

Experimental Investigation of Microexplosion Occurrence in Water in Diesel Emulsion Droplets during the Leidenfrost Effect

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ABSTRACT: Microexplosion phenomenon is attributed for achieving simultaneous reduction of particulate matter and nitrogen oxides in diesel engine exhaust when water in diesel emulsion is used as fuel. In this work, an emulsion droplet suspended on a wire-type thermocouple on a hot plate as the heat source was used to study the evolution of microexplosion phenomenon of emulsions prepared by two different methods. Microexplosion behavior of emulsions produced by a homogenizer and mechanical stirrer with 5, 10, and 20% water by volume was visualized. A high-speed camera synchronized with a data-logging system was used to capture the events. The results show that the waiting time, puffing frequency, initial temperature drop, and microexplosion temperature were affected by the size and distribution of the dispersed water droplets. No microexplosion was observed for all of the homogenized emulsions, while all of the mechanically stirred emulsions developed microexplosions.

1. INTRODUCTION

Strategies to reduce pollutants from the combustion of diesel fuel include the admission of water into the fuel. Water in diesel emulsion is considered as a possible alternative fuel for reducing both particulate matter (PM) and nitrogen oxides (NO_x) from diesel engines. Studies showed that water emulsified in fossil fuels used in all combustion systems not limited to compression-ignition (CI) engines can lead to reductions in the adiabatic flame temperature, resulting in measurable reductions of NO_x emissions.^{1–4} While the presence of water acts as a heat sink,⁵ during combustion it reduces the formation rate of soot particles and enhances their burnout by an increased concentration of oxidation species, such as OH .⁶ Because of the difference in the evaporation rates of liquid diesel and water, the water molecules reached their superheated stage faster than the diesel, creating vapor expansion breakup. It is at this stage that the two phenomena, microexplosion and puffing, exist. Microexplosion is the rapid breakup of the emulsion droplets into smaller droplets, while in puffing, water leaves the droplets in a very fine mist. These microexplosions result in a fast breakdown or secondary atomization of the fuel droplet, which, in turn, causes rapid fuel evaporation and, hence, leads to an improved air-fuel mixing. Despite water in diesel emulsion (WiDE) being the most effective method to reduce NO_x and PM simultaneously, Cherng et al.⁷ reported that the emulsion with a mean dispersed water droplet size of $2.1 \mu\text{m}$ combusted in a multi-cylinder diesel engine has produced higher NO emissions. This can be correlated to the outcome of single-droplet experiments by Kimota et al.⁸ with water/heavy oil emulsion and Califano et al.⁹ with water/diesel emulsion. They endorse that too small diameter water droplet and uniform distribution will lead to either weak or no microexplosion. This state is can be attributed for the increase NO emissions, when WiDE with very small water droplet size is used as fuel. Available information on emulsified single-droplet experiments were limited to the study of base fuel, such as kerosene,¹⁰ sunflower oil,¹¹ *n*-hexadecane,¹² and *n*-decane.¹³ Information on water in diesel emulsion⁹ by the Leidenfrost

effect is scarce. Hence, the current study addresses the microexplosion evolution of WiDE blended by two different methods, i.e., mechanically stirred and homogenized, enabling the determination of the influence of the distribution and dispersed water droplet size on microexplosion occurrence. Microexplosion temperature, temperature drop, waiting time, and change in emulsion droplet diameter were also discussed.

2. EXPERIMENTAL SECTION

The experiment includes setting up a visualization technique to capture the evolution of microexplosion and laboratory preparation of WiDE samples. The current experimental study targets the examination of the evolution of microexplosion phenomenon of a WiDE droplet suspended on a thermocouple wire, which was brought to a close contact with a hot plate. To eliminate the droplet from being evaporated rapidly, the Leidenfrost regime was maintained throughout the study. The microexplosion phenomenon was studied by capturing a series of images of the event and data logging the corresponding temperature.

