Effects of Temperature Changes, Air Velocities and Volume Fractions on the Single Droplet Evaporation Behaviors at High Ambient Temperatures

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ABSTRACT

This study is aimed to investigate the effects of temperature changes and air velocities on the evaporation behaviors of the single droplet single component (pentadecane C-15) and binary mixtures (pentadecane C-15 and dodecane C-12 at 3:1, 1:1 and 1:3 volume ratios) in a heated chamber at high ambient temperatures of 91-98, 110-118, 129-145 and 155-170°C. The effects of volume fractions on the binary mixture single droplet evaporation characterisitics are also evaluated. The droplet diameter is measured at the forward scattering region. The time dependent changes of the droplet diameters are calculated from the Morphology Dependent Resonances (MDRs) of the refractive index which are measured in the backward region. The evaporation rates of the droplet increased with increased ambient temperatures. There is no effect of ambient air velocities on the droplet evaporation rates, owing to the small relative velocities between the droplets and the air. For the single component droplets, the ambient temperature is the most influent parameter on droplet evaporation rates and evaporation rate changes. For the binary mixture droplets, the volume fraction is the most influent parameter on droplet evaporation rates and evaporation rate changes. The results from this study can be applied for a better understanding of the fuel droplet in the combustion chamber of the engines.

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Introduction

Numerous studies on the droplet dynamic behaviors including evaporation of single and multi-component droplets in a chamber at room temperature and volume fraction by the rainbow refractometry technique have been examined by Wilms [1]. The Interferometric Laser Imaging for Droplet Sizing (ILIDS) technique was used by Glover et al [2], Kobayashi et al. [3] and Kawaguchi et al. [4] to measure the droplet size [2] and the spatial distribution of the droplet size in two-phase flows [3,4]. Fieberg et al. [5] have performed an experimental and numerical investigation of droplet evaporation. Phase Doppler Anemometry (PDA) has been used to investigate the droplet evaporation under the engine diesel condition (high pressure and high temperature conditions) at 293-550 K.

The droplet temperatures and air velocities around the droplets are very important parameters to investigate evaporation rates. These parameters can affect the behaviors and efficiency of the fuel droplet in the combustion chamber. There are numerous studies focusing on droplet temperatures. The evaporation of dodecane, decane and nonane droplets in small size of less than 100 μm at low Reynolds number and increased ambient temperatures has been demonstrated both by numerical and experimental techniques [6]. Results indicated that the evaporation rates at the peak temperature were well predicted. However, during the prolonged expansion phase, the evaporation rates were over predicted, while during the transitional heating phase, the rates were under predicted. The heating process of a mono-disperse fuel droplet injected into a hot gaseous environment by the two color laser induced fluorescent techniques which can measure the temperature distribution within a droplet by scanning the droplet volume has been investigated [7]. The temperature field within the combusting ethanol droplets in a linear stream by the two color laser induced fluorescent techniques and a heat transfer model for the droplet internal fluid circulation, according to the hill vortex pattern have been developed [8].

There are few studies on the effects of air temperatures, ambient air velocities and volume fractions on droplet evaporation behaviors. In fact, Honnery et. al. [6] have investigated the increasing ambient temperaturs, but not the air velocities on droplet evaporation behaviors. Kitano et al. [9] studied a numerical model of the multi-component droplets. Jet-A was used as a liquid fuel. The one component (n-decane), two components (n-decane and 1, 2, 4-trimethylbenzene) and three components (n-dodecane, iso-octane and toluene) have been used as a surrogate fuel, but no investigation on the effects of ambient the temperature changes and the volume fractions as well as the air velocities on the droplet evaporation behaviors. Thus, the objective of this present study was to investigate the effects of the temperature changes, air velocities and volumne fractions on the evaporation behaviors of the single droplet of the single component (using pentadecane as a model liquid) and the binary mixture (using pentadecane and dodecane as model liquid mixtures at 3:1, 1:1 and 1:3 volume ratios) in order to obtain information for the evaluation of the fuel droplet in the combustion chamber.

Experimental Method

The setup of the heated chamber equipped with a linear CCD camera, a cooling device and a laser according to our previous study [10] is presented in Figure 1. Axis *x*, and *z* are the directions of the droplet traveling in the heated chamber and the perpendicular to the heater surface, respectively. The temperature profile increase gradually until it constant as shown in Figure 2. The starting point and ending point have already shown also in Figure 2. The heater is controlled by the heater box. The droplet is generated by the droplet generator. The droplet is really small and can only visible with the lamp. Before starting the experiment, it must be sure that the generator generated only a single droplet without the satellite droplet by observing the droplet generator via the lamp. The size has already measured and the droplet size is constant. The further details can be found in Manosroi et al [10]. For this study, the droplet shape can assumed to be a sphere, because the droplet is very small (40 µm)

For the measurement procedure, the hydrocarbon liquid (pentadecane) is first put in the droplet generator and the droplets are then injected from the droplet generator at the room temperature into the heated chamber. The laser is turned on and the droplets flowed along the laser beam from the bottom to the top of the chamber. The flow is caused by a chimney effect. At the same time, the light is scattered from the droplet. The camera and the PSD (Position Sensitive Detector) sensor captured the scattered light. The PSD sensor is an optical position sensor that can measure a position of a light spot in two dimensions on a sensor surface. After the PSD sensor captures the light, it sends a signal to the servo-motor to close the valve in order to stop the droplet floating upwards and keep it staying longer in the heated chamber to have sufficient time to investigate the effects of the ambient air temperatures and velocities on the droplet evaporation. The droplet diameters are measured in the forward and and the changes of the droplet diameter and the volume fraction are calculated from the Morphology Dependent Resonances (MDRs) of the refractive index which are measured in the backward region.

