a completely different way by hitting the wall and being ripped off again, leading to different, most likely enhanced, evaporation rates. Additionally, these droplets may show considerable non-uniform distribution due to the interaction with coherent or turbulent flow vortices. For example, Hardalupas & Horender [8] characterized the cold spray in a swirl stabilized burner by Phase-Doppler technique and measured the concentration fluctuations of the droplets. Two mechanisms were identified as sources of concentration unsteadiness, the liquid break-up process during atomization, which is based on growing instabilities with distinct frequencies, and the interaction with the large precessing vortex due to the swirl in the flow. Such local concentration fluctuations can also occur in turbulent flows due to large coherent structures. Early work on this effect is summarized in [9]. Measurements on particle concentration fluctuations in a jet were performed by Longmire & Eaton [10] and in a shear layer by Horender & Hardalupas [11], [12]. The effect of droplet segregation on evaporation was studied numerically by Reveillon & Demoulin [13]. They modelled homogeneous isotropic turbulence by forced direct numerical simulations and found decreased droplet evaporation in the later stages when a considerable amount of vapour had concentrated around the droplets. Hence, similar effects may be experienced in spray jets. Therefore, we designed an experiment to study evaporating droplets with minimized effects due to droplet turbulent dispersion, collisions and consequently coalescence or secondary atomization. A single chain of nearly mono-sized droplets or a “spray” of 5 parallel chains were injected in an upward flow. Since laminar flow conditions are not to be achieved in such a set-up, it was decided to use a grid-generated turbulent flow as carrier-gas, because this flow is fairly simple, without mean flow gradients and well understood.

Evaporation of liquid droplets is, beyond physical properties, governed by the difference of partial vapour pressure in the gas phase and the vapour pressure at the liquid surface. Hence, evaporation is smaller in dense sprays compared to dilute sprays, since the vapour pressure in the gas phase is larger due to evaporation that had occurred further upstream. This effect has to be incorporated into models for spray evaporation and the effect was
studied experimentally by Swindal et al. [14], who found decreased evaporation for the central jet in 9 parallel droplet chains injected into a laminar flow. One of the purposes of the current work is to examine experimentally the effect of the partial vapour pressure in the gas phase on the evaporation of droplets. Therefore, measured evaporation rates of a single droplet stream (or chain) are compared with that of 5 parallel streams (or spray).

An indirect driving force for evaporation is the heat transferred from the gas to the droplets. One of the widely used evaporation models was proposed by Abramzon & Sirignano [15] accounting for Stefan flow. The transport process inside the droplet was assumed to be either negligible following an infinite conductivity model, being diffusion limited or being additionally increased by an internal vortex. A review and test of available numerical models for droplet evaporation can be found in Miller et al. [16]. These models have been continuously extended and, for example, Zhang et al. [17] developed a model for n-heptane droplet evaporation under high pressures, including the effect of dissolving of the surrounding gases into the droplets.

Brenn et al. [18] stated that within engineering accuracy models for droplet evaporation are sufficiently developed, however more work is required for predicting evaporation of mixed liquids. Therefore they studied evaporation of acoustically levitated droplets with diameters 1.5 mm of mixed liquids containing up to four species. This resulted in valuable time history information for the droplet diameters. However, due to the method of acoustic levitation, a stationary flow with special turbulence properties is produced. The evaporation times were of the order of 100 s due to low surrounding air temperatures, which were below the lowest boiling point of the chosen liquids. The diffusion limited mixing times, estimated as $D^2/\gamma$ which will be discussed below, were around 25 s. The authors stated that the acoustically induced flow field will also decrease this mixing time inside the droplets, hence for their modelling the assumption of well mixed droplets can be accurately applied. In many other situations, the gas temperatures are much higher, hence evaporation is faster, and perfect mixing of species and temperature inside the droplets is not achieved. Therefore, we used our experimental set-up also to produce a data set for mixed liquid droplet evaporation.

Another motivation of the current measurements was to study the effect of additional steam present in the flow on droplet evaporation. In liquid fuelled gas turbine combustors this increases their efficiency and improves temperature distributions within the combustion chamber. This is of interest, since avoiding temperature peaks leads to lower thermal NOx emissions. Lee & Law [19] studied the evaporation of heptane and alcohol droplets in a CO flame to produce a hot environment without water present and a methane flame to produce a humid and hot environment. They found no difference when comparing heptane droplet combustion for the two flames while the evaporation history changed for the alcohol droplets. The difference was explained based on the fact that water and heptane are immiscible while alcohols and water are miscible, which allows the water to diffuse into the droplets. Marchese & Dryer [20] modelled burning droplets composed of methanol and found that water, which is a combustion product, condenses on the droplets, diffuses and builds up a relevant water content influencing the evaporation history. To study the pure effect of steam on evaporating alkanes without chemical reactions being present, the current experiments were accordingly extended by injection of steam.
The manuscript presents the experimental results of these measurements and is structured as follows. In Chapter 2 the details of the flow set-up, droplet injection and measurement technique are described. After that the results section presents and discusses the evaporation measurements of pure liquids, their mixtures, heptane droplets at elevated loading and evaporation measurements with steam added. The paper ends with a summary of the main findings and conclusions.

2. EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUE
2.1. The flow

Figure 1 a) shows the set-up of the atmospheric pressure wind tunnel designed for droplet evaporation experiments. Fresh air is entrained and pre-heated in a heat exchanger using the heat from the air leaving the test section, which is exhausted to the environment. A non closed loop of the air flow is necessary so that previously evaporated fuel does not influence the measurements. Behind the heat exchanger, the

![Image](image_url)

**Figure 1:** a) Set-up of the flow facility. b) Droplet injector.
fresh air is led downwards and then through two bends with flow straighteners to a chamber that leads to the contraction (see Figure 1a) passing the air to a turbulence generating grid. This consists of 10 mm circular holes with a centre-to-centre distance of 15 mm in a staggered configuration in one direction and on line in the other direction, resulting in a flow blockage of 65%. The flow issued to the 2.0 m long and 300 mm squared test section with glass walls of thickness 3.0 mm.

The facility allows continuous adjustment of the air velocity between 0 and 20 m/s and is monitored by a pressure sensor located at the exhaust pipe approximately 4 m behind the heat exchanger. The air velocity in the channel was set to 5.0 m/s for all experiments presented here and allowed temperatures up to 455 K, which could not be achieved for much higher velocities.

