

## **REDUCED COALESCENCE OF DROPLETS DUE TO EVAPORATION**

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### **ABSTRACT**

The purpose of the current work is to study the influence of droplet evaporation on the probability of droplet coalescence. Therefore, a stream of nearly monodisperse droplets with diameter around 220  $\mu\text{m}$  was injected in a upward grid generated turbulent flow. Hexane and decane were investigated for temperatures of the gas flow of 100, 150 and 200°C. The droplet diameters were measured by an image processing system. In parallel, a LDA system was used to measure the droplet mean and rms velocities.

Since the droplets were monodisperse, droplet coalescence led to multi modal size distributions, which allowed the calculation of the rate of coalescence. The velocity characteristics were equal within measurement uncertainties for all conditions, hence the rate of droplet collisions was identical, so the rate of coalescence could be discussed as a function of the evaporation rate.

It was found that the probability of coalescence was decreasing with increased evaporation rates for the decane droplets, whereas for the hexane droplets the opposite behaviour was found. Possible effects that lead to these trends are discussed.

### **INTRODUCTION**

Modelling of evaporation of fuel for combustion applications relies on the prediction of correct droplet diameters, which may be changed by droplet collisions and subsequent permanent coalescence. Especially in direct injection internal combustion engines the flow properties could enhance droplet collisions and coalescence. Additionally, droplet coalescence is responsible for the large scale behaviour of many systems, such as rain formation in the atmosphere or formation of agglomerates in spray dryers.

Experiments on droplet evaporation usually rely on measurements of droplet sizes, e.g. Swindal et al. [1], who used Laser resonance to determine sizes of evaporating droplet chains. Together with the experimental work, a variety of numerical models has been developed and evaluated [2]. Usually, droplet collisions and coalescence are not modelled in CFD calculations, although nonwetting of droplets on surfaces is a well known phenomenon [3]. However, a detailed understanding of the physics has not been achieved yet. All models describe the phenomenon by the existence of a gas layer between the colliding droplets. The thickness of the gas film may be increased by evaporation and, hence, coalescence is suppressed. Additionally, Qian and Law [4] found that the gas properties of the separating layer are important. Their experiments of evaporating water and tetradecane droplets in different gas atmospheres showed that an increased viscosity of the gas layer could decrease droplet coalescence, since the gas film cannot be discharged sufficiently fast so that the droplets can merge. In an additional experiment, they studied coalescence of tetradecane droplets in a gas atmosphere consisting of a mixture of nitrogen and ethylene. They found that an increased fraction of ethylene led to increased coalescence.

The purpose of the current work is to present measurements of droplet coalescence rates as a function of the ambient temperature and evaporation rate and to show that evaporation can either enhance or reduce the probability of droplet coalescence. The paper is structured as follows. The first chapter describes the wind tunnel, the droplet injection and the measurement technique. After that experimental results for droplet velocities and evaporation rates are presented. The paper ends with the discussion of the findings and some conclusions.

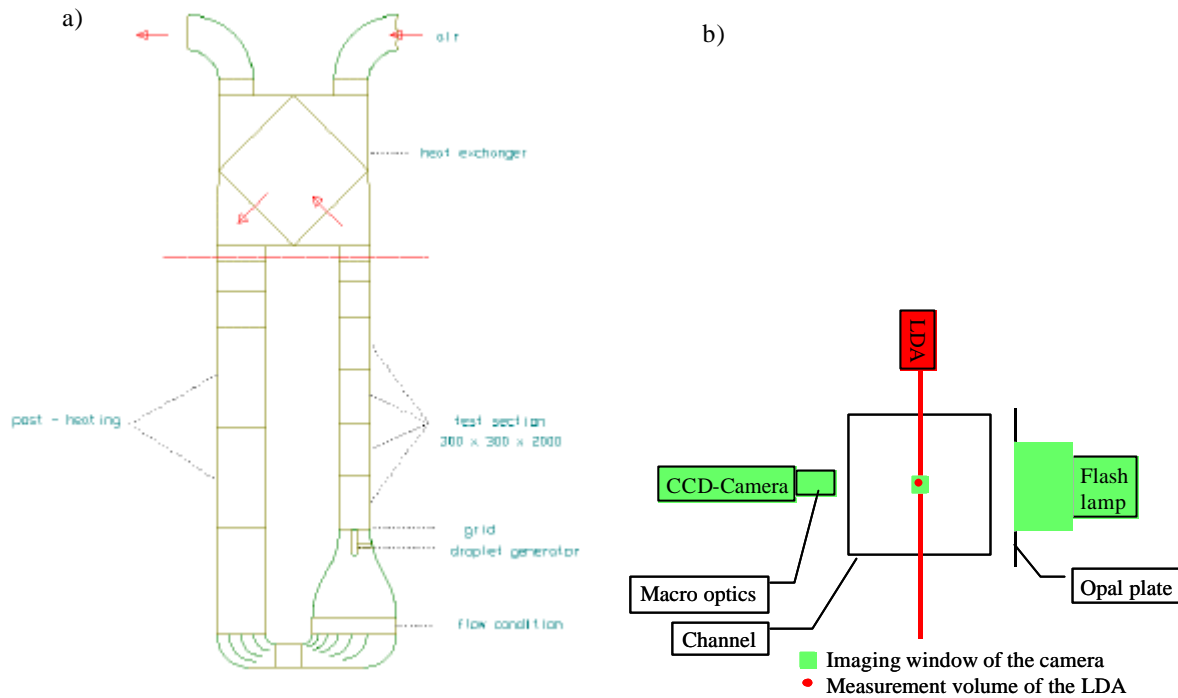
### **EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUE**

