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1 **Progress in experimental investigations on evaporation**
2 **characteristics of a fuel droplet**

3
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19 **Abstract**

20 Investigating the evaporation characteristics of a fuel droplet is critical for understanding
21 spray and combustion processes, which provides valuable information and guidance for
22 optimizing engine performance. This paper systematically reviews the droplet evaporation
23 characteristics of various fuels. Firstly, experimental methods for fuel droplet evaporation are
24 introduced, including flying droplet, suspension and levitation, of which the latter two are the
25 most widely applied due to their simple setups and convenient measurements. Secondly, droplet
26 evaporation mechanisms of different fuels are comprehensively discussed. The evaporation
27 process of single-component fuel droplets includes transient heating and equilibrium
28 evaporation phases. Miscible and immiscible multi-component fuel droplets could experience
29 puffing and micro-explosion phenomena, which increase droplet surface area and evaporation
30 rate. Droplet evaporation may be the best when light component concentration is around 50%
31 due to the strongest puffing and micro-explosion. The water droplets in emulsified fuel are
32 slightly superheated by 0 to 30 °C when micro-explosion occurs. Nanoparticles could enhance
33 droplet evaporation at low concentrations (0-1.25%) but inhibit droplet evaporation at higher
34 concentrations. Finally, future research directions of fuel droplets are elaborated. More
35 advanced experimental and numerical methods should be developed. Meanwhile, investigations
36 on droplet evaporation should be combined with spray and combustion.

37

38 **Keywords:** Liquid fuels; Fuel droplet; Evaporation characteristics; Puffing; Micro-
39 explosion

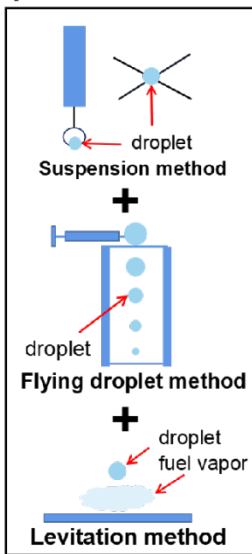
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41 **Highlights**

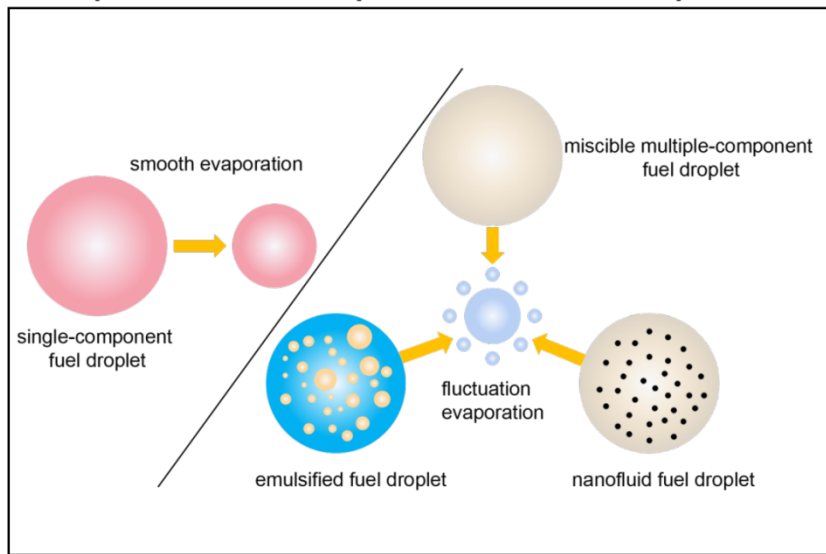
- 42 • Evaporation of single-component droplet includes transient heating and equilibrium
43 evaporation.
- 44 • Puffing and micro-explosion promote evaporation of multi-component fuel droplet.
- 45 • Bubble growth and rupture cause micro-explosion of miscible multi-component fuel
46 droplet.
- 47 • The dispersed phases in emulsion droplet aggregate and coalesce before micro-explosion.
- 48 • A lower concentration of nanoparticles enhances the evaporation rate of nanofluid fuel
49 droplet.

50 **Graphical abstract**

Experimental methods



Evaporation of fuel droplets with different components



51

52

53 Nomenclature

CO	Carbon monoxide
PM	Particulate matters
NO _x	Nitrogen oxides
HC	Hydrocarbons
ICE	Internal combustion engine
OA	Oleic acid
LA	Linoleic acid
ABE	Acetone-butanol-ethanol
FAME	Fatty acid methyl ester
BD	Biodiesel
GTL	Gas-to-liquid
d	Instantaneous droplet diameter
d_s	Support diameter
d_t	Thermocouple diameter
d_0	Initial droplet diameter
κ	Thermal conductivity
K	Evaporation rate constant
t	Heating time
m	Mass
ρ	Density
V	Volume
d^2/d_0^2	Normalized square diameter
t/d_0^2	Normalized time

54

55 **1. Introduction**

56 The rapid population and economic growth promote the use of automobiles for
57 transportation, which greatly increases the proportion of energy consumed by automobiles in
58 the total energy consumption from 23% in 1971 to 29% in 2015 [1, 2], emitting a large amount
59 of greenhouse gas emissions that cause global warming [3]. Meanwhile, the rapid increase in
60 the number of automobiles also poses a significant burden on the environment. Harmful exhaust
61 emissions such as carbon monoxide (CO), particulate matters (PM), nitrogen oxides (NO_x) and
62 hydrocarbons (HC) have caused serious air pollution [4, 5]. These problems are threatening
63 human health and survival [6, 7]. Therefore, improving the thermal efficiency and emissions
64 performance of internal combustion engines (ICEs) has become one of the hottest issues
65 concerned by the engine industry worldwide [8]. In recent years, searching for alternative fuels
66 such as biodiesels [9-11], alcohol fuels [12, 13] and emulsified fuels [14] is a major promising
67 solution for energy saving and emissions reduction of ICEs.