The temperature of the flow can be elevated by 10 electric heating pipes which are located in the down-flow section (the insulated part on the right hand sight of Figure 1a). One of the pipes is connected with a controller to keep the temperature constant within \( \pm 3 \) K. The temperature sensor for this controller is mounted approximately 1 m below the last heating pipe and, therefore, the temperature is lower at the inlet to the test section, where the turbulence generating grid is positioned. A calibration with a temperature sensor placed just behind the turbulence grid gave that controller settings of 373, 398, 423, 448 and 473 K result in temperatures in the test section of 365, 388, 412, 430 and 455 K. To estimate the temperature decay within the test section we performed CFD calculations with heat transfer through the glass window. These showed that the temperature within the channel was reduced nearly linearly by approximately 11, 15, 19 and 26 K (for the above stated temperature settings) within 1.2 m of the test section. We performed some simple temperature measurements to confirm this trend and found that the temperatures are less than 3 K smaller at streamwise position \( x = 1000 \) mm compared to \( x = 0 \). The difference might be explained by the fact that in the calculations the temperature of the surrounding air was set to constant 293 K at the outer side of the glass windows, neglecting the existence of a thermal boundary layer. Hence we conclude that the temperature decrease of the flow is small and of the order of the error in the temperature control.

2.2. Droplet injection

The liquids were stored in a pressurized tank at 2.5 bar (meaning 1.5 bar plus atmospheric pressure) and a volume of 6 l. A 2.0 mm inner diameter and 3 m long pipe made out of plastic was connected to the bottom of the tank and delivered the liquid to the injector. Approximately 0.5 m in front of the injector a filter was placed with pore size 1 \( \mu \text{m} \) and an area of approximately 3 cm\(^2\) to avoid blockage of the injector pin hole by dirt. The liquid was led to the injector body on which the actuators were placed, and the injector was covered by a ceramic body. A small amount of air was led to this body through an additional pipe, so that the actuators did not become too hot and damaged.

The droplets were injected centrally at the streamwise position of the grid through the piezoelectric droplet generator, see Figure 1b), actuated at the natural frequency of 38 kHz and an orifice with diameter 150 \( \mu \text{m} \) located centrally, which produced a chain of nearly monodisperse droplets of diameter 230 \( \mu \text{m} \). Hence, the liquid injection rate was
38.000 $V_d \, 1/s = 0.76 \, l/h$. The plates with the pin holes were made out of 0.5 mm thick copper. The thickness was important for their robustness and initial tests with thinner plates, through which the holes were laser machined, failed due to their mechanical sensitivity. Hence, the holes were drilled, which is possible down to diameters of 0.1 mm. For a detailed description of the physics of this type of droplet generators see [21]. An additional plate was manufactured with five holes, one centrally and four uniformly distributed around on a circle of radius 1.5 mm. The flow rate for this set-up was 3.8 l/h.

Based on the droplet size measurements starting 30 mm downstream of the injector, the initial droplet diameters (or better volume equivalent sphere diameters) were estimated to be 225 $\mu m$ for pure decane and the 50%hexane/50%decane mixture, and 230 $\mu m$ for the 25%hexane/75%decane mixture. For hexane, heptane and their mixtures the initial modal diameter was 234 $\mu m$. The reasoning will be explained in detail below and is related to the droplets not having equal injection velocities due to different viscosities of the applied liquids. Therefore, the liquid with larger viscosity left the pinhole with smaller velocities due to the increased pressure drop in the liquid supply line, the inserted filter and the pin-hole.

A ceramic insulation was mounted around the injector and cooled by an air flow to avoid damage of the piezo actuators at the highest temperatures the facility was operated. This air also cooled the pipe delivering the fuel to the injector. Above the insulation a pipe with inner diameter 5.6 mm and length 60 mm led the fuel to the pin hole, see Figure 1 b). Nevertheless, this set-up led to an increase in liquid temperature and the exit liquid temperature has to be known for validation of numerical models. To obtain the droplet temperature as inlet condition, a small thermocouple was inserted inside the injector just below the orifice. This had to be performed in a separate measurement, since the thermocouple might have disturbed the liquid flow towards the orifice and led to broadened size distributions. For air temperatures 365, 388, 412, 430 and 455 K the hexane liquid temperatures were 320, 329, 333, 341 and 350 K. Hence, for the highest air flow temperature the liquid hexane had a temperature above its boiling point at ambient pressure, which was possible due to the larger pressure inside the nozzle upstream of the orifice. Reitz [22] visualised a water jet issuing into ambient pressure and found that flash-boiling started for liquid temperatures above 409 K (see his figure 5), corresponding to 36 K above the boiling point. Since we had, for the highest air temperatures applied, only liquid temperatures of 8 K above the boiling point, flash-boiling did not happen.

The liquid bulk velocity through the pin-hole was 12 m/s based on the flow rate and results in a Reynolds number, defined as $Re = U \cdot D/v$ and based on the pin-hole diameter, of 3,700 for hexane. Since the Reynolds number of the upstream flow is much smaller and therefore the flow approaching the pin-hole is laminar, the flow through the pin-hole might be transitional but not turbulent. The flow profile through the pin-hole might therefore be approximately parabolic, possibly slightly flattened, with zero velocity at the edge and, if perfectly parabolic, 24 m/s on the centre line. As will be seen later in the evaporation measurements of the mixtures, which suggest mixing inside the droplets being much faster than estimated by pure diffusion, we suppose that there is a strong internal vortex inside the droplets when the liquid jet disintegrates. Estimating the internal Reynolds number with the flow velocity of initially 0 m/s assumed for the
surface of the droplets and 12 m/s for their centre, results in 5,600 for hexane, indicating that the internal flow is turbulent at the beginning of the injection.

The droplet velocity directly at the injector could not be measured, since optical access was only possible 30 mm above the turbulence generating grid. These measurements will be presented later and showed that the droplets initial velocity was approximately 17 m/s (being larger than the bulk flow through the pin-hole, which is in agreement with a parabolic inlet profile), resulting in a droplet Reynolds number of around 100 for the initial flow around the droplets. Hence, a considerable slip velocity between air and droplets was initially present and the droplet velocities showed fluctuations of around 1 m/s.

The droplet relaxation time is a measure of how fast the droplets adapt to the air flow:

\[
\tau_d = \frac{\rho_D D^2}{18 \mu_a}
\]  

(1)

For hexane, heptane and decane droplets this value is approximately 120 ms at room temperature and becomes smaller for higher air temperatures due to the temperature dependence of the air viscosity. The Stokes number of the droplets, defined as the ratio of relaxation time scale of the droplets to the eddy turnaround time scale of the flow, was of the order of 10 and decreased with streamwise position, since the integral time scale becomes larger and the droplets become smaller due to evaporation.

It should be emphasised that due to the placement of the injector one hole of the turbulence generating grid was completely blocked. This results in a wake flow with a dimension of around 25 mm. Hence, a relevant mean reverse flow and increased turbulence levels may act on the injected droplets. It might be possible that any attempts to model accurately our measured evaporation rates need to take that into account.