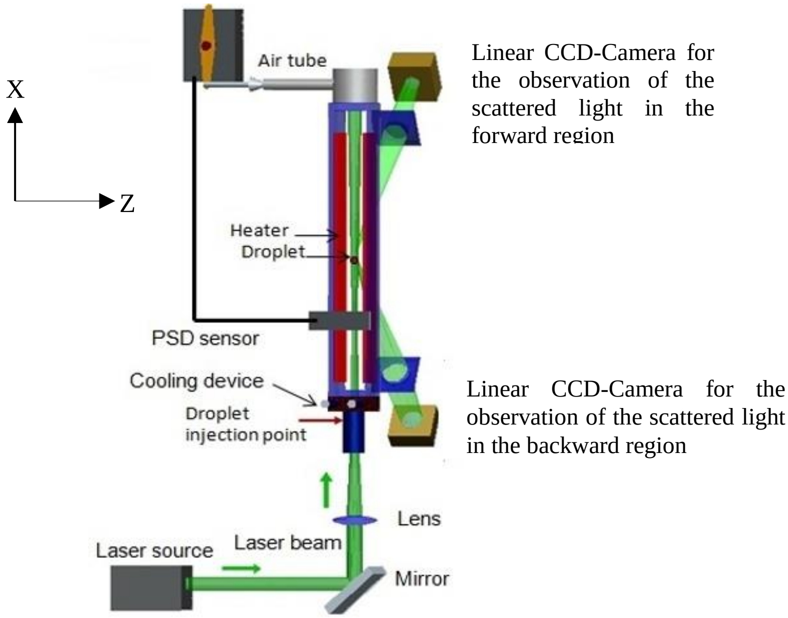

Figure 1: The experimental setup [10]

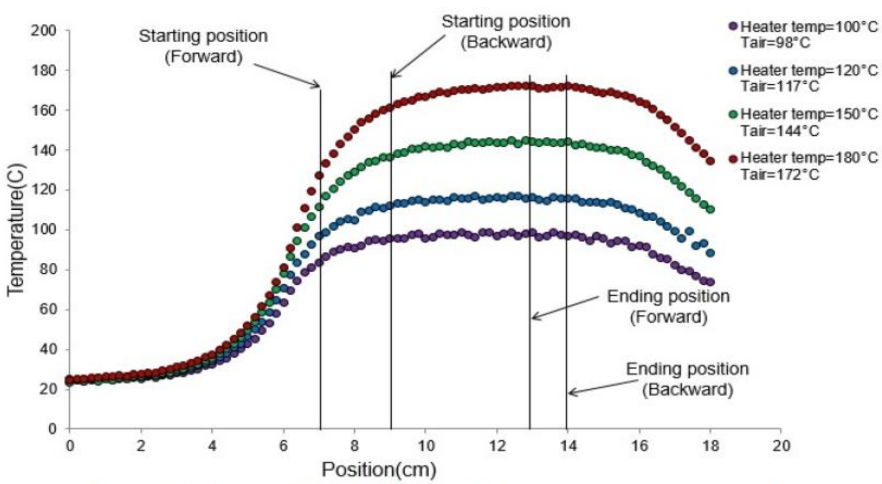

Figure 2: Temperature profiles with the cooling device at the various heater temperatures.

Results and Discussion

Effects of Ambient Temperatures on the Evaporation Rates

Figures 3, 5, 7 and 9 show the effects of temperature changes on the evaporation rates of a pentadecane droplet at the ambient temperatures of 91-98, 110-118, 129-145 and 155-170°C, respectively. Figures 4, 6, 8 and 10 presented the effects of the ambient temperature changes on the evaporation rate changes of a pentadecane single droplet at the heater temperatures of 91-98, 110-118, 129-145 and 155-170°C, respectively.

For the description of the above figures, D_0 is the initial droplet diameter, the experiment is the experimental results which are obtained from the measurement. MDRs are the droplet surface diameter obtained by MDRs (Morphology Dependent Resonances). D square model is the calculation model from the D^2 law model. RMM model is the "Rapid Mixing Model" (Infinite Conduction Model).

"Diff D square model" is the differentiation of the surface diameter D/D_0^2 over time $t/(D_0)^2$ from the D^2-law. "Diff MDRs" is the differentiate of the surface diameter $(D/D_0)^2$ over times $t/(D_0)^2$ from the surface droplet obtained from the MDRs and the ambient temperature is the ambient or air temperature inside the heated chamber. To be noted, the differential of the D^2 law could be done only if the ambient temperature is known, because the ambient temperature in the heated chamber is only measured at every 2 mm. The differential of the experimental results and models (Diff exp, Diff MDRs and Diff D square model) are calculated by a linear regression method.

From Figures 3 to 10, the droplet surface did not decrease linearly at the beginning. The differentiation of the droplet surface (Diff D square model, Diff exp and Diff MDRs) decrease with increasing ambient temperatures and then is constant when the temperature do not change. Hence, the droplet evaporation rates increase with increasing ambient temperatures and are constant when the ambient temperature is stable. There are some fluctuations of the droplet surface from the experiment (Diff exp) because the calculation of the Diff exp is divided in parts and the fluctuation from the experimental data is caused by noises of the measurement. There are also some discrepancies between the differentiation of the experiment (Diff exp) and the D^2 law model (Diff D square model), and also between the differentiation of the MDRs (Diff MDRs) and the D^2 law model (Diff D square model), owing to the discrepancy between the experimental results and the model. This is caused by the saturation at the beginning of the measurement. In addition, the deviation increased with increasing heater temperatures. When the D^2-law is used to compare the experimental results at the constant temperature region, they showed a really good agreement.

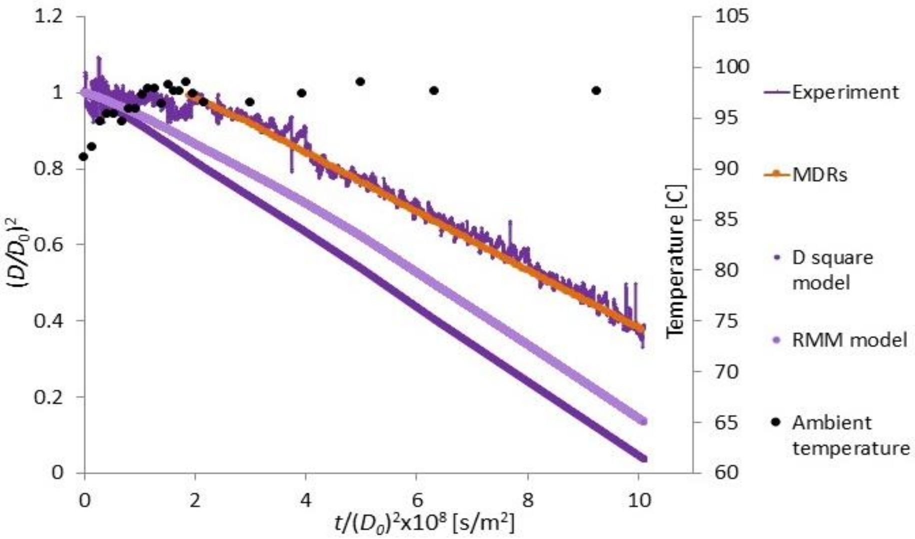

Figure 3: Effects of temperature changes on the evaporation rates of the pentadecane droplet surface at the ambient temperatures between 91-98°C