68 As far as liquid fuels are concerned, the form of their utilization in ICEs is to convert
69 chemical energy into heat energy through combustion, which drives the piston to output useful
70 work. Consequently, the quality of combustion process determines the performance of ICEs,
71 including torque, fuel economy and pollutant emissions. Fuel cannot be fully utilized under a
72 poor combustion, leading to decreases in output power and increases in fuel consumption and
73 pollutant emissions. Improving the spray evaporation characteristics of liquid fuels is the key
74 to optimize engine combustion [15].

75 Spray evaporation refers to the process that a fuel is injected by an injector to generate a
76 jet, which breaks up due to aerodynamic forces, and finally disperses into a large number of
77 droplets and mixes with air to form a combustible mixture [16]. However, it is difficult to
78 quantitatively investigate the spray evaporation characteristics by experimental methods due to
79 its complexity. Therefore, investigations on the evaporation of a fuel droplet are often used as
80 an alternative for revealing the underlying mechanisms of those processes [17]. In fact, many
81 droplets are formed after spray atomization and breakup, and droplet evaporation is the basis
82 and determines the performance of spray evaporation [18]. Therefore, investigations of a fuel
83 droplet are critical for characterizing and understanding spray evaporation [19]. Moreover,
84 spray eventually develops into discrete droplets that are far apart [20], which makes the

85 hypothesis of an isolated droplet reasonable. It is often necessary to study a droplet first when
86 studying the influence of engine operating conditions on fuel evaporation process [21].
87 Consequently, investigations on the heating and evaporation processes of fuel droplets are of
88 great significance for improving engine performance [22].

89 Many scholars have studied the fuel evaporation characteristics by investigating a fuel
90 droplet. A few reviews have also been published on specific aspects of droplet evaporation,
91 which can be divided in experimental studies and mathematical modelling.

92 1.1. Experimental investigations

93 Experimental investigations on the evaporation process of a fuel droplet provide the first
94 hand information on its evaporation characteristics, which is of significance for the applications
95 of a fuel in real engines. They also provide valuable information for the development and
96 validation of droplet/spray evaporation and combustion models. Thus, experimental
97 investigations are widely adopted for understanding the fuel droplet evaporation processes.
98 Birouk and Gokalp [23] introduced the effect of turbulence intensity on evaporation of a fuel
99 droplet. Téré et al. [24] described evaporation phenomenon and mechanisms of an isolated fuel
100 droplet and the impacts of natural and forced convection. Basu and Miglani [25] reviewed the
101 thermo-physical processes during the evaporation of a nanofluid fuel droplet and their
102 influencing factors (e.g. nanoparticle concentrations and types). Emekwuru [26] reviewed the
103 evaporation mechanisms of a nanofluid fuel droplet. It was summarized that nanoparticles could
104 facilitate droplet evaporation by increasing heat transfer to the droplet by radiation absorption
105 and causing droplet micro-explosion. Wang et al. [27] discussed the impact of nanoparticles on
106 fuel droplet evaporation at different ambient temperatures. They reported that nanoparticles
107 inhibited droplet evaporation at low temperatures, but increased droplet evaporation at high
108 temperatures due to micro-explosion.

109 1.2. Mathematical modelling

110 Mathematical modelling of fuel droplets could quantify the amount of evaporated fuel and
111 visualize its mixing and distribution in the ambient air, leading to more accurate simulations
112 under actual engine conditions. Therefore, numerical simulations were also commonly used to
113 understand the heating and evaporation of fuel droplets. Sazhin et al. [28] presented liquid and
114 gas phase models for fuel droplet heating and evaporation. Raghavan [29] reviewed the
115 numerical models that were used to simulate evaporation process of a fuel droplet under high

116 pressure conditions. Sazhin [30] introduced the modelling methods for the droplet evaporation
117 process, including Discrete Component Model (DCM) and Multi-Dimensional Quasi-Discrete
118 Model (MDQDM), and their applications for different fuel droplets. The development of gas
119 phase evaporation model was discussed and some unsolved problems were also proposed. Al
120 Qubeissi et al. [31] described DCM, MDQDM, Complex Fuel Surrogate Model (CFSM),
121 Transient Multi-Dimensional Quasi-Discrete Model (TMDQDM) and their implementations
122 into numerical codes.

123 1.3. Motivation and outline of this review

124 The above reviews mostly focused on the evaporation investigations of specific fuel
125 droplets (i.e. nanofluid fuel) and numerical investigations of fuel droplet evaporation. So far,
126 there is a lack of critical evaluation and review on experimental investigations of evaporation
127 characteristics of single- and multi-component fuel droplets. Recently, increasing experimental
128 investigations have been conducted to explore the evaporation characteristics of fuel droplets.
129 Therefore, this paper aims to systematically review and analyze the research findings on
130 evaporation characteristics of fuel droplets, including both single and multi-component fuels.
131 The multi-component fuels are further classified into miscible, liquid-liquid immiscible and
132 liquid-solid immiscible fuels. This paper focuses on the state-of-the-art progress on
133 experimental investigations of a fuel droplet with different components. This review should
134 provide helpful guidance on the scientific research and practical applications of fossil and
135 renewable fuels.