As evaporating liquids industrial grade (95% purity) n-hexane, n-heptane and n-decane were used. Their physical properties are summarized in Table 1.

**Table 1: Physical properties of the different liquids. [16] [23] [24]**

| Substance                        | hexane | heptane | decane | water |
|----------------------------------|--------|---------|--------|-------|
| **Liquid properties**            |        |         |        |       |
| Boiling point (ambient pressure) [K] | 342    | 371     | 448    | 373   |
| Density [kg/m³]                  | 664    | 706     | 731    | 1000  |
| Surface tension (room temperature) [mN/m] | 18     | 20      | 21     | 72    |
| Viscosity (room temperature) [mPa·s] | 0.32   | 0.41    | 0.92   | 1.0   |
| Heat capacity [J/(kg·K)]         | 2302   | 2384    | 2520   | 4184  |
| Heat conductivity [J/(m·s·K)]    | 0.12   | 0.12    | 0.13   | 0.60  |
| Thermal diffusivity [m²/s]       | 6.8 × 10⁻⁸ | 1.5 × 10⁻⁷ | 5.7 × 10⁻⁸ | 1.4 × 10⁻⁷ |
| Vaporization heat [kJ/kg]        | 372    | 366     | 354    | 2439  |
| **Gas properties**               |        |         |        |       |
| Viscosity at 450 K [m²/s]        | 3.4 × 10⁻⁶ | 1.1 × 10⁻⁵ | 1.2 × 10⁻⁵ | –     |
| Diffusivity in air at 450 K [m²/s] | 1.4 × 10⁻⁵ | 1.3 × 10⁻⁵ | 1.2 × 10⁻⁵ | –     |
2.3. Steam injection

Additional steam could be injected approximately 200 mm in front of the turbulence grid through a 12 mm outer and 9 mm inner diameter pipe. This resulted in a steam cone around the droplet injector with a diameter of approximately 10 cm. The steam was generated by boiling water in a 6 litre pressurized vessel at approximately 4 bar and the generator delivered 15 kg of steam per hour. The flow rate of the steam towards the injection pipe has not been measured and was estimated by the consumption of water per time. Therefore, the generator was run for several periods of 3 min and after that the water consumption has been measured. It should be noted, however, that the steam flow rate may show considerable fluctuations as was observed by eye. The resulting mean steam loading in the flow was approximately 15% based on mass and the steam temperature based on the pressure in the vessel was approximately 421 K. Continuous operation was only possible for around 3 min, since after that the heat supply to the vessel is not sufficient to keep the steam properties appropriately constant.

2.4. Image processing technique

Previous size measurements of evaporating droplets were performed using phase-Doppler Anemometry (PDA). However, droplet shape oscillations and the unknown refractive index, depending on unknown and inhomogeneous droplet temperature and mixture of species, led to large sizing errors. Since the droplets were fairly large, the most relevant source of errors was the unsteady deviation of the droplet shapes from a perfect sphere, especially in the vicinity of the injector. Additionally, the achieved data rates were low, since droplet dispersion increased with streamwise distance. Therefore, the PDA technique was substituted by a combination of an imaging technique (for sizing) and a one-component LDV (for velocity measurements), see Figure 1 a).

An object recognition software, which was developed in our institute, was applied and used the determination of gradients of the images to detect single droplets. Bröder & Sommerfeld [25] applied a similar system in a bubbly flow and their system was modified by using macro optics, which comprised a 85 mm Nikkor lens with an additional extension ring of length 25 mm between the lens and the camera (PCO 12 bit, 1280 × 1024 pixel) to increase the magnification. This resulted in an image size of 20 mm times 16 mm. The processing was done online with a rate of 3 images per second on a 2 GHz PC. A flash lamp illuminated the droplet chain from behind so that the shadows of the droplets, which do not depend on the refractive index, were imaged. 8000 droplets were recorded for each measurement position to ensure the accuracy of the obtained size distribution. Therefore, approximately 500 to 1000 images had to be processed.

Digital edge detection was applied and the edges were segmented to measure the droplet area and the result of each diameter measurement is an equivalent diameter of a circle. As validation criterion the individual radii around the droplet contour were compared and the ratio of maximum to minimum edge radius had to be smaller than 1.7 for a droplet to result in a validated measurement. For the hexane droplets we calculated the cross-correlation of this maximum to minimum ratio and the measured diameter for each droplet and found that these quantities were uncorrelated. Hence, possible shape
oscillations of the droplets might only have negligible influence on the diameter measurements and might broaden the size distribution but do not change the most likely diameter in the PDF. More details on the technique can be found in Bröder [26], where the sizing error for the current magnification is estimated as 1 to 3% of the droplet diameter. This led to an absolute error of the normalized droplet surface $D_0^2/D^2$ of 0.065 close to the nozzle and became 0.04 when the droplets reduced their volume by 25%.

To describe the decreasing size for many evaporating droplets, in the current work the mode or modal value will be applied. This corresponds to the most likely value of the probability density function. It should be noted that the mean or any higher order measures have not been used, since we experienced a small degree of droplet coalescence, which strongly affects the mean and higher order values. However, the mode is not affected for an initially nearly monodisperse size distribution when only a small fraction of the droplets collide and subsequently coalesce and form larger droplets.

It should be noted that the measurements started downstream of the grid at $x = 30$ mm. This was necessary, to ensure that nearly the whole area of the lens was used to observe the droplets and that the view was not blocked by the rim of the glass test section, which can be seen on Figure 1 a). There the camera is placed for a measurement at position $x = 30$ mm.

2.5. Laser-Doppler system

The air and droplet velocities were measured using a one component DANTEC LDV system with a 10 mW He-Ne Laser and a focal length of 600 mm. The probe volume had a size of approximately 1 mm in length and a diameter of 50 µm. A frequency shift of $+ - 40$ MHz was applied to either beams to be able to distinguish between positive and negative velocities. The Doppler signals were recorded by the photo multiplier in back-scatter mode, digitized and evaluated by a FFT processor. The digital processing delivered velocities with a resolution of 8 bit. The optics can be seen on the image of Figure 1 a).

3. RESULTS AND DISCUSSION

This section presents the experimental results on droplet evaporation in the described facility. First, the characteristics of the air turbulence are presented and after that the velocity and dispersion characteristics of the droplets. Finally, the measured surface reduction rates first for the pure and mixed liquids at small droplet loadings, then at increased loadings for heptane only are presented and discussed. After that the measurements of hexane, heptane and decane droplets evaporating in an air/steam mixture are shown.