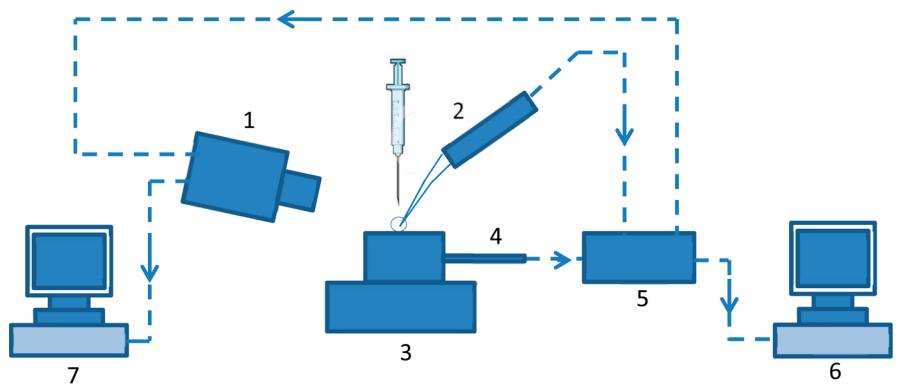
2.1. Visualization Technique. Figure 1 shows the schematic diagram for the microexplosion visualization technique. A National Instrument controller (5) was employed to trigger the high-speed camera (1) for image capturing and recording of both the measured temperatures of the hot plate (3) and suspended emulsion droplet from the respective thermocouples (2 and 4).

PHOTRON FASTCAM-X 1280PCI high-speed camera was used to capture the microexplosion event. The camera was triggered at a predefined temperature of 140°C for all WiDE samples. The captured image were analyzed for waiting time, coalescence or phase change, and change in droplet diameter by PHOTRON FASTCAM Viewer-3 software. The image acquisition rate was set at 500 fps with the resolution of 1280×1024 pixels through the experiment. A square aluminum plate of $100 \times 100 \times 10$ mm thick with a mirror surface finish was used as the hot plate. The plate temperature was maintained at 500°C throughout the study by digital temperature control. A syringe with a 0.8 mm diameter orifice was used to dispense the

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1. High Speed Camera 2. Thermocouple for droplet temperature 3. Hot plate 4. Thermocouple for hot plate temperature 5. N.I. Controller 6&7. PC for Data Acquisition and Image processing.

Figure 1. Schematic diagram of the experimental setup for the visualization technique.

droplet onto the end point of the thermocouple, and the droplet was suspended above the hot plate. The diameter of the suspended droplet was about 3.6 mm. The gap between the thermocouple and the hot plate was kept at 2 mm with the help of a feeler gauge. A K-type thermocouple with a wire diameter of 200 μm was used to measure the droplet temperature. A Leica KL2500 light reflector lamp was used as the source for illumination. Two separate computers were used to record the temperatures from the NI controller and captured images, respectively.

The WiDE samples were characterized for density, surface tension, and particle distribution. The densities of WiDE samples were measured using an Anton Paar density meter DMA 4500M at 20 °C, while the surface tension was measured by the pendant drop method. A syringe with an orifice diameter of 0.5 mm was used to form the drop, and it was photographed using a digital camera. The shape of the drop was evaluated using software SCA-20, and measurements were recorded at 20 °C. The water droplet and distribution were captured using a Leica DMLM microscope, and measurements were made using software Dino-Capture. The volume of the suspended droplet was obtained by individually weighing each emulsion droplet 3 times and deposited on a digital scale with known density. The surrounding atmosphere conditions were assumed to be constant, so that its influence on the experimental outcomes was negligible.

2.2. WiDE Preparation. The WiDE samples were prepared by blending distilled water into the diesel fuel at diesel/water ratios of 95:5, 90:10, and 80:20. The emulsions were stabilized by adding in-house-developed surfactant with 1.5% water volume. Two different types of blending were employed, i.e., mechanical stirrer (case A) and homogenizer (case B), as shown in Table 1. The blending methods

positioned at different angles fitted to an electric motor capable of rotating at 20 000 rpm was used to blend.