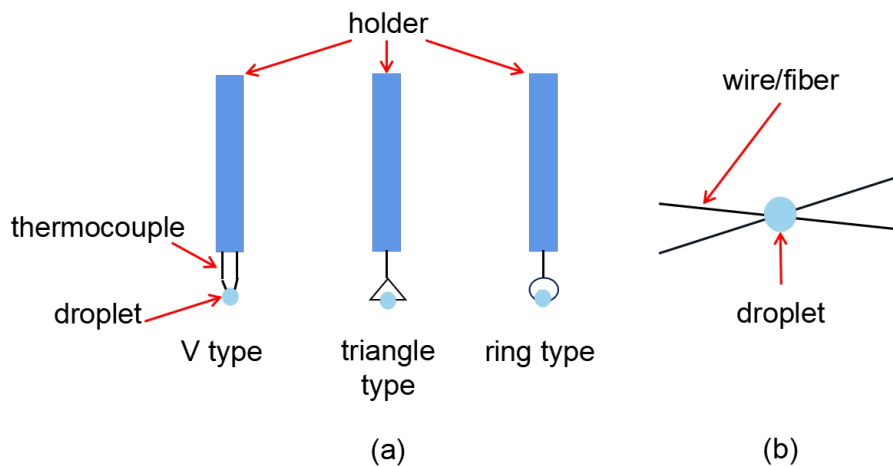
136 The remaining of this paper is organized as follows. Firstly, the experimental methods for
137 studying evaporation of fuel droplets are introduced and compared in Section 2. Secondly, the
138 evaporation characteristics of single-component fuel droplets are presented in Section 3. Then,
139 recent studies on evaporation characteristics of multi-component fuel droplets are reviewed,
140 including miscible (Section 4), liquid-liquid immiscible (Section 5) and liquid-solid immiscible
141 (Section 6) multi-component fuels. Finally, the challenges and future research directions on
142 evaporation of fuel droplets are elaborated in Section 7.

143

144 2. Experimental methods

145 Currently, there are mainly three experimental methods for studying the evaporation of a
146 fuel droplet, namely suspension, flying droplet and levitation. **Table 1** compares the

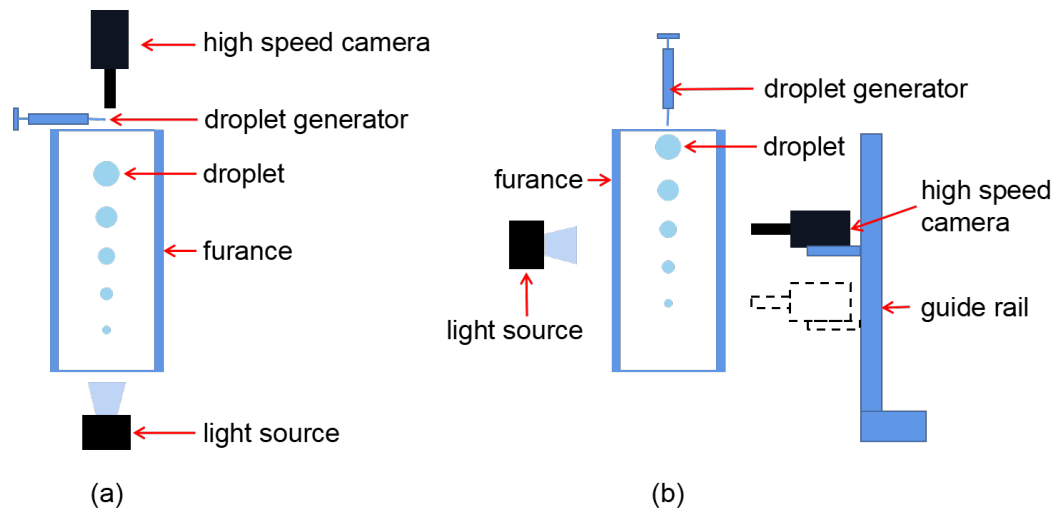
147 mechanisms, advantages and limitations of these research methods. As shown in **Table 1**, each
 148 method has its own advantages and disadvantages that determine their applications according
 149 to the experiment needs and purposes. The suspension method (**Fig. 1**) uses an intersection of
 150 quartz wires/fibers [19, 32], ceramic wires/fibers [33, 34] or junction of thermocouples [35-38]
 151 as the support to hang a droplet for heating and evaporation. This method is simple to generate
 152 a droplet under a static state, which is convenient for measurement of droplet parameters such
 153 as diameter and temperature. The disadvantage is that the droplet size is usually much larger
 154 than that produced in a real engine spray. In addition, the suspension support affects droplet
 155 evaporation. **Table 2** concludes the studies on the influence of support on droplet evaporation.
 156 Generally, the support promotes droplet evaporation by increasing heat transfer to the droplet.
 157 However, this impact can be ignored when the support size is sufficiently small (less than 1/10
 158 of the droplet size) and thermal conductivity of support is low (less than 80W/m-K). The
 159 suspension method is widely applied to investigate the evaporation characteristics of fuel
 160 droplets under different working conditions.



161
 162 **Fig. 1.** Schematic diagrams of different forms of suspension methods: (a) vertical
 163 thermocouple, (b) cross-wire/fiber.

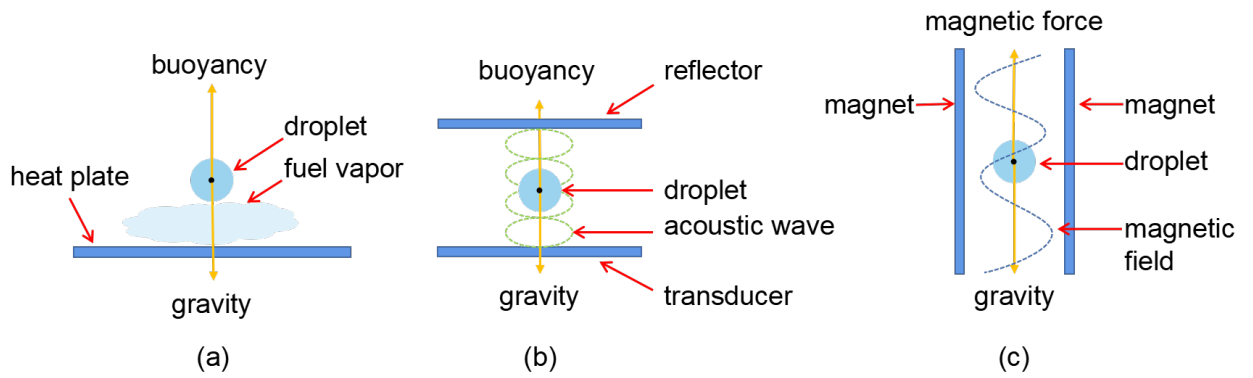
164 In the flying droplet method (**Fig. 2**), the droplet undergoes a free falling motion in the
 165 experimental chamber. Images of the falling droplet are captured by a wide-angle fixed camera
 166 or by changing the camera position. This method can produce relatively small droplet and
 167 allows the droplet to evaporate freely without influence from any foreign parts (e.g. the
 168 suspension support in **Fig. 1**). Moreover, there is no sealing problem for experiments under high
 169 ambient pressure. However, the disadvantages are that it has high requirements for equipment