3.1. Air and droplet velocity characteristics and droplet dispersion

Figure 2 a) shows the streamwise development of the streamwise fluctuating air velocity, the Kolmogorov length scale and the Eulerian integral length scale, which was based on the autocorrelation functions of streamwise fluid velocity fluctuations shown in Figure 2 b). The Kolmogorov scale can be estimated based on the dissipation rate,
which in decaying isotropic turbulence is $\varepsilon = -d(3/2u'^2)/dt$ and $\eta = (v^3/\varepsilon)^{1/4}$. This estimation for $\varepsilon$ might show some inaccuracies for larger streamwise positions were the turbulent kinetic energy produced in the boundary layer has been transported towards the centre. Hence, the dissipation rate might actually be larger far downstream of the grid and, as a consequence, the Kolmogorov length scale slightly smaller. The mean velocity is not presented since it was constant with 5.0 m/s. The first LDV measurement has been obtained 30 mm downstream of the grid due to limited optical access. Since this corresponds only to approximately two grid periodicities, the first measured value may not be constant across the flow, since it is still influenced by the recirculation zones and jets close to the grid. Hence, possible modelling attempts have to be validated for the decay of the turbulence, since usually grid generated turbulence is not created by a “numerical turbulence grid” but by setting a turbulent kinetic energy and a turbulent length scale, which are constant across the flow.

**Figure 2:** a) Air velocity fluctuations, Kolmogorov and integral length scales of the air flow as a function of distance from the grid. b) Autocorrelation functions for all streamwise positions. c) Zoom of autocorrelation functions for small time lags.
In Figure 2 b) the autocorrelation functions for different streamwise positions are presented. Figure 2 c) shows the same data zoomed for smaller delay times, to present more clearly their behaviour for the smallest streamwise positions. These curves are coded by different line patterns (dashed, dotted...) to indicate which curve belongs to which streamwise position. For positions larger than $x = 280$ mm the curves can be distinguished, since the integral of the curves becomes monotonically larger with streamwise position.

From the air velocity autocorrelation function at $x = 30$ mm it can be seen that distinct extrema and negative loops exist. This shows the existence of coherent structures due to the shear dominated flow close to the turbulence generating grid. The first maximum is at time lag 7 ms, which, for mean velocity 5 m/s, corresponds to the size of the turbulent large scale structures of 35 mm, which is approximately twice the grid constant. It is interesting to note that the autocorrelation function at $x = 30$ mm shows a smaller decay compared to the ones at the larger positions $x = 55$ and 80 mm, maybe due to the strong presence of coherent structures. The integral time scales for streamwise positions $x = 80, 130$ and 180 mm are approximately 1, 1.5 and 2 ms. Since this is approximately two orders of magnitude smaller than the droplet relaxation times turbulent dispersion should be negligible close to the turbulence grid. However, there may still be a relevant influence of gas phase turbulence on heat and mass transfer on the droplets surfaces.

For accurate validation of possible numerical calculations of the current flow, Figure 3 shows the measured mean and rms droplet streamwise velocities for different air temperatures for hexane. The mean droplet velocities hardly show any difference for the different temperatures, although the droplet sizes, as will be shown below, differ considerably due to different evaporation rates. Also the change in air density and viscosity, due to different temperatures, did not show a noticeable effect on the droplet velocities, despite their influence on the drag coefficient. Figure 3 presents only mean velocities for decane droplets and a 25%/75% hexane/decane mixture (based on mole fraction) at temperatures 412 and 430 K. For these liquids the mean velocity did also not show a clear dependence on the air temperature. The decane droplet mean streamwise velocities were approximately 2.0 m/s lower and, for the mixed droplets, 1.0 m/s lower compared to that for the hexane droplets. This is attributed to the larger viscosity of the liquids, which led to a larger pressure drop in the pipe to the pressurized vessel. It should be added here that we inspected the mean velocity data for heptane also, however they did not differ from the hexane measurements, since viscosity differences are small.

Some scatter exists for the measured droplet velocity fluctuations close to the exit of the injector up to around $x = 180$ mm. It must be stressed however, that this value may show a fair degree of uncertainty close to the injector, since the droplets form a chain, which did not disperse significantly close to the injector. This is shown in Table 2 and discussed below. Droplets were only measured at the centre line by the point measurement technique and if there was a correlation between dispersion due to cross-stream velocity and streamwise velocity fluctuation this might bias the measurement of rms of velocity fluctuations (however the size measurement with the imaging system was independent of this effect). For larger streamwise positions, the differences in velocity fluctuations for the different liquids and temperatures disappeared. The decane and the mixed droplets
showed similar trends for the rms of the velocity fluctuations and hence are not presented. Generally, there is a weak trend that increasing the air temperature increases the rms velocity for the injected droplets. One inconsistency happens for hexane at 365 K, which led us to re-inspection of the locked data and we found that this was the only data point, where the injector was accidently agitated at 35 instead of 38 kHz, which led to this larger velocity fluctuations and more broadened size distribution. However, at the largest air temperature of 455 K the droplets showed even larger velocity fluctuations, which may be attributed to a relevant mass transfer already during formation of the droplets at the pin-hole. Similar cross-stream velocity fluctuations due to mass transfer of droplets issuing from a pipe into a different liquid were found by Eiswirth and Barth [27].

**Figure 3:** Mean and rms of velocity fluctuations of hexane and decane droplets and a 25/75% mixture for air temperatures of 365, 388, 412, 430 and 455 K.

**Table 2: Dispersion characteristics in terms of root mean square displacement in mm as function of streamwise position x for different liquids.**

| Liquid (T<sub>a inlet</sub>) | x = 30 mm | x = 80 mm | x = 130 mm | x = 230 mm | x = 330 mm | x = 400 mm |
|-----------------------------|-----------|-----------|------------|------------|------------|------------|
| Hexane (365 K)              | 0.40      | 1.1       | 2.1        | 3.0        | 3.6        | 4.5        |
| Hexane (412 K)              | 0.34      | 0.78      | 1.3        | 2.4        | 3.5        | 4.2        |
| Hexane (455 K)              | 0.34      | 0.76      | 1.3        | 2.5        | 3.4        | 4.2        |
| Decane (365 K)              | 0.29      | 0.75      | 1.3        | 2.2        | 3.3        | 4.1        |
| Decane (412 K)              | 0.29      | 0.78      | 1.3        | 2.4        | 3.4        | 4.1        |
| Decane (455 K)              | 0.29      | 0.70      | 1.2        | 2.3        | 3.1        | 3.9        |
| 50%Hex/Dec (430 K)          | 0.24      | 0.69      | 1.1        | 2.2        | 3.2        | 4.0        |
It should be mentioned here that numerical simulations [28] of the current flow, which used one-way momentum coupling and the drag coefficient for a rigid sphere, over predicted the deceleration of the droplets shown in Figure 3. Hence, we suggest to use improved correlations for the drag coefficient taking into account the moving surface. Additionally, the mass loading, which is the local ratio of droplet mass to carrier gas mass, at the exit of the injector is locally large. We estimated the local maximum mass loading to be approximately 0.5 at \( x = 200 \) mm. At \( x = 30 \) mm, the local maximum mass fraction is around 25, since the droplets have a root mean square displacement which is less than twice their radius, and corresponds to a local volume fraction of 0.03. This makes necessary to consider the momentum-coupling of droplets and air, however requires a fairly fine grid close to the injector. Additionally, droplet collisions occur, which can be seen in the obtained droplet size distributions and will be discussed below.