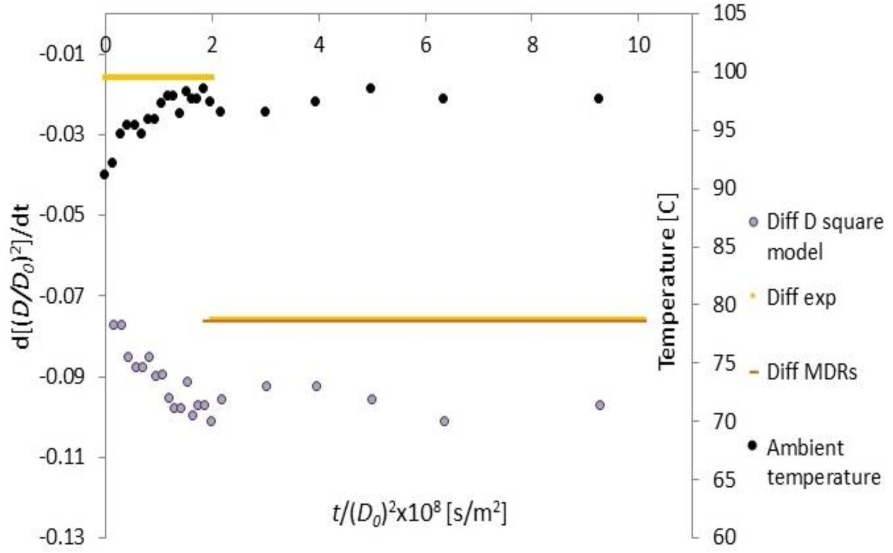

Figure 4: Effects of temperature changes on the evaporation rate changes of the pentadecane droplet surface at the ambient temperatures between 91-98°C

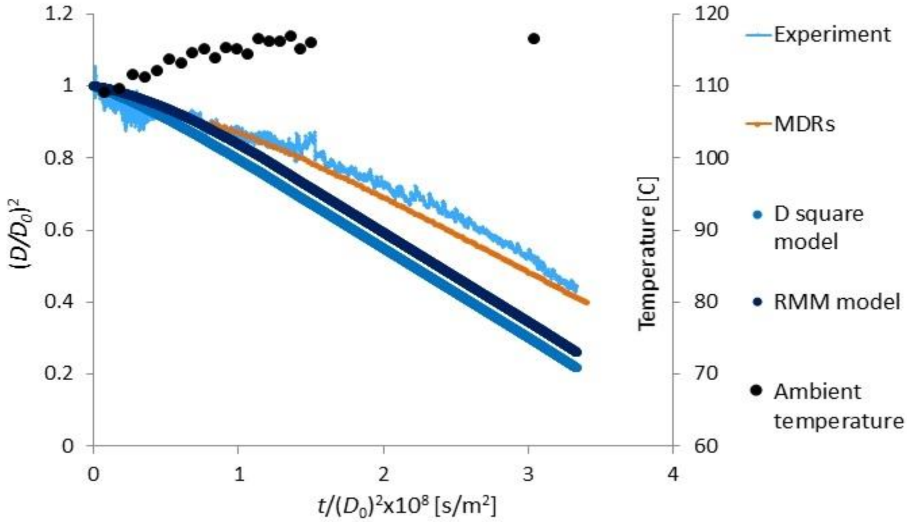

Figure 5: Effects of temperature changes on the evaporation rates of the pentadecane droplet surface at the ambient temperatures between 110-118°C

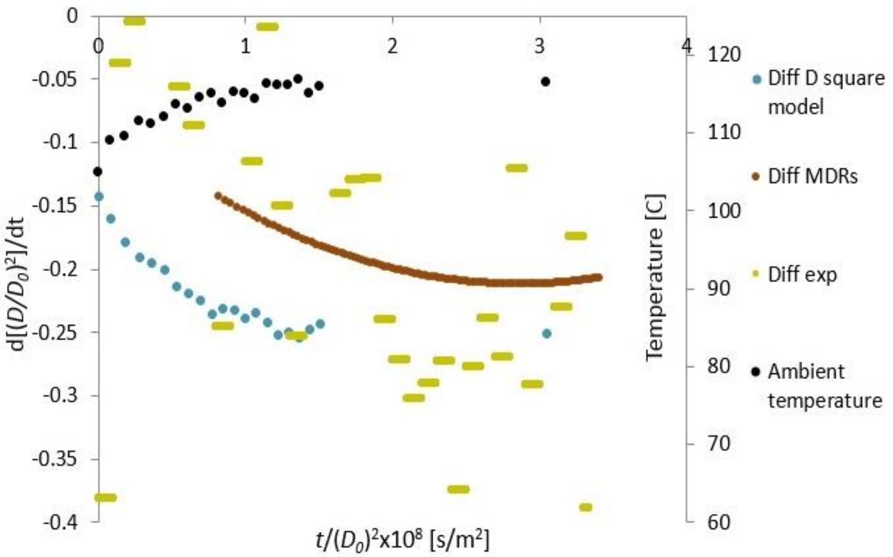

Figure 6: Effects of temperature changes on the evaporation rate changes of the pentadecane droplet surface at the ambient temperatures between 110-118°C

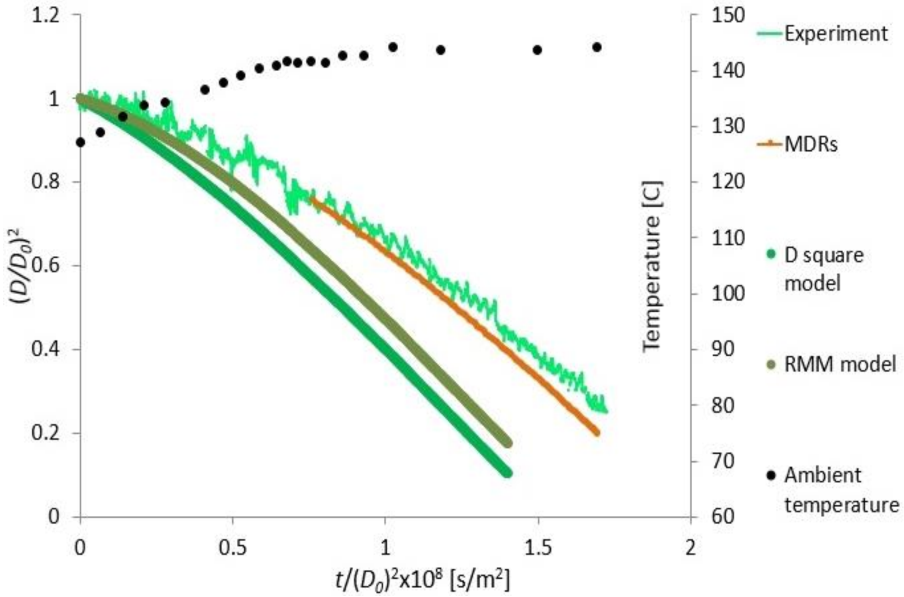

Figure 7: Effects of temperature changes on the evaporation rates of the pentadecane droplet surface at the ambient temperatures between 129-145°C