170 and it is difficult to measure some droplet parameters (e.g. temperature). The interactions
 171 between the droplet and the surrounding flow field have great influences on the evaporation
 172 process if the droplet is too small. When the droplet fell, there was a relative velocity between
 173 droplet and surrounding gas. This meant that the droplet evaporated in a convective
 174 environment, which promoted droplet evaporation and caused experimental error. Overall, the
 175 flying droplet method has great advantages in simulating the evaporation process of an
 176 atomized droplet in engine cylinders when compared with other methods.



178 **Fig. 2.** Schematic diagram of flying droplet method: (a) wide-angle fixed camera, (b) moving
 179 camera.

180 The levitation method (**Fig. 3**) balances the buoyancy or magnetic force of a droplet with
 181 its gravity by fuel vapor (i.e. Leidenfrost phenomenon), magnetic field or acoustic levitator, so
 182 as to levitate the droplet. In this method, the droplet is approximately spherical and more stable
 183 compared to the flying droplet method. Meanwhile, it has no foreign part disturbance compared
 184 to the suspension method. It can also observe the droplet for a long time [39], which is suitable
 185 for droplet evaporation investigation under atmospheric pressure. However, it takes time for the
 186 levitation droplet to stabilize, during which the droplet will evaporate and the data is
 187 unmeasurable. In particular, higher ambient temperature greatly increase the droplet mass loss
 188 due to evaporation. Therefore, levitation method cannot be applied under high ambient
 189 temperature conditions. Finally, if droplet was levitated by acoustic and magnetic fields, there
 190 was a coupling effect of multiple fields, making it different from actual fuel droplet evaporation.



191
 192 **Fig. 3.** Schematic diagram of the levitation method: (a) levitating by fuel vapor, (b) levitating
 193 by acoustic levitator, (c) levitating by magnetic force.

194

195

Table 1. Comparison of research methods for fuel droplets.

Methods	Mechanisms	Advantages	Disadvantages
Suspension	Suspending droplets by quartz wires, thermocouples or other fibers	Simple to generate droplets Easy to measure droplet parameters	Thermal conductivity of support Large droplet size Ellipsoidal droplets
Flying droplet	Free falling motion of droplets in experimental chamber	Simple to generate droplets No foreign part disturbance Small droplet size Easy to achieve high pressure conditions	Difficult to measure droplet parameters Droplet-air interactions
Levitation	Levitating droplets by buoyancy, magnetic or acoustic force	No foreign part disturbance Spherical droplet Easy to measure droplet parameters	Coupling effect of multiple fields Low ambient temperature

196

197

Table 2. Effect of suspension support on droplet evaporation.

Refs.	Support materials	Key results
Volkov and Strizhak [40]	Copper, aluminum, ceramics, steel and nichrome	Support form and material affected heating and evaporation times, respectively.
Wang et al. [41]	Quartz, iron and copper	Evaporation rate constant and lifetime were linearly correlated with d_s^2 and κ ; Heat transfer of support would lead to micro-explosion when $d_s > 0.15$ mm or $\kappa > 400$ W/m-K; Support had little effect on evaporation when $d_s < 0.10$ mm and $\kappa < 80$ W/m-K.
Chauveau et	Quartz fiber	Support had little effect on droplet evaporation when using cross-fiber

al. [42]		and $d_s=14\ \mu\text{m}$; Evaporation rate increased linearly with d_s^2 .
Rehman et al. [43]	Thermocouple and glass fiber	Droplets on thermocouples evaporated faster when d_s was the same; Larger d_s led to faster droplet evaporation; Influence of support could be ignored when $d_s^2/d_0^2 < 0.01$.
Han et al. [44]	Thermocouple and quartz fiber	Droplets on thermocouples evaporated faster; Droplet evaporation rate increased first and then decreased with d_t .

Symbols: d_s , support diameter; d_0 , initial droplet diameter; κ , thermal conductivity; d_t , thermocouple diameter.

198

199 3. Evaporation characteristics of single-component fuel droplets

200 The evaporation of a droplet is usually characterized by the variation of droplet diameter
 201 with time [45]. According to the classical droplet evaporation theory [46], it is necessary to
 202 normalize droplet diameter and time to eliminate the influence of difference in initial droplet
 203 diameter caused by surface tension and other factors [47]. In addition, droplet lifetime and
 204 evaporation rate are also widely used to analyze the droplet evaporation process.