3. RESULTS AND DISCUSSION

The results from the analysis of the WiDE samples are discussed first, followed by the observation of microexplosion.

3.1. Emulsion Size and Distribution. The images of WiDE samples examined under an optical microscope at 100 \times for mechanical stirring and 400 \times for homogenization to observe the water particle size and distribution are shown in Figure 2. It can be seen from the images of the mechanically stirred emulsions (case A) that the distributions of particles were uneven with variation in particle sizes and fragmented. Whereas, in the homogenized emulsion (case B), the dispersed particles were very fine with small size variations and uniformly distributed. It is also noted that the prepared emulsions were stable with the presence of sedimentation after 336 h for homogenized emulsions and 3 h for stirred emulsions. No layer separations were observed during the observation period of 336 h.

The results of physical properties of the WiDE samples are shown in Table 2. The density of the emulsion increases with an increase in the amount of water in the emulsion. This is attributed to the higher density of water that is being added to diesel fuel, which is of lower density. It is found that the surface tension of homogenized emulsions remained almost constant, whereas in the case of mechanically stirred emulsion, the surface tension was found to decrease with increasing water content.

3.2. Microexplosion Phenomenon of Case A Emulsions. The experimental setup used in the present study follows that by Mura et al.¹¹ Initially, the hot plate temperature was maintained at 363 °C, similar to the work. However, the Leidenfrost effect was not attained. Hence, the temperature was gradually increased until the desired Leidenfrost effect was obtained at 500 °C, and thereafter, this temperature was maintained throughout the experiment. This difference in temperature to attain a Leidenfrost effect can be attributed to the material used as the hot plate and its surface finish. In addition to this, the base fuel used by Mura et al.¹¹ was sunflower oil, whereas the present study involves commercial diesel. The boiling temperature is different for sunflower oil and diesel.¹⁴ Mura et al.¹⁵ also confirms that the presence of a thermocouple is not predominant in promoting the microexplosion phenomenon. Another study by Califano et al.⁹

Table 1. WiDE Preparation Matrix

	case A			case B		
blending	mechanical stirrer			homogenizer		
time	100 s			30 min		
speed	20000 rpm			3000 rpm		
WiDE	95:5	90:10	80:20	95:5	90:10	80:20

enabled the observation of variations in sizes and distributions of water particles. First, the required amount of surfactant was mixed to the distilled water until it dissolves completely; then commercial diesel compliance with Euro 2 norms is added; and the mixture undergoes either a homogenizing or blending process. In the homogenizing process, the mixture was made to pass between a stator and a rotor spaced at 50 μm gap with a rotating speed of 3000 rpm for 30 min. During the process, the droplet size was sheared into a micro size level in the order of 1–2 μm . Case A emulsion was prepared by mixing surfactant to the distilled water first until it dissolved before diesel was added to the mixture. A customized stirrer made out of five blades