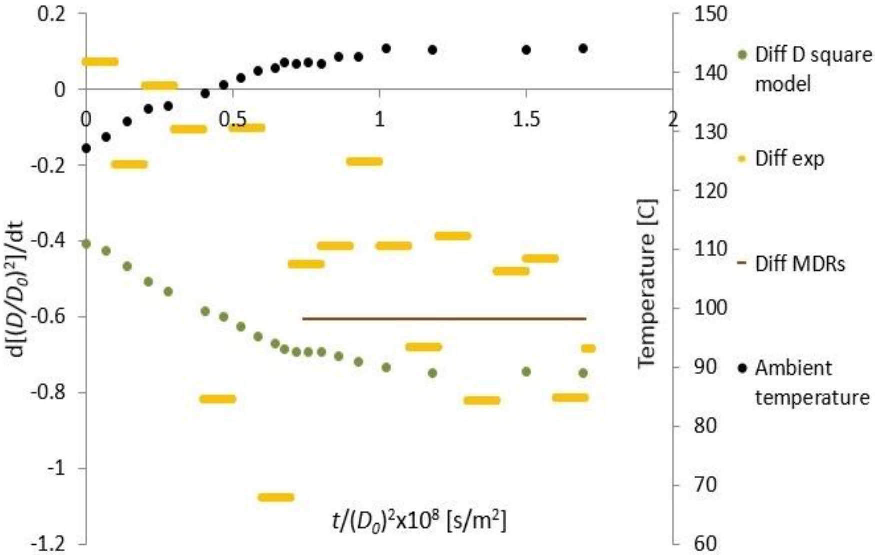

Figure 8: Effects of temperature changes on evaporation rate changes of the pentadecane droplet surface at the ambient temperatures between 129-145°C

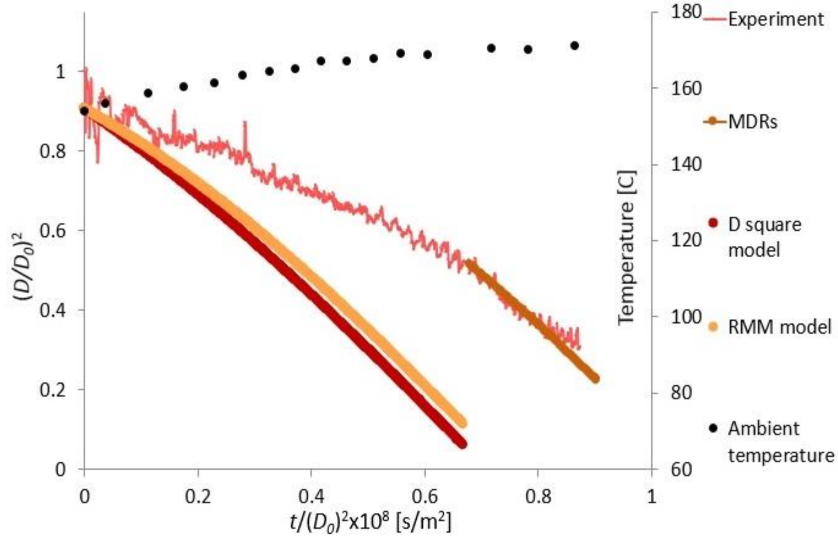

Figure 9: Effects of temperature changes on the evaporation rates of the pentadecane droplet surface at the ambient temperatures between 155-170°C

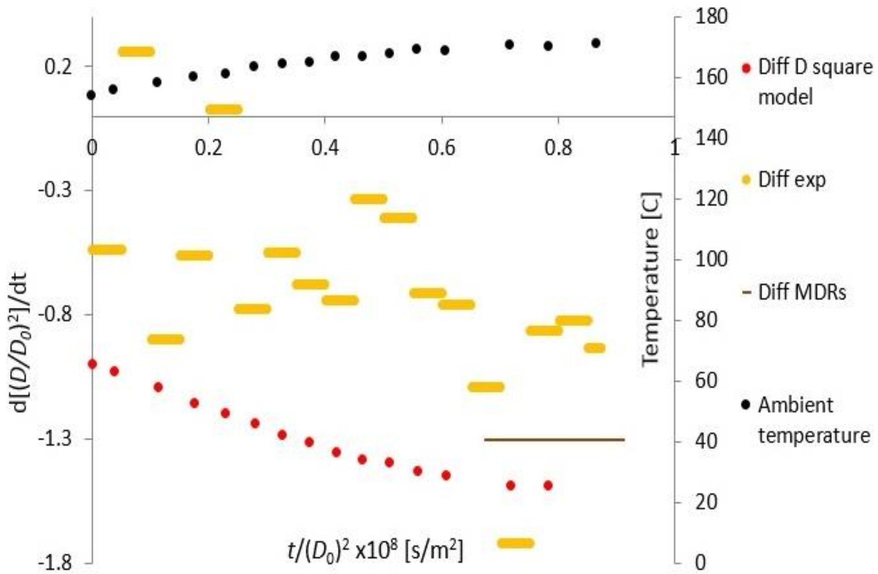

Figure 10: Effects of temperature changes on the evaporation rate changes of the pentadecane droplet surface at the ambient temperatures between 155-170°C

3.2 Effects of Ambient Air Velocities on the Evaporation Rates

Figures 11, 13, 15 and 17 present the effects of ambient air velocities on the evaporation rates of a pentadecane single droplet at the ambient temperatures of 91-98, 110-118, 129-145 and 155-170°C, respectively. Figures 12, 14, 16 and 18 show the effects of the ambient air and relative velocities on the evaporation rate changes of a pentadecane single droplet at the ambient temperatures of 91-98, 110-118°C, 129-145 and 155-170°C respectively. The droplet velocities and ambient air velocities are suddenly decreased when the valve is closed. This indicated that the air velocities around the droplets have no influence on the droplet evaporation rates and the evaporation rate changes. This may be due to the small relative velocities between the droplets and the air (at the ambient temperatures of 91-98, 129-145 and 155-170°C, the value is 1 cm/s, while it is 2 cm/s at 110-118°C) in comparing to the velocities of the droplets and the air. It can be conclude that the parameter which give the most influence on the droplet evaporation rates and the evaporation rate changes is the ambient temperatures which have already mentioned and discussed in topic 3.1.