205 A single-component fuel refer to a fuel that only composes of one component, such as the
 206 ethanol fuel and the n-hexadecane fuel. The evaporation processes of different single-
 207 component fuels are similar, which demonstrate two stages. Ma et al [48] divided the
 208 evaporation process of n-hexadecane droplet into transient heating and equilibrium evaporation
 209 based on the variation of normalized square diameter (d^2/d_0^2) with normalized time (t/d_0^2) at
 210 523 K. They defined a critical point for heating process when d^2/d_0^2 was one. This was
 211 consistent with the division of evaporation stages for oleic acid (OA) and linoleic acid (LA) by
 212 Wang et al. [49]. Xi et al. [50] also divided the evaporation processes of n-hexadecane and n-
 213 butanol droplets into transient heating and stable evaporation. However, Chaitanya and Basu
 214 [51] defined the evaporation process of n-decane droplet as preheating and linear regression
 215 regimes. Although the stage definitions may be different among scholars, there are common
 216 features in each stage. In the first stage of droplet evaporation, the heat absorbed by droplet is
 217 mainly used to increase its own temperature due to low droplet temperature [48] and only a
 218 small part is used for evaporation. In this stage, the droplet temperature rises rapidly [50],
 219 resulting in a decrease in the droplet density [52]. According to the relationship (i.e. $V=m/\rho$) of
 220 mass (m), density (ρ) and volume (V), the droplet volume increases if the decrease in density
 221 is greater than the mass loss caused by surface evaporation (i.e. thermal expansion rate is greater
 222 than surface evaporation rate). Otherwise, the droplet volume decreases [53]. In the second
 223 stage, the droplet temperature slowly approaches the boiling point and reaches a relatively

224 stable state since it cannot exceed the fuel boiling point [54], which is called a quasi-steady
225 state [53]. In this stage, all the absorbed heat is used for droplet evaporation. The d^2/d_0^2 of
226 droplet decreases linearly with t/d_0^2 and the evaporation rate remains unchanged [48], following
227 the classical d^2 law of $d^2 = d_0^2 - K * t$ where d is instantaneous droplet diameter, d_0 is initial
228 droplet diameter, K is evaporation rate constant and t is heating time.

229 Many scholars have studied the impact of various factors on the evaporation of single-
230 component fuel droplet to comprehensively understand their evaporation mechanisms. This
231 section systematically reviews the effect of fuel properties, initial droplet diameter, ambient
232 temperature and pressure, and turbulence on the evaporation characteristics of single-
233 component fuel droplet.

234

235 *3.1. Effect of fuel properties and initial droplet diameter*

236 The differences in fuel properties lead to different evaporation behaviors. Generally, a
237 higher boiling point causes a longer first stage of droplet evaporation process, a more obvious
238 increase in diameter, a smaller evaporation rate and a longer lifetime. Ma et al. [48] found that
239 the diameter of n-hexadecane droplet (boiling point: 287 °C) increased significantly during the
240 transient heating stage. Javed et al. [55] showed that the initial heating phase of n-heptane
241 droplet (boiling point: 98 °C) was very short, and the expansion in droplet diameter was also
242 very small. Pinheiro et al. [21] reported that the transient heating phase of ethanol droplet
243 (boiling point: 78 °C) was basically not observed. However, Wang et al. [49] discovered that
244 LA (boiling point: 407 °C) had the shortest transient heating stage and OA (boiling point: 361 °C)
245 had the longest transient heating stage at 873 K. The increase of LA droplet diameter was
246 smaller than that of OA droplet. Meanwhile, Ma et al. [48] observed that n-hexadecane droplet
247 (boiling point: 287 °C) had shorter lifetime and higher evaporation rate than n-butanol droplet
248 (boiling point: 118 °C) at 623 and 723 K, which was consistent with Xi et al. [50]. Patel and
249 Sahu [56] also found that although n-heptane had a higher boiling point than ethanol, its
250 evaporation rate was greater than that of ethanol at 609 K. This means that in addition to the
251 boiling point, other fuel properties, such as latent heat [48, 50, 57] and mass diffusivity [56],
252 also affect the droplet evaporation behaviors.

253 Initial droplet size affects evaporation surface area, thereby affecting the droplet lifetime
254 [45]. Verwey and Birouk [58] studied the impact of d_0 on the evaporation rate of n-decane and
255 n-heptane droplets. The results indicated that the evaporation rate increased linearly with d_0 .

256 They suggested that droplet evaporation rate was affected by natural convection and molecular
257 diffusion. The former was linearly correlated with d^3 , while the latter did not theoretically
258 depend on d . The increase of initial droplet size may enhanced the contact area between
259 atmosphere and droplet, which promoted natural convection and thus increased the evaporation
260 rate [59].

261

262 *3.2. Effect of ambient temperature and pressure*

263 Ambient temperature determines the heat transfer between environment and droplet.
264 Droplets could absorb more heat under a higher ambient temperature, thus accelerating the
265 droplet evaporation and shortening the droplet lifetime. Chen et al. [60] found that n-decane
266 droplet evaporated faster at 703 K than that at 503K. Verwey and Birouk [58] reported that the
267 promoting effect of turbulence and initial droplet size on droplet evaporation was weakened
268 with the increase of temperature, indicating that temperature had a greater influence on droplet
269 evaporation compared with other factors. Ma et al. [48] concluded that the lifetimes of n-
270 hexadecane and n-butanol droplets decreased by 97% and 79%, respectively as ambient
271 temperature rose from 423 to 723 K, implying that ambient temperature had a greater effect on
272 fuel evaporation than boiling point.

273 Researchers have reached a consensus on the effect of ambient pressure on droplet lifetime,
274 i.e. droplet lifetime increases with ambient pressure. However, the results on evaporation rates
275 varied. Verwey and Birouk [58] reported that high pressure suppressed diffusion of fuel
276 molecular on the droplet surface. This contributed to a longer lifetime at ambient pressure of
277 10 bar than 1 bar. They found that the droplet evaporation rate gradually decreased as pressure
278 rose from 1 to 10 bar. The effect of higher ambient pressure (1-3 MPa) on n-hexadecane droplet
279 evaporation under the microgravity condition at 773 K was studied by Nomura et al. [53]. They
280 found that the evaporation rate decreased linearly with the ambient pressure when pressure was
281 greater than the fuel critical pressure of 1.41 MPa, which was due to the larger isobaric specific
282 heat capacity of fuel vapor near the critical point and the smaller difference in temperature
283 between droplet surface and experimental atmosphere. However, the evaporation rate increased
284 linearly with ambient pressure until it reached the critical pressure, which was due to the larger
285 heat conductivity of gas mixture and the smaller density and latent heat of fuel. Although the
286 evaporation rate improved with ambient pressure at subcritical condition, the droplet
287 evaporation lifetime prolonged. They explained that it was due to the fact that fuel boiling point

288 rose with ambient pressure, leading to the increase in the initial heating period that exceeded
289 the decrease in the quasi-steady evaporation stage.