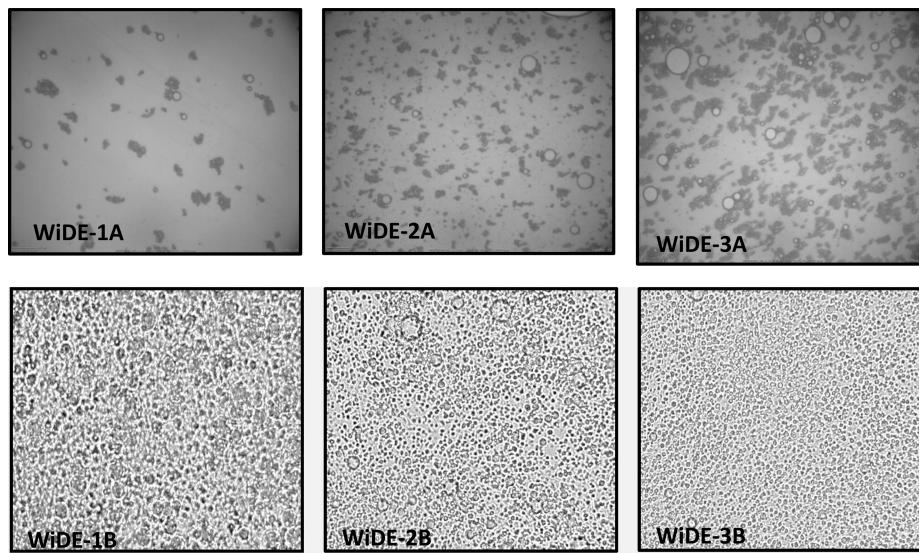


Figure 2. Images of WiDE samples depicting droplet distribution with 100 \times and 400 \times magnification.

Table 2. Physical Properties of WiDE Samples

	sample ID	density at 20 °C (kg/m ³)	surface tension at 20 °C (mN/m)	average size of dispersed water particle (μ m)	average volume of suspended droplet (mL)
case A	WiDE-1A	847.85	25.01	33.42	0.013
	WiDE-2A	857.81	22.82	32.43	
	WiDE-3A	870.41	19.01	30.70	
case B	WiDE-1B	849.76	25.23	1–2	0.010
	WiDE-2B	854.44	25.75		
	WiDE-3B	870.17	25.51		

supports that the behavior of the droplet with and without a thermocouple remains the same. Pertaining to these findings, the present study did not consider the presence of the thermocouple in the event of microexplosion phenomenon. Because WiDE was at room temperature, the initial contact of the WiDE droplet with the thermocouple caused its temperature to suddenly drop before rising again. Once the temperature reached 140 °C, the camera was triggered and the droplet images were captured along with corresponding temperatures. From the captured images, the suspended droplet was initially opaque because of the reflection of the light and the presence of water particles for both cases A and B.

Figure 3a shows the evolution of microexplosion for WiDE-1A with 5% water. The increase in the temperature of the