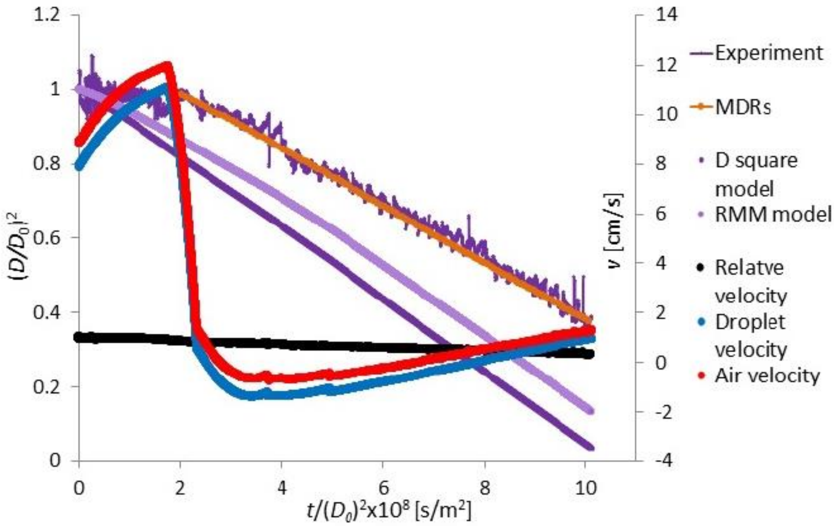

Figure 11: Effects of the ambient air and relative velocities on the evaporation rates of the pentadecane single droplet surface at the ambient temperatures between 91-98°C

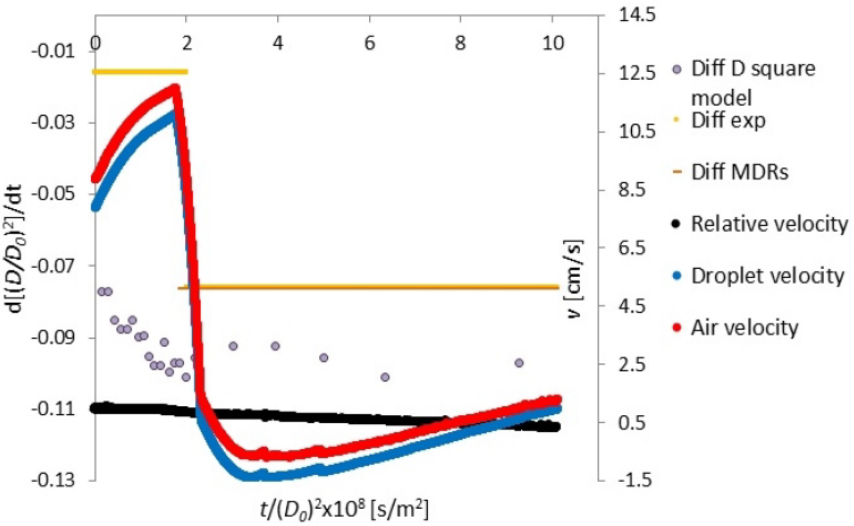

Figure 12: Effects of the ambient air and relative velocities on the evaporation rate changes of the pentadecane single droplet surface at the ambient temperatures between 91-98°C

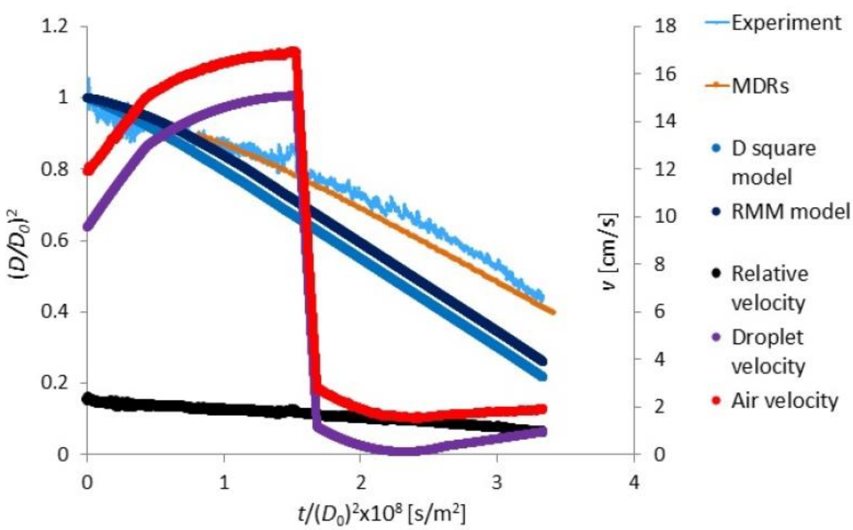

Figure 13: Effects of the ambient air and relative velocities on the evaporation rates of the pentadecane single droplet surface at the ambient temperatures between 110-118°C

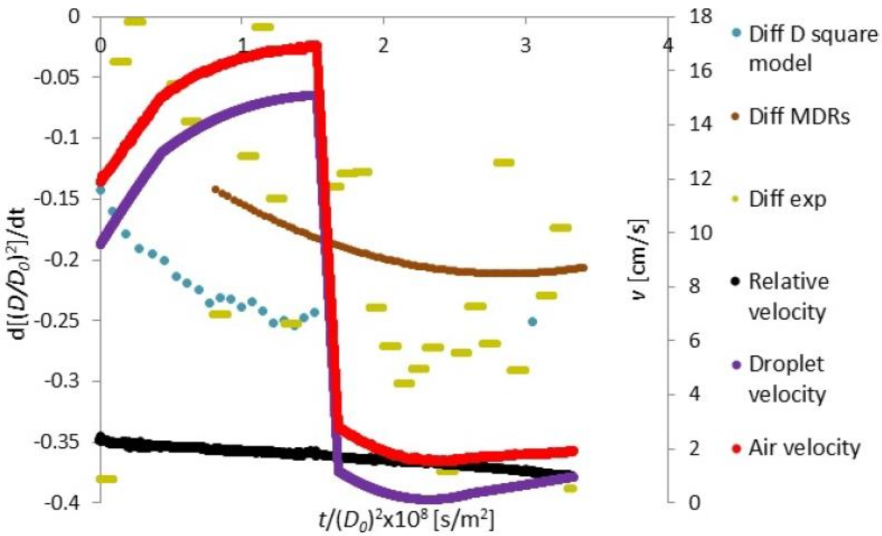

Figure 14: Effects of the ambient air and relative velocities on the evaporation rate changes of the pentadecane single droplet surface at the ambient temperatures between 110-118°C