#### **Wind tunnel and droplet injection**

Figure 1a shows the set-up of the upward wind tunnel designed for droplet evaporation experiments. Fresh air is entrained and heated up in the heat exchanger using the heat from the air leaving the test section, which is exhausted to the environment. It should be noted that 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 fresh air is led through two bends with flow straighteners to a chamber that leads to the contraction passing the air to a grid with 10 mm circular holes to generate nearly isotropic turbulence. The velocity of the channel was set constant to 5m/s for all experiments. The turbulent integral lengthscale hence can be assumed to be equal to the grid size of 10 mm. With the measured gas rms velocity 100 mm behind the grid of 0.8 m/s, the turbulent time scale becomes about 12 ms. The temperature of the flow was monitored and adjusted automatically within 3°C.

The droplets are injected centrally at the position of the grid through a piezoelectric droplet generator actuated at the natural frequency of 38 kHz and an orifice of 150  $\mu\text{m}$ , which produced a chain of nearly monodisperse droplets of diameter 220  $\mu\text{m}$ . The droplet velocity at the injector was 18 m/s, resulting in an initial droplet Reynolds number of around 150, with a fluctuating velocity of 1 m/s, hence a considerable slip velocity between air and droplets was present at the inlet. The Stokes number of the droplets, defined as the ratio of relaxation time scale of the droplets to the turbulent time scale of the gas, was of the order of 10 and decreased with streamwise position.

As evaporating liquids hexane and decane were used, with boiling points of 60.2°C and 174°C, respectively. At room temperature, the surface tension was  $18 \cdot 10^{-3}$  and  $21 \cdot 10^{-3}$  N/m and the density was 660 and 730 kg/m<sup>3</sup>.



**Figure 1.** a) Drawing of the wind tunnel. b) Set-up of the imaging and LDA system seen from the top.

### Image processing system

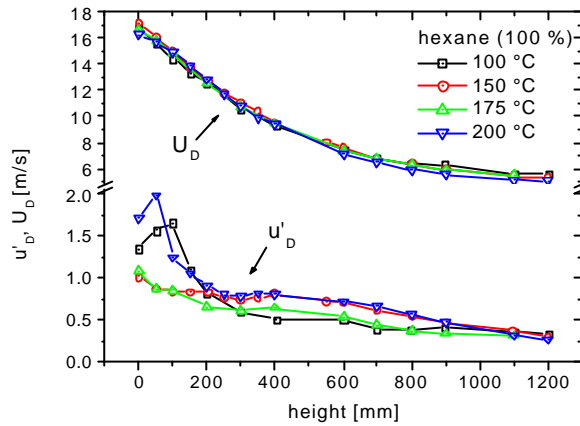
Previous size measurements of evaporating droplets were performed using phase-Doppler Anemometry (PDA). However, droplet shape oscillations and the unknown refractive index, depending on unknown and inhomogeneous droplet temperature and mixture of species, led to large sizing errors. Additionally, the 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 Laser Doppler Anemometer (for velocity measurements). A drawing of the set-up is shown in figure 1b.

An object recognition software, which was developed in the institute was applied and used the determination of gradients of the images to detect single droplets, which were sharply imaged. The processing was done online with a rate of 3 images per second on a 2GHz PC. A flash lamp illuminated the droplet chain from behind so that the shadows of the droplets, which did 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. Bröder & Sommerfeld [5] applied a similar system in a bubbly flow and their system was modified by using a macro optics, which comprised a 85 mm Nikkor lens with an additional extension ring of length 25 mm between the adapter and the camera to increase the magnification. This resulted in an image size of 20 mm times 16 mm. More details can be found in Bröder [6], where the sizing error is estimates as 1 to 3% for the current magnification. It should be noted that the measurements started 40 mm downstream of the grid, and there the origin  $x=0$  is placed in the following text and figures. This shift was necessary, since the lens mounted on the camera had a diameter of 80 mm, so it was ensured that the hole are of the lens was used.