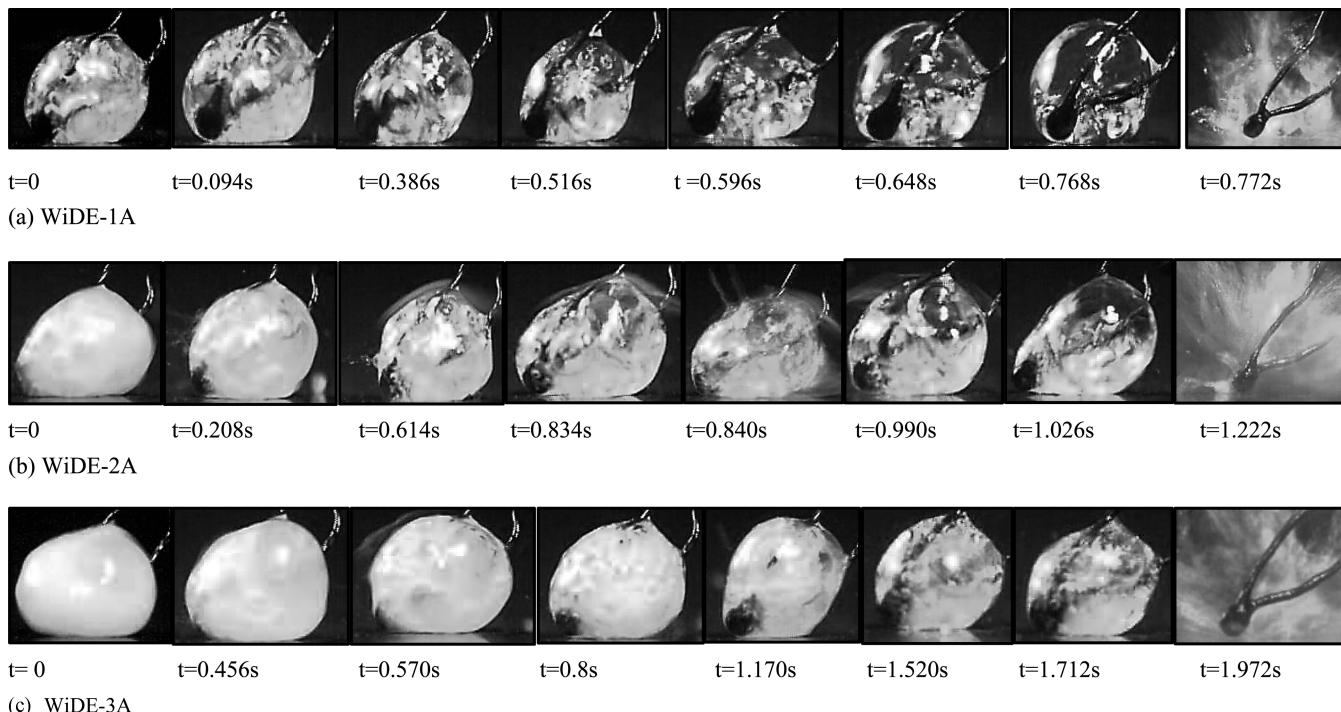


Figure 3. Sequence of images showing microexplosion behavior of case A WiDE.

droplet enhances the aggregation and coalescence, which were visible between $t = 0.094$ and 0.516 s. The droplet became transparent followed by water boiling and finally microexplosion at $t = 0.772$ s. The explosion temperature was recorded at 155°C . In the case of WiDE-2A with 10% water, more intensive and frequent puffing were observed compared to WiDE-1A, as shown in Figure 3b. The starting point of puffing occurred when $t = 0.208$ s. Puffing was observed 7 times in WiDE-1A and 12 times in WiDE-2A before microexplosion. The phase change began and led to a semi-transparent droplet between $t = 0.614$ and 1.026 s. Finally, microexplosion of the droplet occurred at $t = 1.222$ s with a temperature recorded at 139.5°C without attaining complete transparency. Evolution of microexplosion of WiDE-2A took a comparatively longer time than WiDE-1A. Qualitatively, a similar behavior was observed in the case of WiDE-3A with 20% water. However, the whole event of microexplosion took a time span of 1.972 s, as shown in Figure 3c, which is 2.5 times longer than WiDE-1A and 1.6 times longer than WiDE-2A. The explosion temperature was at 153°C . In addition, puffing was observed 15 times in WiDE-3A. The difference in microexplosion waiting time and temperature among the emulsions in case A can be attributed to the amount of water content and particle diameter. Figure 4

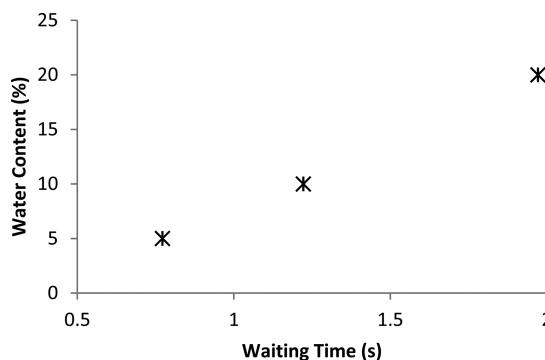


Figure 4. Water content versus waiting time of case A WiDE.

represents the relation between the water content and waiting time for microexplosion. This leads the researchers to believe that the smaller the water droplet size, the longer the waiting time would be. The influence of a surfactant in the duration of microexplosion is not considered because the same proportion of surfactant was maintained in all of the WiDE samples.