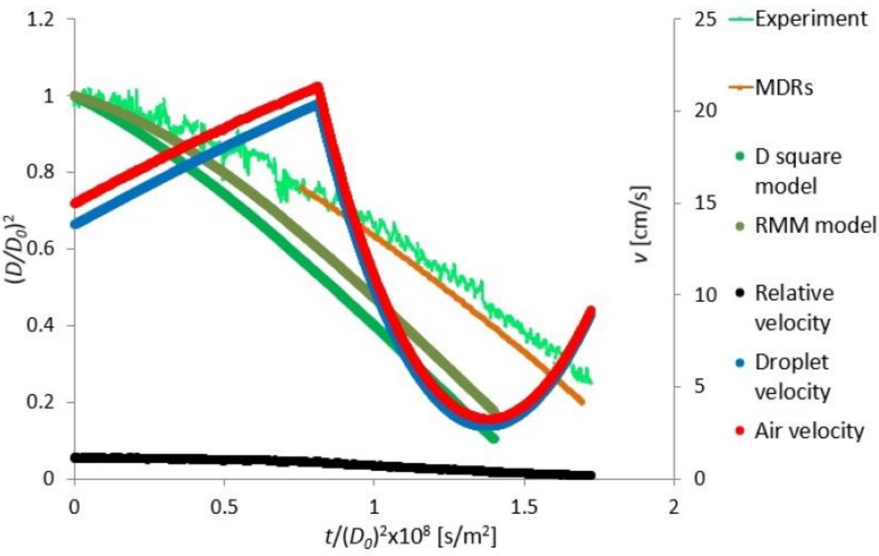

Figure 15: Effects of the ambient air and relative velocities on the evaporation rates of the pentadecane single droplet surface at the ambient temperatures between 155-170°C

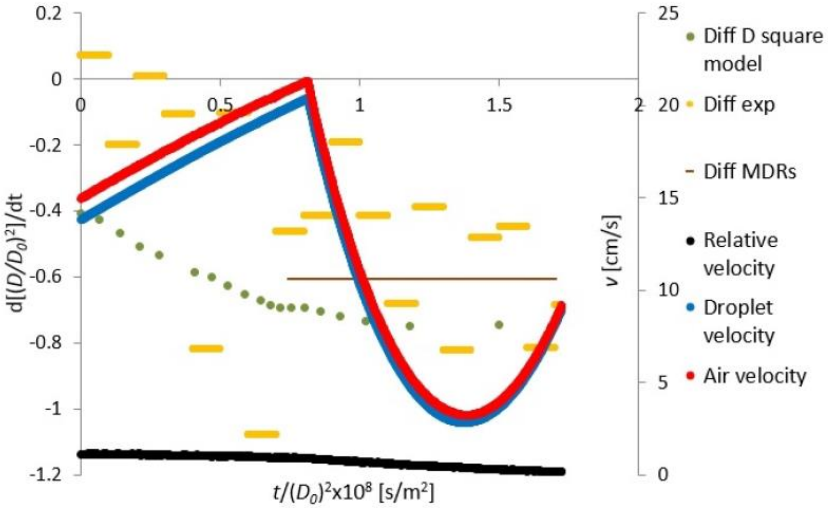

Figure 16: Effects of the ambient air and relative velocities on the evaporation rate changes of the pentadecane single droplet surface at the ambient temperatures between 155-170°C

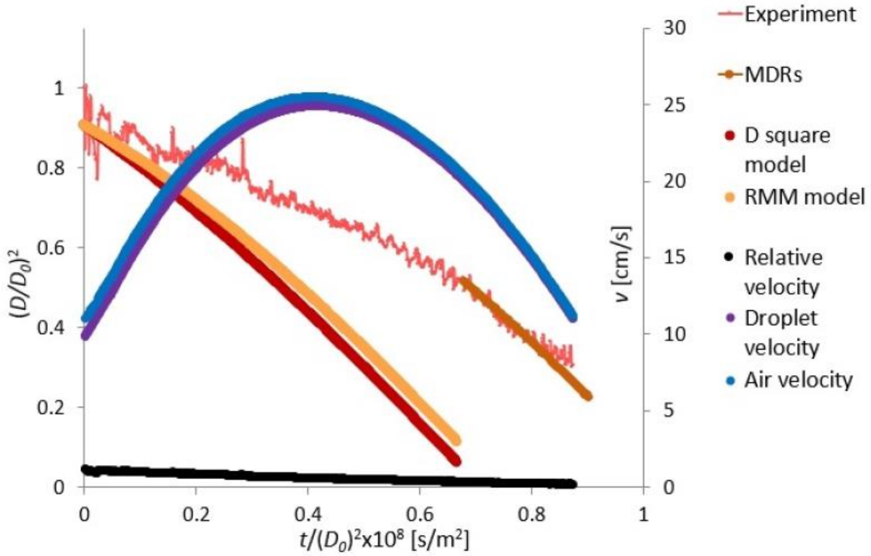

Figure 17: Effects of the ambient air and relative velocities on the evaporation rates of the pentadecane single droplet surface at the heater temperatures between 155-170°C

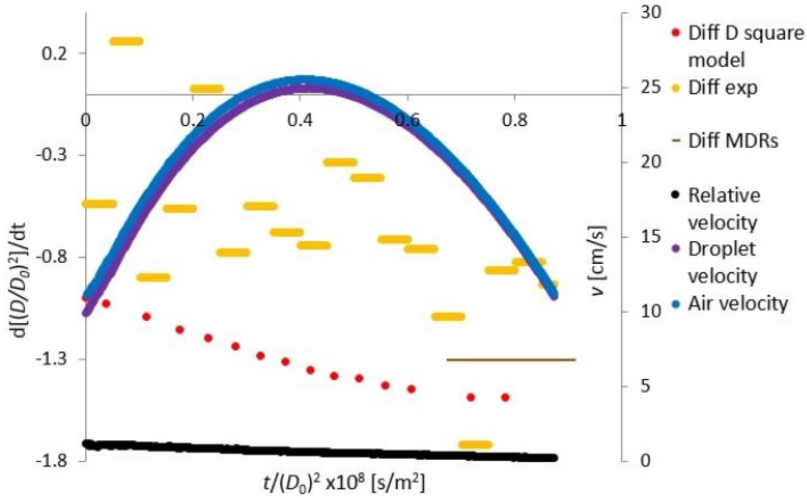

Figure 18: Effects of the ambient air and relative velocities on the evaporation rate changes of the pentadecane single droplet surface at the ambient temperatures between 155-170°C

Effects of Volume Fractions on the Evaporation Rates

Figures 19, 21 and 23 show the effects of ambient temperature changes on the evaporation rates of the pentadecane and dodecane surface droplet at the volume ratios of 3:1, 1:1 and 1:3 at the ambient temperatures between 91-98 °C, respectively. Figures 20, 22 and 24 display the effects of the ambient temperature changes on the evaporation rate changes of the pentadecane and dodecane surface droplet at the volume ratios of 3:1, 1:1 and 1:3 at the ambient temperatures between 91-98 °C, respectively.