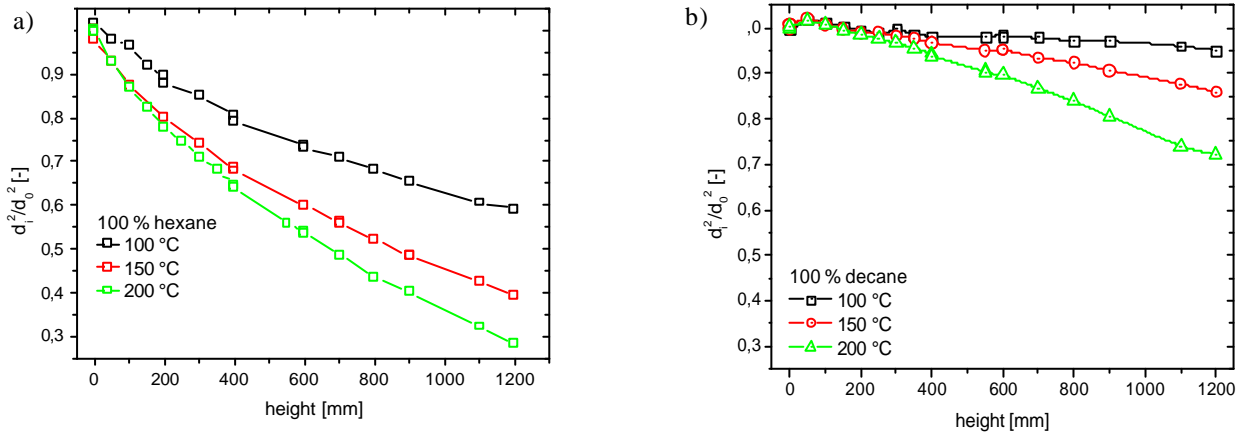
## RESULTS

Figure 2 shows the mean and rms streamwise velocities for the hexane droplets for three different temperatures. The deceleration of the droplets could be observed and the rms velocities were largest at the injection position and reduced with streamwise position. The mean velocity did not vary with the temperature of the air flow while the rms velocities showed values between 1 and 2 m/s directly behind the point of injection. However, no clear dependence of the trend of the rms velocities with temperature variation can be seen in the figure, hence the reason may have been some measurement uncertainties related to a miss alignment of the LDA probe volume out of the centre of the droplet jet, where the rms velocity was increased.

Figure 3 shows the decrease of the squared droplet diameters due to evaporation for a) hexane and b) decane. Especially for the decane droplets it could be observed that the droplets first grow by around 2% in diameter before evaporation reduces their size. This corresponds to a rise in droplet temperature of 50°C, hence it actually could be observed that the droplets are first heated up. The hexane droplets of course evaporated much faster.



**Figure 2.** Streamwise mean and rms droplet velocities for n-hexane at different temperatures.



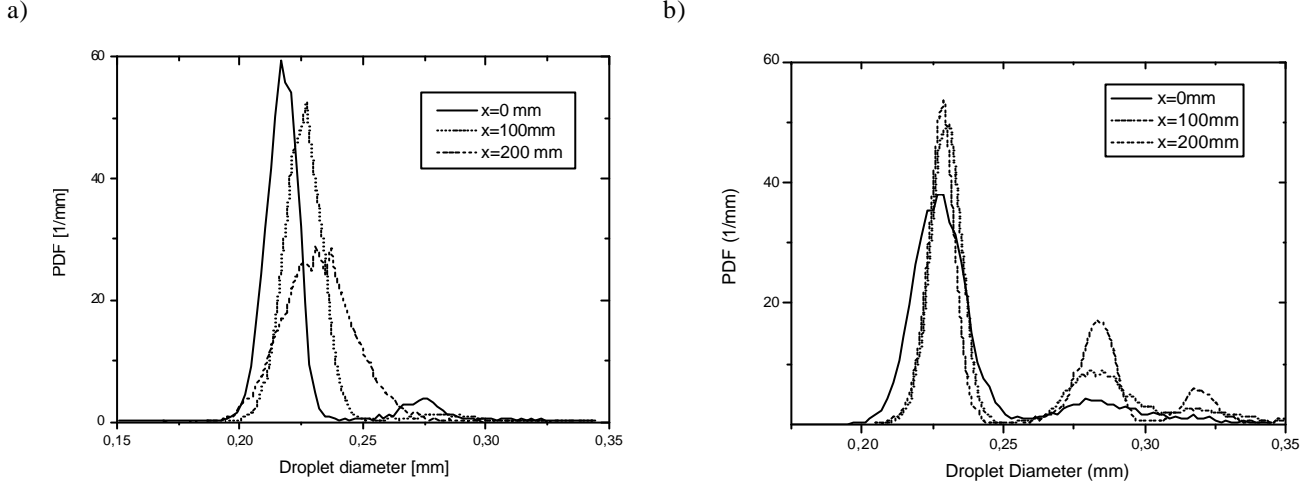
**Figure 3. a)** Local modal droplet diameter squared and normalised with its initial value as a function of streamwise distance for n-hexane at different temperatures. **b)** Same data for n-decane.