For all three WiDE samples in case A, it was well-noticed that, as the temperature of the droplet increased, the rate of change of water into vapor also rapidly increased, which causes the disruption of the primary droplet and violent ejections of smaller droplets into the atmosphere. These secondary droplets evaporated rapidly and were dispersed in a big volume, thus improving the air-fuel mixture. Violent ejections of smaller droplets visually observed from the parent droplet were found to be increasing with an increased water content in the emulsions; hence, the amount of ejection was higher for WiDE-3A compared to the two other case A emulsions.

3.3. Evolution Behavior of Case B Emulsions. Evolution behaviors of case B homogenized emulsions are shown in a series of images in Figure 5. The moment that WiDE-1B with 5% water touches the thermocouple, the volume of the droplet increases until $t = 0.608$ s. The droplet reduced in size simultaneously during the phase change, which started from the top of the droplet toward the bottom surface, i.e., from opaque

or milky white to transparent clear droplet. During the phase-change process, numerous tiny bubbles had formed and combined to form bigger bubbles, which lead to puffing.

The start of phase change was noticed at $t = 0.140$, 0.148 , and 0.154 s for WiDE-1B, WiDE-2B, and WiDE-3B, respectively. The duration of complete phase change was at $t = 0.818$, 1.154 , and 1.330 s, respectively.

Ejected water particles were roughly tiny size compared to those in case A emulsions. The water particles in case B emulsions were too small ($1\text{--}2\ \mu\text{m}$) and uniformly distributed, which attributed to more stable emulsions. These caused a low rate of coalescence; hence, the formation of the transparent region takes longer compared to that in case A emulsions. This confirms the findings by Califano et al.⁹ and Mura et al.¹¹ The frequency of puffing was high in all case B emulsions (19 times in WiDE-1B, 26 times in WiDE-2B, and 20 times in WiDE-3B) which led to reduction of the droplet volume, changing the water droplet sphere shape. This observation was in agreement with that by Suzuki et al.¹⁰

Figure 6 represents the change in diameter of each suspended droplet with respect to time (in accordance with images obtained) for case B emulsions. Once the bubble formation was saturated, the droplet was found to be less excited and eventually behaved very similar to the evaporation of pure diesel.

3.4. Temperature Profiles of Case A and Case B Emulsions.

Temperature profiles of cases A and B were plotted in Figures 7–9 for the 5, 10, and 20% water, respectively. The plot represents the temperature of a single droplet for each case corresponding to the images in Figures 3 and 5. The free thermocouple temperature was maintained at 370°C . For the 5% water temperature profile shown in Figure 7, the lowest temperature recorded for the initial contact of the droplet with the thermocouple was 136 and 144°C for case A and case B emulsions, respectively. The temperature drop for case 1A was 234°C , and the temperature drop for case 1B was 226°C , from the free thermocouple temperature.

Figure 7 also depicts that, for case A emulsions, the same temperature was maintained for $t = 0.430$ s, rose to 155°C within 10 ms, and was maintained until $t = 0.330$ s and, subsequently, microexplosion occurred, whereas the initial temperature for case B emulsion droplet lasts up to $t = 0.850$ s and gradually rises to 222°C at $t = 1.710$ s. The complete evaporation time for case B emulsions is not shown in the graph.

Figure 8 shows the temperature profiles for 10% water of both case A and case B emulsions. The initial temperature of case 2A emulsion droplet was about 114°C for an interval of $t = 0.420$ s, increased to 139.5°C , and was maintained at this temperature before explosion. Case 2B emulsion recorded a minimum temperature of 130.6°C for $t = 0.840$ s and then to 212°C at $t = 2.060$ s, comparatively longer than case 1B. The temperature drop of 256°C was recorded for case 2A, whereas it was 230.5°C for case 2B emulsion.