290

291 3.3. *Effect of turbulence*

292 Turbulence can take away fuel vapor from droplet surface, which facilitates the formation
293 of vapor concentration gradient and thus promotes droplet evaporation. Marti et al. [61]
294 revealed that increasing turbulence intensity resulted in a slight improvement in the evaporation
295 rate of n-heptane. Patel and Sahu [56] found that the d^2/d_0^2 of ethanol, n-heptane and n-decane
296 droplets basically changed linearly with t/d_0^2 under different turbulent kinetic energies,
297 suggesting that the d^2 law was also applicable in turbulence. The evaporation rate also increased
298 with the turbulence intensity, while the degree of increase gradually decreased, because the
299 ability of vapor molecules to follow the fluid material reached their limit. They also observed
300 that turbulence had a greater effect on the evaporation of less volatile fuels, while fuel vapors
301 with larger mass diffusivity in the atmosphere were less influenced by turbulence. Rehman et
302 al. [43] confirmed that the effect of low convective velocity on droplet lifetime was greater than
303 that of high convective velocity, which was similar to the results reported in [56]. This may be
304 attributed to the reason that low convective velocity has a greater influence on the vapor
305 concentration gradient on droplet surface.

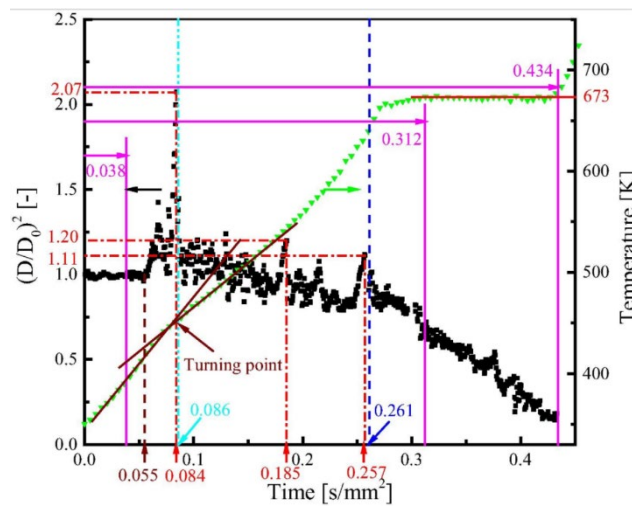
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307 **4. Evaporation characteristics of miscible multi-component fuel droplets**

308 Miscible multi-component fuel is a mixture of two or more mutually soluble components.
309 Compared to single-component droplet, the diameter of multi-component droplet fluctuates
310 when it evaporates, which is caused by the different evaporation rates of each component due
311 to their different physical properties. When the droplet temperature is higher than the boiling
312 points of light components but lower than the boiling points of heavy components, the light
313 components evaporate inside the droplet to generate bubbles. The bubbles burst once the bubble
314 pressure is larger than the sum of droplet surface tension and ambient pressure, resulting in
315 different degrees of droplet breakup [45, 59, 62], such as puffing and micro-explosion. This
316 increases droplet surface area, thereby promoting droplet evaporation and shortening droplet
317 lifetime [63, 64]. This is of great significance in improving fuel atomization and combustion.

318 Zhang et al. [52] divided the evaporation process of biodiesel-butanol droplet into three

319 phases: transient heating, fluctuation evaporation and equilibrium evaporation, as shown in Fig.
 320 4. In the first phase, the d^2/d_0^2 of droplet remained roughly constant due to the equilibrium
 321 between the droplet evaporation and thermal expansion rates. In the second phase, the droplet
 322 diameter fluctuated frequently. It was because not only the fuel on the droplet surface
 323 evaporated, but also the light components inside the droplet evaporated to form bubbles which
 324 grew up and burst, resulting in droplet expansion and breakup. This process continued until
 325 butanol in the droplet was almost completely evaporated. The third phase was mainly the
 326 evaporation of heavy components, causing the d^2/d_0^2 of droplet to decrease linearly which
 327 followed the classic d^2 law. Wang et al. [45] divided the evaporation process of soybean oil
 328 droplet into four phases: transient heating, micro-explosion evaporation, equilibrium
 329 evaporation and residue evaporation. Although the definitions of the first three phases were
 330 different from Zhang et al. [52], the features of each phase were similar. The formation of
 331 residue evaporation phase was mainly due to the decomposition of macromolecular substances
 332 in the fuel into small free radicals at high temperature, followed by free radical polymerization
 333 to produce viscous gelatinous substances [65].



334
 335 **Fig. 4.** Variation of the normalized squared diameter of biodiesel-butanol droplet with the
 336 normalized time at 1073 K [52].