To further investigate the injection quality of the droplet chain, Figure 4 shows the number concentration profiles for hexane and decane droplets for air temperature 365 K at streamwise positions \( x = 30, 230 \) and 430 mm. Table 2 shows the rms of these distributions for additional measurement sets. The root mean square displacement grows nearly linearly with distance from the injector. Since the droplet relaxation time (120 ms) is larger than the time required to reach 400 mm (\( \approx 40 \) ms), the reason for that can not be fluid dynamic interaction, hence also not turbulent dispersion. This dispersion could possibly be caused by fluctuations of the shapes of the droplets exiting the pin hole, leading to a range of angles of their trajectories.

The root mean square of the droplet displacements is only around 50% larger than the droplet diameters at position \( x = 30 \) mm. Hence, a significant amount of droplets will

![Figure 4](image-url)
collide, due to their deceleration as shown in Figure 3, and might form larger droplets. This is shown in Figure 5, where the measured size distributions for hexane and decane at temperature 455 K are presented. It can be seen that the droplets are not perfectly mono-sized and the diameter distribution has a half width of 15 µm 30 mm downstream of the injector. Additionally, the decane droplets showed a slightly larger degree of coalescence, which might be attributed to their smaller evaporation rate. When droplets coalesce they oscillate and the ligaments between the droplets, which are stretched periodically due to this oscillation, can evaporate quickly for hexane. This happens to a smaller extend for decane due to the higher boiling point. In the following discussion on droplet evaporation, always the maximum (modal) value of the first peak is presented. Hence, coalescence does not influence the results on evaporation due to change in droplet size.

### 3.2. Evaporation results for hexane, heptane and decane

Figure 6 a) shows the droplet surface normalized by its initial value as a function of distance from injection for hexane droplets at air temperatures 365, 388, 412 and 455 K. It should be noted again that the data set at the lowest temperature might show a larger deviation from a monodisperse size distribution due to the wrong excitation frequency. Additionally, a few data points comprise two independent sets of measurements and the scatter observed is similar to the estimated measurement error presented above. The measured initial droplet sizes for the different temperatures did not show any significant difference and were 231, 232, 231 and 230 µm for temperatures...
Evaporation of nearly monosized droplets of hexane, heptane, decane and their mixtures in hot air and an air/steam mixture

365, 388, 412 and 455 K, although the droplets had been exposed to the flow for 30 mm. For the measured positions larger $x = 30$ mm, the droplets show the expected trend that increased air temperatures lead to increased evaporation rates. If one extrapolates the measured evaporation curves to $x = 0$ it can be seen that the droplets did all have very similar initial diameters. Evaporation started immediately, which is expected for injection temperatures close or slightly above the boiling point. Figure 6 b) shows the same evaporation data as a function of time based on the droplet velocity data of Figure 3. It is clear that the surface reduction scales not linearly with time and the evaporation rate decreases with time. Two reasons could be responsible for that. First, the droplets cool

Figure 6: Normalized surface of hexane droplets as function of a) streamwise positions and b) time of flight for different temperatures. c) Surface reduction rates as function of the parameter $Re^{1/2}Sc^{1/3}$. Large $Re^{1/2}Sc^{1/3}$ relate to small streamwise positions.
down along their trajectory due to evaporation, leading to reduced evaporation. Second, turbulence intensities of the flow are larger and the length scale is smaller close to the injector, hence the Damköhler number is smaller, which leads to an increased evaporation rate [5]. This phenomenon is discussed in more detail for the evaporation results of the decane data, since their surface reduction rate scales nearly linearly with time. Figure 6 c) scales the surface reduction rate $K$ with the product of the droplet Reynolds number power $1/2$ (based on the slip velocity, the current droplet diameter and the temperature dependent kinematic viscosity of air) and the Schmidt number power $1/3$ (based on the diffusivity of hexane vapour in air). This is known as Frössling correlation which relates evaporation in laminar convective environment to evaporation in quiescent environment as $K_l/K_q = 1 + 0.18 \ Re^{1/2} \ Sc^{1/3}$ [5]. In our measurements, a nearly linear behaviour is observed, except for large $Re^{1/2}Sc^{1/3}$, where the temperature of the droplets was larger due to the heat up of the liquid in the injection pipe and therefore the droplets cooled down with time. As will be discussed later, effects of the flow turbulence alone cannot be responsible for such a large increase of the surface reduction rate.

From the one dimensional heat transfer equation an estimation of the time scale for heat transfer inside a droplet with radius $D/2 = 115 \ \mu m$ can be obtained as $D^2/4\alpha$, which becomes approximately 190 ms for the hexane droplets. After this time the droplet has left the test section. It should be emphasized that this time scale for heat transport corresponds to a rate of temperature change and after this time not necessarily a constant temperature inside the droplet is achieved. Zhang et al. [17] (their Figures 2 and 3) show the time history of the centre temperature of an evaporating stagnant heptane droplet at elevated pressure of 1 MPa with $d = 100 \ \mu m$ for a model calculation. Estimating the time scale for internal heat transfer for their situation in the way as described above results in 16 ms, which fits very well with [17].

In [15] it is discussed that an internal vortex structure due to the air drag on the surface may reduce the mixing time by a factor of 2.7, which also is in agreement with the findings in [17]. They also discuss a correlation for the maximum surface velocity due to the fluid drag on the droplet, which for the current case results in approximately 1 m/s. However, as discussed in Section 2.2, close to the injection the internal flow could be more pronounced, which will be confirmed by the evaporation measurements of mixed liquids. As conclusion we stress that the temperature inside the droplets for the current test case is not necessarily uniform along all their trajectory, which has to be taken into account for accurate modelling of the evaporation rates.