All descriptions in all graphs are the same as in topic 3.1, except Diff RMM model is the differentiation of the surface diameter $(D/D_0)^2$ over time $t/(D_0)^2$ from the RMM (Rapid Mixing model). In this topic, RMM model is calculated by Marlan [11]. As mentioned earlier, evaporation rates of the single component droplet depended only on the ambient temperatures. But, for the binary mixture, the evaporation rates also depend on the volume fractions of the components. From Figure 20 (pentadecane and dodecane at 3:1 volume ratio), Diff exp, Diff MDRs and Diff RMM model values increased with the increase of the pentadecane (low volatile) volume fraction and then are constant due to the remaining of the lower volatile substance (pentadecane) in the droplet. The trend of Diff MDRs from Figure 22 (pentadecane and dodecane at 1:1 volume ratio) and Diff RMM from Figures 22 and 24 (pentadecane and dodecane at 1:1 and 1:3 volume ratios) are similar to that in Figure 20 (pentadecane and dodecane at 1:1 volume ratio).

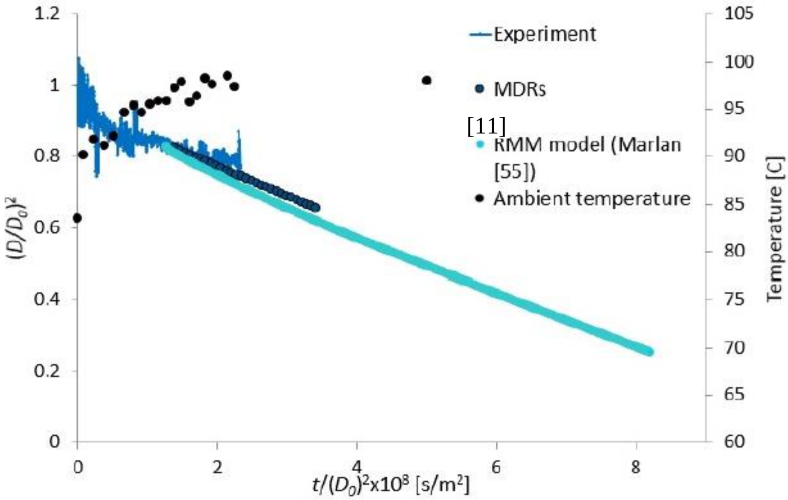

Figure 19: Effects of the ambient temperature changes on the evaporation rates of the pentadecane and dodecane droplet surface at 3:1 volume ratio of the ambient temperatures between 91-98°C

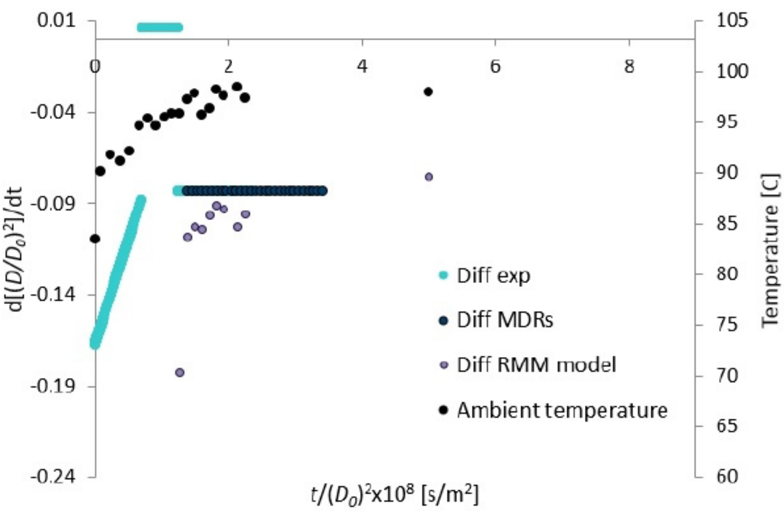

Figure 20: Effects of the ambient temperature changes on the evaporation rate changes of the pentadecane and dodecane droplet surface at 3:1 volume ratio of the ambient temperatures between 91-98°C

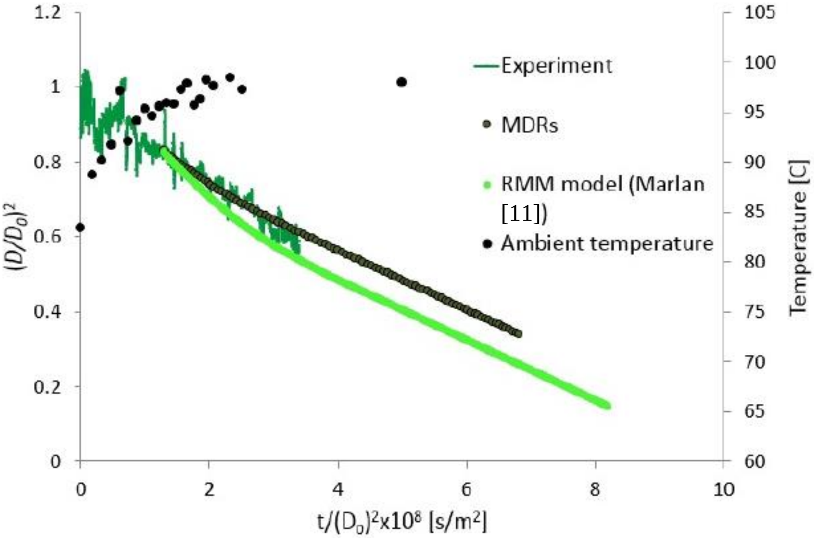

Figure 21: Effects of the ambient temperature changes on the evaporation rates of the pentadecane and dodecane droplet surface at 1:1 volume ratio of the ambient temperatures between 91-98°C