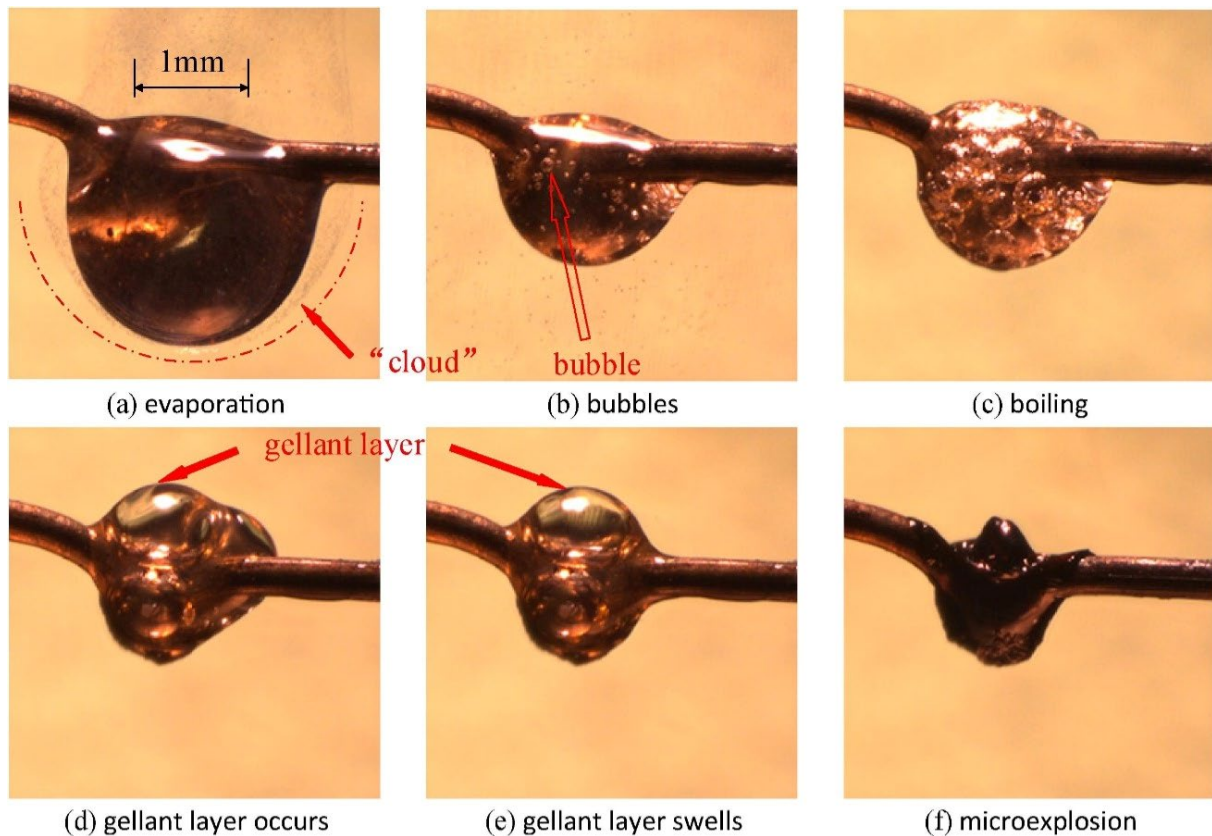
337 In this section, the effect of various factors on the evaporation characteristics of miscible
 338 multi-component fuel droplets is reviewed and the relevant studies are listed in **Table S1**. In
 339 addition, the mechanisms of micro-explosion of miscible multi-component fuel droplet are
 340 concluded and micro-explosion modes are proposed.

341

342 *4.1. Effect of difference in boiling points of fuel components*

343 Since the puffing and micro-explosion of miscible multi-component droplets are the
344 results of the first evaporation of light components, they are influenced by the difference in the
345 boiling points of fuel components [65, 66]. In fact, a greater difference in boiling points between
346 the components is favorable for occurrence of puffing and micro-explosion.

347 Han et al. [67] found that puffing or micro-explosion did not occur in the evaporation
348 process of dodecane/hexadecane blended droplets. This was because the difference of boiling
349 points between dodecane (218 °C) and hexadecane (287 °C) was too small (69 °C). Won et al.
350 [68] also observed no puffing or micro-explosion in the evaporation process of n-heptane/n-
351 decane blended droplet due to the small difference in their boiling points (76.2 °C). However,
352 Chow et al. [69] found that ethanol/palm biodiesel blended droplet (the difference in boiling
353 points was over 222 °C) experienced bubble formation, growth and explosion, which shortened
354 the evaporation duration. Yang et al. [70] compared the evaporation processes of pure kerosene
355 and kerosene gel droplets. The boiling points of pure kerosene and gellant are 180-270 and
356 450 °C, respectively. Compared with the small fluctuation in the diameter of pure kerosene
357 droplet, kerosene gel droplet exhibited a different evaporation process due to the larger
358 difference in boiling points (180-270 °C), which was divided into three stages: kerosene
359 evaporation, gellant layer formation, and gellant layer swell and micro-explosion. There was a
360 gellant layer on the droplet surface to prevent fuel vapor from diffusing outside because the
361 mass diffusion rate of kerosene towards surface was lower than its evaporation rate on the
362 surface, leading to generation of many bubbles in the droplet. Then they accumulated, swelling
363 the droplet and thinning the gellant layer. Micro-explosion occurred when bubble pressure
364 exceeded the sum of surface tension of gellant layer and ambient pressure, resulting in the
365 breakup of droplet and further accelerating the droplet evaporation, as shown in Fig. 5.



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Fig. 5. Comparison of the d^2/d_0^2 of kerosene and kerosene gel droplets [70].