Figure 4 presents the droplet size distributions as a function of streamwise position for the two liquids. The temperatures were chosen so that the hexane droplets evaporated strongly and the decane droplets evaporated hardly, to show the influence of the evaporation rate on the development of the droplet size distributions. The focus of the current work is on coalescence of droplets and since nearly mono-dispersed droplets were injected during the current experiments, the effect of coalescence can be seen in the different peaks of the size distributions. For both liquids, it could be observed that coalescence occurred mostly directly after injection up to streamwise position 200 mm. The reason for that is that the velocity fluctuations, which determine the collision rate, decreased with streamwise position, see figure 2, and that the particle number density also decreased with streamwise position due to turbulent dispersion. For the decane droplets, also collisions of three and more droplets occurred, since the rate of coalescence was generally larger. Obviously, three droplets did not coalesce instantaneously but a considerable amount of droplets consisting already of two droplets merged with another one.

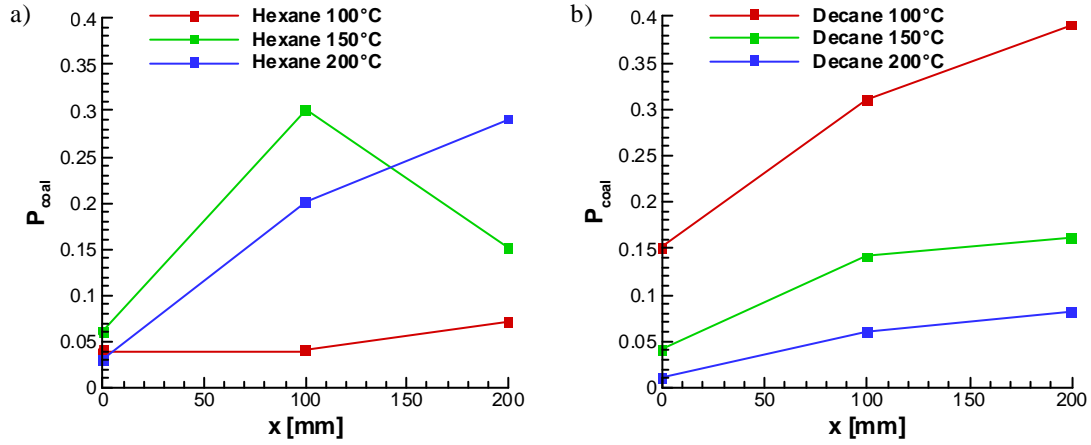
Figure 5 shows the probability of coalescence of the droplets obtained from the size distributions of figure 4. The probability at each streamwise position was calculated as the percentage of particles which have grown due to collisions and consequent coalescence according to

$$P_{coal} = \frac{N_{coal}}{N_{total}} \quad (1)$$

Surprisingly, different trends could be observed for hexane and decane droplets. For the hexane droplets the rate of coalescence increased with the temperature of the surrounding gas, while the rate of coalescence decreased for the decane droplets with increasing temperature of the surrounding gas. It can be seen that the decane droplets at 200°C show a similar rate of coalescence as the hexane droplets at 100°C and for these two conditions the evaporation rates were similar, see figure 3. The next chapter will discuss this trends together with possible physical explanations.



**Figure 4** a) Size distribution for hexane droplets for gas temperature 100°C. b) Size distribution for decane droplets for gas temperature 100°C.