Figure 7 a) shows the droplet surface normalized by its initial value as a function of distance from injection for heptane droplets at air temperatures 365, 388, 412, 430 and 455 K. Droplet diameters measured at $x = 30 \ mm$ were 234, 233, 228, 226 and 227 for temperatures 365, 388, 412, 430 and 455 K, respectively. Hence, there is a relevant difference for large and small air temperatures. The droplet velocities measured at $x = 30 \ mm$ were 16.5, 16.3, 16.3, 16.3 and 16.7 for the different flow temperatures. Reinspection of the raw data files showed that there was a one hour break between the measurements at 365 and 388 K and the larger temperatures. This could have led to inaccuracies in the amplitude of the piezo actuator. Another, however speculative, reason
could be evaporation of ligaments between the disintegrating structures close to the nozzle, since these exist for longer times compared to hexane due to the larger viscosity. Figure 7 b) shows the normalized droplet surface as function of time and Figure 7 c) shows the surface reduction rate $K$ as a function of the droplet Reynolds number and Schmidt number. A nearly linear scaling with $Re^{1/2}Sc^{1/3}$ can be observed for small Reynolds numbers only, corresponding to residence times above 80 ms, corresponding to $x > 750$ mm. For this positions turbulence properties do hardly change any more (see Figure 2 a), hence turbulence effects are difficult to separate from initial droplet temperature effects for these measurements.

**Figure 7:** Normalized surface of heptane droplets as function of a) streamwise positions and b) time of flight for different temperatures. c) Surface reduction rates as function of the parameter $Re^{1/2}Sc^{1/3}$. Large $Re^{1/2}Sc^{1/3}$ relate to small streamwise positions.
Figure 8 a) shows the droplet surface normalized by its initial value as a function of distance from injection for decane droplets at air temperatures 365, 412 and 455 K. Droplet diameters measured at $x = 30$ mm were 227, 226 and 225 µm for temperatures 365, 412 and 455 K, respectively. For the smallest air temperature it was observed that the droplet surfaces increased by approximately 2% for a flight distance of 50 mm and for higher air temperatures this effect was smaller. The droplets first heat up and increase their volume due to a thermal expansion coefficient of 0.00095 1/K [29]. Assuming that no evaporation occurs and temperature distribution is uniform inside the droplet, this suggests a temperature

![Figure 8](image_url)

**Figure 8:** Normalized surface of decane droplets as function of a) streamwise positions and b) time of flight for different temperatures. c) Surface reduction rates as function of the parameter $Re^{1/2}Sc^{1/3}$. Large $Re^{1/2}Sc^{1/3}$ relate to small streamwise positions.
increase of 21 K. This is by a factor of 4 larger compared to our own numerical simulations [28], which however did not consider turbulence effects and the recirculation zone directly behind the injector, resulting in larger initial slip velocities in the experiments and, hence, led to larger heat transfer. The volume expansion of the liquid may not be the most important reason for initial droplet growth, because we expect the simulations not to be wrong by so much, since evaporation rates were predicted fairly well. Another reason for this initial increase in diameter could be droplet oscillations. The droplets leave the pin-hole with cylindrical like shapes, with their longest axis in streamwise direction, and simple geometrical considerations show that the projection of a cylinder is smaller than that of a volume equivalent sphere. The droplets will oscillate but must maintain an axisymmetric shape with respect to the streamwise direction and hence appear flattened at their other reversal point, also having a smaller projection area than a volume equivalent sphere. These oscillations will decay with a rate of $\frac{\rho \cdot d}{20 \mu}$ [30], which for the decane droplets at room temperature is 2 ms and for hexane this time becomes 5 ms. The droplets on average appear smaller during these oscillations and for the decane droplets the oscillations have not stopped at the first measurements position $x = 30$ mm, corresponding to time 1.8 ms. But at position 80 mm, corresponding to 5 ms, the oscillations have disappeared and therefore the droplets appear, on average, larger. Also the temperature dependence of the increase of decane droplet surfaces is in agreement with this argument. For larger air temperatures the liquid decane has a larger temperature, hence a smaller viscosity and therefore larger decay time. As a consequence, the oscillations are present for larger times also letting the droplets appear smaller at the second measurement position $x = 80$ mm. For hexane and heptane droplets evaporation starts immediately and the oscillations are still present at positions 80 mm, due to smaller viscosity and larger decay time, letting the droplets still appear smaller. Therefore, for these liquids this initial droplet growth was not observed. After the discussed initial increase, the decane droplet diameters decrease continuously, however at a considerably lower rate than for hexane and heptane.

Figure 8 b) shows the normalized droplet surface as function of time and Figure 8 c) shows the surface reduction rate $K$ as a function of $Re^{1/2}Sc^{1/3}$. Negative values of $K$ correspond to the above described droplet growth due to thermal expansion and measurement ambiguities due to shape oscillations. The linear behaviours of the surface reduction rates start closer to the injector compared to the other liquids and surface reduction rates are nearly constant. Hence, evaporation is not larger for large slip velocities (hence larger $Re$). However, as discussed by [3], [5], the turbulence of the air has an influence on evaporation processes. We modelled decane evaporation [28] and found a continuous increase in surface reduction rate along the droplet trajectories as a consequence of a continuous heat up of the droplets. This is not observed in the measurements of Figure 8 c), where the surface reduction rate is constant after a short initial period. The reason could be that for large $Re^{1/2}Sc^{1/3}$ (corresponding to positions close to the injection) turbulence was more intense and had smaller integral length scales, see Figure 2 a). Birouk & Gökäl [5] suggested that
the Damköhler number, defined as ratio of turbulent time scale to evaporation time scale

\[ Da = \frac{t_{ed}}{t_v}, \quad t_{ed} = \left( \frac{D_0^2 L}{u'} \right)^{1/3}; \quad t_v = \frac{\delta_u}{v_v} \]  \hspace{1cm} (2)

could be used to correlate the surface reduction rate in the laminar convective case with the turbulent one as:

\[ \frac{K_i}{K_l} = 0.74 \cdot Da^{-0.115} \]  \hspace{1cm} (3)

Since for decane evaporation the surface reduction rate is constant over all the measurement range, we assume that \( t_v \) is constant and \( Da \) is only a function of the turbulence properties. Then \( Da \) becomes one order of magnitude smaller for \( Re^{1/2} Sc^{1/3} \) of 0.5 compared to 5. This smaller \( Da \) leads to smaller surface reduction rates by a factor of approximately 2 (eq. 3), which is not observed in the measurements. The surface reduction rate could be constant if the droplets had larger temperatures for small \( Re^{1/2} Sc^{1/3} \) (corresponding to large \( x \) and \( t \)), so that the vapour pressure was a factor of 2 larger. Consequently, the droplets must have heated up by around 15 K [31] between streamwise positions 400 and 1000 mm. This temperature increase was predicted quite exactly by our CFD simulations [28]. Hence, we conclude that air turbulence increased evaporation close to the injector, and the heat up of the droplets increased evaporation further downstream, so that both effects led to constant surface reduction rates for decane over all the test section.