Temperature profiles for 20% water are shown in Figure 9. Case 3A recorded an initial temperature of 126°C and further declined to 110°C in 440 ms, which is 260°C less than the free thermocouple temperature. The droplet reached a temperature of 153°C and was stable for 300 ms before microexplosion occurred. Case 3B attained a low temperature of 125°C , a decline of 245°C from the free thermocouple temperature, and recorded a rise of 23°C to reach 148°C over a time interval of 820 ms. For the shown time frame, it reached

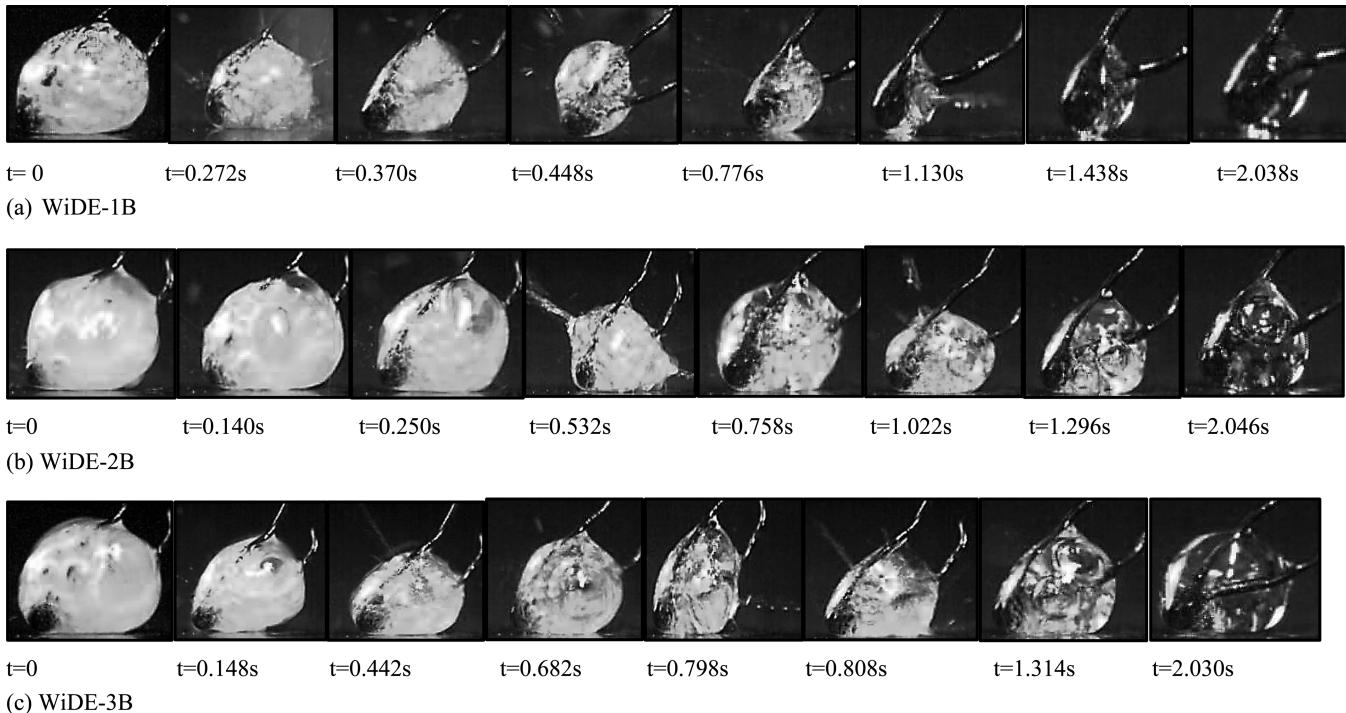


Figure 5. Sequence of images showing evolution behavior of case B WiDE.