**Figure 5.** Rate of coalescence as a function of streamwise position for a) hexane and b) decane.

## DISCUSSION

### Collision rate

Droplet collision rates can be obtained from geometric considerations based on kinetic theory, e.g. Abrahamson [7]. Additionally, it has to be taken into account that the velocity of colliding droplets are correlated, if they follow, even partly, the turbulent fluctuations of the carrier fluid, e.g. Sommerfeld [7]. However, for the current Stokes numbers around 10, this effect may be negligible and the particle velocity fluctuations  $u_{diff}$  are uncorrelated and the collision rate becomes:

$$P_{coll} = 2^{3/2} p^{1/2} \cdot n \cdot d^2 \cdot u_{diff} \quad (2)$$

Since it is difficult to obtain the local mean droplet concentration for a dispersing droplet chain it seems to be difficult to estimate the collision rates based on geometric principles according to [7]. Hence, the coalescence rates for different species and temperatures at the same streamwise position are compared to each other in the following paragraph.

It should be noted that droplet evaporation has an additional effect on the collision rate due to the reduction of droplet diameters. However, for decane this effect was negligible and for hexane this effect reduced the collision rate by around 20% at streamwise position 200 mm, since there  $(d/d_0)^2$  was around 0.8, see figure 3a.

### Coalescence rate

The observed coalescence rate may be explained by the different Weber number of the droplets, defined as:

$$We = \frac{u_{diff}^2 \cdot \rho \cdot d}{\sigma} \quad (3)$$

Ashgriz & Givi [9] reviewed measurements of coalescing droplets and stated that for  $We$  numbers below 2 droplets bounce and for  $We$  numbers from 2 to 15 droplets coalesce. For the current experiments, assuming an average collision velocity of 1 m/s, which corresponds to the rms velocity of the droplets for streamwise positions smaller 200 mm,  $We$  became 8.0 for the hexane droplets and 6.5 for the decane droplets, hence coalescence is expected for the current flows. It should be noted that the collision velocity of course is not constant but covers a range. Additionally, Ashgriz & Givi [10] showed in their experiments that coalescence of two droplets is very sensitive to the Weber number. A more detailed study was performed by Qian and Law [4], as described in the introduction. Based on their observations, it may be argued that a small evaporation rate could enhance the gas film between the two colliding droplets but does not change its viscosity significantly. This could lead to a reduced rate of coalescence for increased evaporation rates, as it was observed for the decane droplets in the current experiments. If the evaporation becomes stronger, there is not only an effect on the gas mixture in the gap between the droplets but also the overall concentration of vapour in the air is larger. Qian and Law [4] found that an increase of gas viscosity by 10% could promote droplet bouncing, since the gas with larger viscosity is more difficult to discharge from the gap between the touching droplets. Hence, the different gas viscosities for hexane or decane and air could contribute to the observed trends, since the gaseous alkanes have a viscosity which is approximately a factor of 3 smaller compared to air. Hence, for large droplet evaporation rates, the viscosity of the vapour-air mixture in the gap between the droplets may be reduced which increased droplet coalescence.

Additionally, Qian and Law [4] also observed that ethylene vapour which was used as gas instead of nitrogen increased coalescence of tetradecane droplets, and they concluded that the presence of fuel vapour in fuel sprays could promote coalescence. As a possible reason they mentioned that the vapour may modify the surface tension of the droplets which promotes droplet merging. This is also in agreement with the findings that for increased evaporation rates of the hexane droplets coalescence was increased.

## CONCLUSIONS AND OUTLOOK

Measurements of the sizes of evaporating droplets were performed for hexane and decane at different temperature in a turbulent flow using an imaging technique to derive rates of droplet evaporation and coalescence. The findings of the current work are summarised as follows:

1. The coalescence of the decane droplets decreased with increased evaporation rate, while the hexane droplets showed exactly the opposite behaviour.
2. Evaporation can either reduce or enhance the probability of droplet coalescence.
3. A qualitative explanation based on microscopic effects on the droplet surfaces was attempted. Reduction of coalescence due to evaporation occurs due to a gas layer between the two colliding droplets. Increased coalescence due to evaporation may occur due to a reduction of the viscosity of the gas layer between the colliding droplets.

As consequence more measurements of colliding and evaporating droplets are needed to identify the effects that could describe the effect of evaporation on droplet coalescence. Currently experiments with mixtures of alkanes, droplet clouds rather than chains and additional water steam contained in the gas phase are carried out.

## ACKNOWLEDGEMENTS

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## SYMBOLS

$d$	droplet diameter [m]	$U_{diff}$	velocity difference between droplets [m/s]
$n$	droplet number density [ $1/m^3$ ]	$U_d$	droplet diameter [m]
$P_{coal}$	coalescence [dimensionless]	$x, h$	streamwise position or height [m]
$P_{coll}$	rate of collision [ $1/s$ ]	$\rho$	density [ $kg/m^3$ ]
$We$	Weber number [dimensionless]	$\sigma$	surface tension [N/m]

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