### 3.3. Evaporation results for mixtures of hexane/decane and hexane/heptane

Figure 9 shows the normalized surfaces for the 25% hexane/75% heptane droplets for air temperatures 365, 388, 412, 430 and 455 K. Again, as for pure heptane the initial droplet diameters varied by around 5% for the different flow temperatures. One data set for a 50%/hexane/50%/heptane mixture was measured for temperature 365 K and shows obviously faster evaporation compared to the 25%/75% mixture. At streamwise positions larger 800 mm the surface reduction rate decreases, which might indicate that all the hexane has evaporated and only heptane is left. This is supported by the fact that this happens when 50% of the liquid has been evaporated, corresponding to surface area of \( 0.5^{2/3} = 0.63 \). Additionally, at 455 K the channel air velocity was set to 7.5 m/s. Close to the injector this resulted in faster evaporation, since the injected liquid leaves the injector at a larger temperature due to the increased heat transfer to the injector below the turbulence generating grid. For larger streamwise positions the evaporation rate is smaller compared to 5 m/s air velocity, since the droplets have a larger streamwise velocity and, consequently, less time to evaporate.

A mixing time scale can be estimated in the same way as for the temperature distribution inside the droplet presented above. Diffusion coefficients are presented by Li
& Yue [32] and are of the order of $\gamma = 4 \cdot 10^{-9} \text{ m}^2/\text{s}$. This value depends on the fraction of the actual species, which diffuses, and can change by approximately 10%. This is, as well as the temperature dependency, not important for the current estimate of the mixing time scale, which becomes 3.3 s. This shows that the droplets cannot be well mixed in the current experiments due to diffusion. However, the measurements presented in the next section indicate strong preferential evaporation, which indicates strong internal mixing.

Figure 10 presents normalized surfaces of 25% hexane/75% decane droplets for air temperatures 388, 412, 430 and 455 K a) as a function of streamwise position and b) as a function of time of flight. Additionally at 388 K the channel was operated also at 10 m/s, which led to decreased evaporation due to larger droplet velocities and hence less evaporation time. For temperature 388 K, where very small evaporation of decane is expected, it could be observed that the surface reduction rate is reduced downstream of the location $x = 500$ mm, corresponding to time 40 ms. Brenn et al. [18] observed similar slope changes. At this time, approximately 25% of the volume has evaporated, corresponding to $D_v/D_0^2 = 0.75^{2/3} = 0.82$, relating exactly to the initial fraction of hexane. This suggests that at the beginning of the evaporation process mostly hexane evaporated due to its lower boiling point with nearly linear surface reduction. This however requires that mixing times are considerably smaller than for the diffusion limit. In Section 2.2 we estimated a velocity difference between droplet surface and centre of 12 m/s. Using the droplet diameter as length scale this results in a turnaround time of the vortex of 20 ms, which corresponds to half the time required.
till all the hexane has evaporated, see Figure 10 b). Hence, these evaporation measurements support strong internal mixing being present in the current experiments.

Figure 11 presents measured evaporation rates of 50% hexane/50% decane droplets at temperatures 365, 388, 412, 430 and 455 K as a function of a) streamwise position and b) time of flight. Especially for the largest temperature a sudden change in the slope of the surface area reduction can be observed, which again indicates that firstly most of the hexane evaporates, since this slope change occurred slightly above $D^2/D_0^2 = 0.5^{2/3} = 0.63$ at $x = 400$ mm or $t = 35$ ms. For temperatures 412 K and below a sudden slope change is not that clearly visible, hence preferential evaporation might not be that pronounced.

Figure 10: Normalized surface of 25% hexane/75% decane droplets as function of a) streamwise position and b) time of flight for different temperatures.

Figure 11: Normalized surface of 50% hexane/50% decane droplets as function of a) streamwise positions and b) time of flight for different temperatures.
3.4. Evaporation results for heptane at elevated droplet loading

Figure 12 shows the normalized surface for a single droplet chain of pure heptane and a stream of 5 parallel droplet chains at temperatures 365, 388 and 412 K. Elevated droplet loadings led to decreased evaporation rates for 365 K air temperature. For the larger temperatures this difference became smaller than the expected experimental errors. It must be emphasized that the droplet loading was still far below any combustion application. This was necessary to avoid possible auto ignition and explosion of the facility, which was designed for hot flow and not for combustion.

The experiments show that at larger temperatures the droplet loading had negligible influence on the evaporation rates while evaporation rates were reduced for the smaller temperatures. Evaporation is driven by the difference of vapour pressure on the surface and the partial vapour pressure in the gaseous boundary layer around the droplet. Additionally, the surrounding air is cooled since it supplies energy to the droplets to heat them up and to deliver latent heat for the phase change. Since the vapour pressure increases highly non-linear with temperature, the reduction of evaporation rate due to increased partial pressure as a result of increased droplet loading becomes unimportant at air temperatures 412 K. This behaviour was captured by calculations [28].

Swindal et al. [14] reported measurements of a $3 \times 3$ array of droplets composed of acetone and methanol with ratio 2:9. They measured droplet surface area reduction rates for the corner streams which were reduced to 62% for the streams at the edges, and to

![Figure 12](image-url)
17% for the centre stream. However, they do not give details on the surrounding air temperatures and velocities and also not on the droplet initial temperature, which supposedly both were room temperature. Nevertheless, the quantitative trends of their measurements and the current results are similar. Based on the slope of the droplet surface curves in Figure 12 downstream of $x = 400$ mm, the droplet surface area reduction rates for the elevated loading were approximately 50% of that of the single droplet chain.

3.5. Evaporation results for hexane, heptane and decane in an air-steam mixture

This section presents measurements of surface reduction of the alkane droplets in an environment with additional steam present. As was mentioned in section 2, the steam flow rate supplied by the available equipment showed considerable fluctuations. In an on-and-off modus a semi-continuous operation was realized and measurements of droplet diameters as function of distance from the injection point were obtained only up to streamwise positions $x = 300$ mm. For larger distances the rate of droplet measurements became too small due to dispersion of the droplets, see Figure 4, and it would have not been possible to operate the steam generator for long enough times.