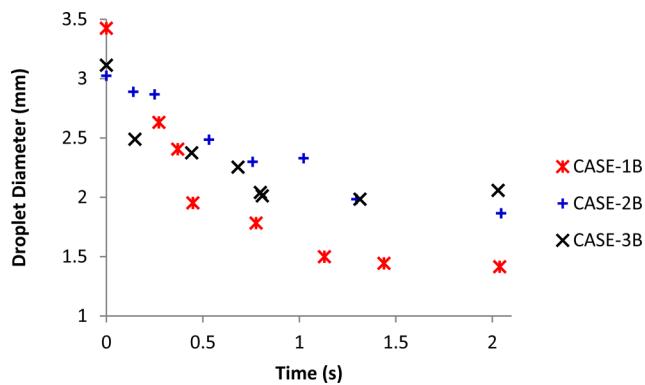


Figure 6. Droplet diameter versus time of case B WiDE.

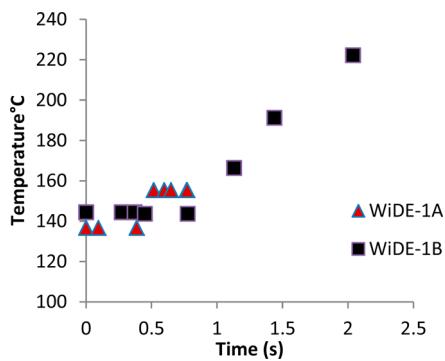


Figure 7. Temperature profile of 5% water.

a maximum temperature of 216 °C. In summary, it was evident from the temperature profiles for both case A and case B emulsions that the temperature drop increased with the increased water content, but in the case of case B, the rise was comparatively less than that in case A emulsion.

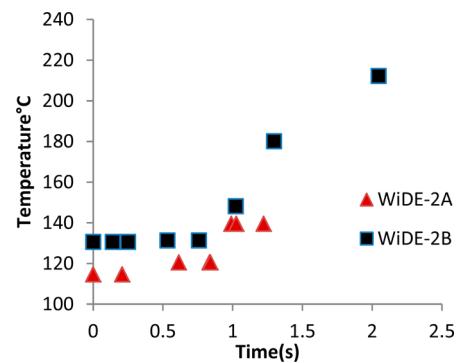


Figure 8. Temperature profile of 10% water.

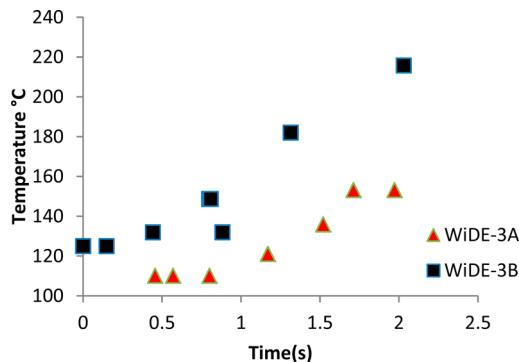


Figure 9. Temperature profile of 20% water.

4. CONCLUSION

The temperature profiles and evolution of microexplosion phenomena of mechanically stirred and homogenized emulsions with different proportions of water content were experimentally studied. The outcome of the results can be

summarized as follows: (1) Microexplosion was observed for all samples of mechanically stirred emulsions, while no microexplosion can be observed from homogenized emulsion. (2) The particle sizes and distribution of WiDE samples from mechanically stirred emulsion were larger and fragmented compared to those from homogenized emulsion. This lead to the suggestion that mechanically stirred emulsion induces a faster coalescence rate (or unstable) and, hence, developed microexplosion, whereas an even distribution (or more stable) with a narrow range of particles in homogenized emulsion slows the coalescence rate, resulting in a phase change but with no microexplosion. Thus, for microexplosion to occur, a faster rate of coalescence of a larger particle must exist. (3) The puffing rate was observed to be higher in case B emulsions than case A emulsions, resulting in droplet volume reduction of the droplet, and hence, reduction in the size of the droplet was observed. (4) The temperature drop with all cases of case A emulsion was found to be higher compared to that with all case B emulsions.

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Notes

The authors declare no competing financial interest.

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