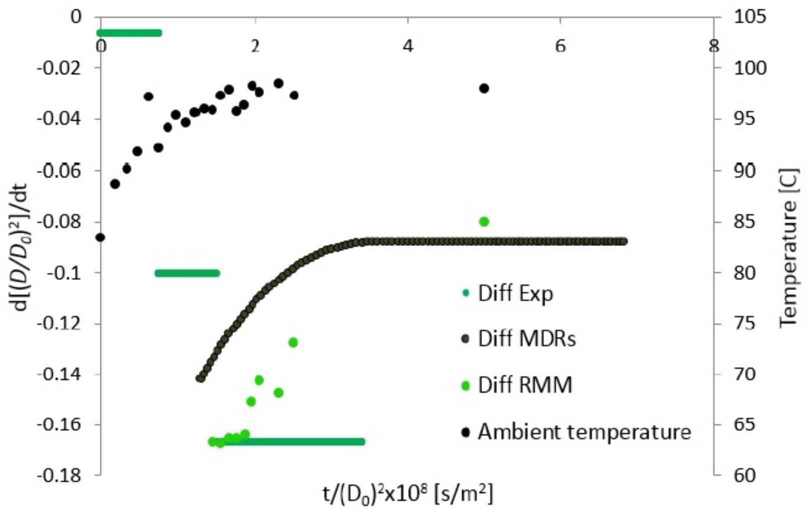

Figure 22: Effects of the ambient temperature changes on the evaporation rate changes of the pentadecane and dodecane droplet surface at 1:1 volume ratio of the ambient temperatures between 91-98°C

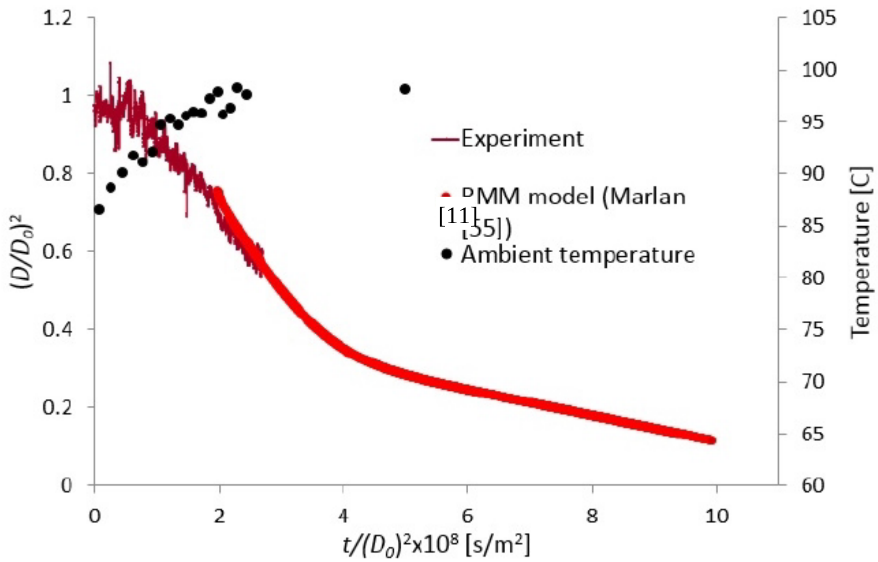

Figure 23: Effects of the ambient temperature changes on the evaporation rates of the pentadecane and dodecane droplet surface at 1:3 volume ratio of the ambient temperatures between 91-98°C

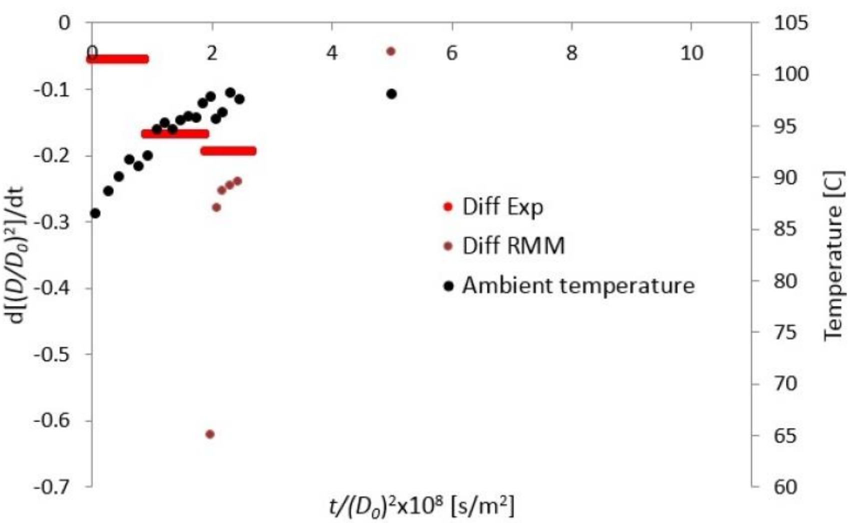

Figure 24: Effects of the ambient temperature changes on the evaporation rate changes of the pentadecane and dodecane surface droplet at 1:3 volume ratio of the ambient temperatures between 91-98°C

However, the Diff exp value increase due to the error from the linear regression calculation caused by noises during the experiment as shown in the experimental results of Figures 21 and 23. This indicated that the effects of volume fraction changes is more than that of the ambient temperature changes at the ambient temperatures between 91-98°C. The pentadecane volume fraction have been previously [12] reported that during the experiment, the volume fractions of pentadecane varied from 0.89 to 1 in the case of 3:1 volume ratio, 0.72 to 1 in the case of 1:1 volume ratio and 0.33 to 1 in the case of 1:3 volume ratio. The measured volume fractions of pentadecane in all cases are more than the initial mixing volume ratios of pentadecane because the measurement start after the droplets reach the heated chamber (according to Figure 1). Hence, for the binary mixture single droplet, the effects of volume fraction changes are the most influent parameter. It has more effect than the ambient temperatures at the ambient temperatures between 91-98°C.

The measurement uncertainties is ±10%. The further details can be found in Manosroi [12].

Conclusion

The evaporation rates increase with increased ambient tempertures. The ambient air velocities around the droplets have no influence on the droplet evaporation rates and the evaporation rate changes. This may be due to the small relative velocities between the droplets and the air. For the single component droplet, the most influence on the droplet evaporation rates and the evaporation rates changes is the ambient temperatures. For the binary mixture droplet, the most influence on the droplet evaporation rates and the evaporation rates changes is the volume fractions.

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