Figure 13 shows the normalized droplet surface as a function of distance from injection for hexane droplets with steam added at air temperatures 365 and 412 K. Evaporation is remarkably increased by adding steam for both temperatures. For air

![Figure 13: Normalized surface of hexane droplets as function of streamwise positions for temperatures 365 and 412 K with steam added.](image-url)
temperature 365 K one important effect could have been that the temperature in the channel was increased due to the hot steam. Calculating the temperature of the mixture of air and steam with steam temperature 421 K, steam mass fraction 0.15 and steam heat capacity approximately twice that of air [16] this results in corrected air temperatures of 379 and 414 K. Hence, for 412 K air temperature this effect is negligible. If one compares the evaporation rates with steam added at 412 K they are even larger than without steam for air temperatures of 455 K, see Figure 6. This shows that the increased channel temperature due to the added steam with temperature 421 K cannot be the only reason for enhanced evaporation. Since the hexane droplets must be colder than the boiling point of hexane, it is likely that steam condenses on the droplet surfaces and delivers energy to the droplets due to the phase change. Additionally, a flow towards the surface is induced by diffusion of water molecules which might weaken the flow induced away from the droplets due to diffusion of the evaporated liquid. As a consequence, the droplets heat up faster with steam added and evaporate faster. Numerical simulations [28] performed within the project support this argument and also showed that the property changes of the surrounding gas due to the presence of steam did not result in enhanced droplet evaporation. Lee & Law [19] studied evaporating droplets of n-heptane and different alcohols in the exhaust gases of a methane/air flame, providing a hot and humid environment, and a CO/air flame, providing a hot and dry environment. Their gas temperatures were 1050 K with steam mass fraction 9.4% and the injected droplets of size 150–250 µm. They did not find increased evaporation after an initial transient period for heptane droplets for the humid case compared to the dry one, while they reported increased evaporation in the humid flame for the alcohols, which are miscible with water. Their evaporation times are comparable with ours, but the surrounding gas temperature was much larger, which could lead to fast heat up of the droplets close to their boiling points. For heptane this is close to water, however for methanol the boiling point is 338 K, which might explain larger condensation of water on methanol independent of effects of miscibility. Since hexane and water are not miscible, the water accumulates on the surface of the droplets. One possibility is a monolayer of water, which could stop evaporation of hexane and the droplet size could not decrease any more. However, due to a slip velocity due to the surrounding air flow, the accumulated water can be driven to the wake side of the droplets. Additionally, we had estimated that there is a surface liquid velocity of 1 m/s, since the droplets are liquid and not stiff. Just to present a rough number, if the water surface is driven towards the wake side with a velocity of 5 m/s, and using the droplet diameter of 200 µm as length scale, this process takes 40 ms. This is approximately equal to the time a droplet requires to reach streamwise position 400 mm. Therefore, steam might condense on the front side of the droplets and deliver heat to the droplets at this position, where anyway most of the evaporation takes place, and is then transported to the wake side. An interesting effect is that when the slip velocity becomes smaller, the water distributes evenly over all the surface and can stop evaporation immediately. This can have important consequences for liquid fuelled mixed air/steam turbines which might show reduced reliability and unwanted blow-off behaviour.
The evaporation or latent heat of water is approximately a factor of 7 larger than that of the alkanes and also the heat capacity of water is larger than that of liquid alkanes by a factor of nearly 2, see Table 1. The heat capacity of steam is only slightly larger than that of hexane vapour [16]. We can estimate the amount of water being present on the droplets by equalling the amount of energy the condensing steam delivers to the droplets and the alkanes consume to evaporate. This suggests that only a fraction of 1/10 mass of water is present on the droplets compared to the extra evaporated alkanes, which agrees with the finding of smaller droplet diameters with steam present.

Figure 14 shows the normalized droplet surface as a function of distance from injection for heptane droplets with steam added at air temperatures 365 and 412 K. The measurements for the larger temperature were carried out twice and show the uncertainties of the measurements, which mostly are related with the steam injection. Again increased surface reduction rates are observed with steam and these are also larger for 412 K with steam compared to the measurements with air temperature of 430 and even 455 K (see Figure 7).

Figure 15 shows the normalized droplet surface as a function of distance from injection for decane droplets with steam added at air temperatures 365 and 412 K. Again, surface reduction rates increase and are also larger for 412 K channel temperature with steam added compared to pure air at temperature 455 K (see Figure 8). Decane has a boiling
point above that of water, hence the condensation will stop after the droplets heated up. However, due to their injection temperatures of around 313–323 K, as described above, this happens for streamwise positions larger $x = 400$ mm, which was also supported by numerical simulations [28]. Hence, condensation of steam on the droplet surfaces was also indicated by the current measurements of evaporating decane droplets.

It should be emphasised that the presented measurements of surface reduction rates with added steam showed some interesting qualitative results: evaporation rates increased for mixed air/steam temperatures even if compared to measurements in pure air for temperatures 30 K above. This allows the conclusion that added steam leads to enhanced evaporation rates due to condensation of steam on the droplet surfaces. Due to the uncertainties related with the quantity of steam supply, an exact quantification of the influence of steam on alkane droplet evaporation must be obtained in a carefully designed flow, with steam injection and dispersion exactly quantified.

5. CONCLUSIONS

This work presented experimental results on surface reduction rates of nearly monodisperse droplet chains of hexane, heptane and decane transported upward against gravity in a grid generated turbulent flow. Additional evaporation measurements at elevated droplet loading for heptane, for mixtures of hexane/heptane and hexane/decane and for the pure liquids with added steam are reported. The droplets had initial mean diameters of approximately
230 µm and initial velocities of 17 m/s, the air velocity was 5 m/s and initial Stokes numbers, based on aerodynamic droplet relaxation times and turbulence time scale, were of the order of 10. Droplet size measurements were evaluated based on the modal value, corresponding to the value of the first peak in the diameter PDF, and therefore were not influenced by collisions and coalescence. This allowed detailed discussion and generation of a data base for accurate validation of droplet evaporation models.

The main findings of the work are summarized as follows.

a) The surface reduction rates did follow a d-square law for decane only. It has been shown in the discussion that in the initial stage of evaporation turbulence might have increased evaporation and in the later stage the droplets might have had larger temperatures; these two effects lead to an overall constant evaporation rate. This was not found for hexane and heptane, which only in the later stage showed constant evaporation, when thermal equilibrium had been reached and turbulence properties were nearly constant.

b) Measurements at elevated droplet loading were performed for heptane and showed that for air temperature close to the boiling point evaporation reduced due to increased vapour loading and hence reduced differential partial pressure of the evaporating substance. For larger air temperatures evaporation hardly changed with droplet loading.

c) The streamwise development of the surface reduction rates for the droplets of mixed hexane and decane showed that in the initial stage preferentially the more volatile species evaporated. This indicated mixing inside the droplets must have been much faster than for pure diffusion, presumably due to an internal vortex structure initiated during droplet generation.

d) Adding steam led to enhanced evaporation of hexane, heptane and decane droplets; most likely this occurs due to additional heat transferred to the droplets by condensation of steam on the droplets surfaces.

e) Suggestions on modelling accurately the current flow were presented throughout the manuscript. These include the use of two-way coupling for the momentum close to the injector due to locally large mass loading, consideration of the recirculation zone close to the injector and the use of a drag coefficient for droplets rather than rigid spheres.

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