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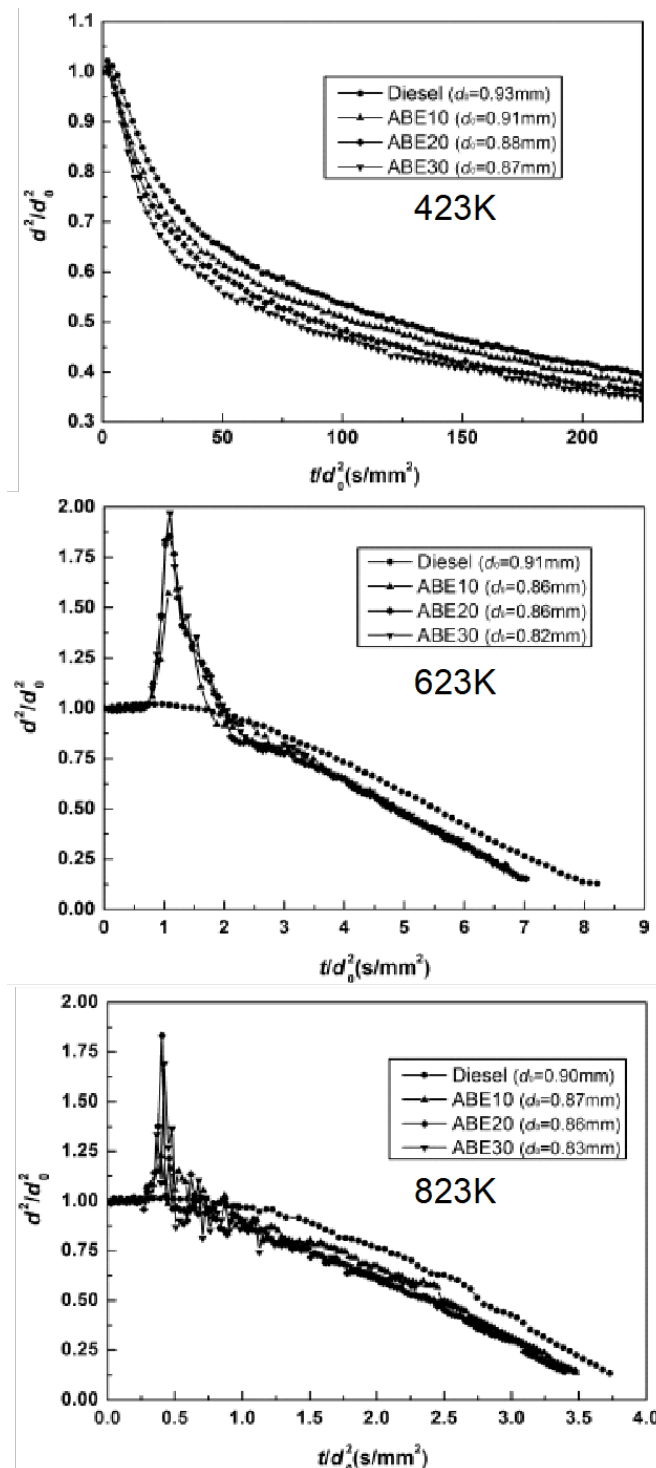
Rao et al. [71] reported that the breakup probability of Jet A-1/butanol droplet was lower than that of Jet A-1/ethanol droplet under the same conditions, indicating that a greater volatile difference between components was favorable to nucleate and generate bubbles. Antonov and Strizhak [72] believed that the mixing of different fuels could produce micro-explosion, which greatly increased the droplet surface area. Moreover, Ma et al. [32] also confirmed that adding light components into diesel caused micro-explosion and shortened droplet lifetime. They explained that light components on the droplet surface evaporated first and then a thin layer of heavy component was formed, which prevented the light component inside the droplet from spreading out, causing its overheating to produce bubbles. Small bubbles gathered into large bubbles and continued to grow. Eventually, the bubble burst when bubble pressure exceeded the limit of the droplet, resulting in micro-explosion and higher droplet evaporation rate. This agreed well with the results of Wang et al. [59] that the addition of ethanol into fatty acid methyl ester (FAME) led to a slight micro-explosion, while pure FAME droplet evaporated smoothly. Therefore, it is feasible to add light components into these fuels with poor evaporation (e.g. heavy fuel oil[73]) to cause puffing and micro-explosion and thus to promote their evaporation.

384 4.2. *Effect of ambient temperature*

385 Similar to single-component fuel droplet, a higher ambient temperature increases the heat
386 supplied to the multi-component fuel droplet and thus accelerates its evaporation. The difference
387 is that ambient temperature also affects the nucleation of multi-component fuel droplet. It is
388 heterogeneous nucleation when the temperature is relatively low, resulting in a weak micro-
389 explosion. Homogeneous nucleation occurs under higher ambient temperature, which increases
390 the frequency of bubble formation and rupture, leading to a strong micro-explosion [45, 65] and
391 thus higher droplet evaporation rate.

392 The evaporation process of diesel blended with acetone-butanol-ethanol (ABE) droplet
393 was investigated by Ma et al. [32], as shown in Fig. 6. They found that the droplet evaporated
394 smoothly at 423 K because the light components inside the droplet had enough time to spread
395 to the droplet surface and evaporate when droplet temperature was low. At 623 K, however, the
396 light components inside the droplet were wrapped by a thin layer of heavy components and
397 were overheated to generate bubbles, leading to micro-explosion. The fluctuation of droplet
398 diameter at 823 K was faster and stronger, because higher ambient temperature increased the
399 heat diffusion inside the droplet, and the generation rate, movement and burst of bubbles. Wang
400 et al. [37] observed a puffing phenomenon in the evaporation process of jatropha straight
401 vegetable oil droplet at 673 K, during which the droplet diameter fluctuated slightly. At 873K,
402 droplet deformation, bubble formation and expansion, ejection and micro-explosion were
403 observed, causing more frequent and violent droplet diameter fluctuations, which increased
404 droplet evaporation rate and shortened droplet lifetime. Huang et al. [74] also reported that the
405 evaporation of biodiesel/propanol droplet was stable at 573 K, but micro-explosion occurred at
406 673 and 773 K. Micro-explosion was strengthened with the increase of ambient temperature,
407 which is similar to the results obtained by Meng et al. [75, 76]. It was believed that ambient
408 temperature was the main external factor that promoted micro-explosion. Han et al. [62]
409 reported that biodiesel/ABE droplet had fewer puffing times at 803 K than 1003 K in a nitrogen
410 atmosphere, resulting in fewer and smaller sub-droplets. Restrepo-Cano et al. [77] investigated
411 the evaporation behaviors of Arabian light crude oil droplet at 620, 710 and 840 K. The results
412 showed that the frequency of droplet break-up events increased with the ambient temperature,
413 while the intensity of break-up was smaller at higher temperature. It might be because there was a
414 membrane on the droplet surface due to the preferential evaporation of light components at low
415 ambient temperature. This increased the surface tension and limited the mass diffusion, leading
416 to accumulation of light component vapor inside the droplet and thus strong micro-explosion.

417 However, both membrane formation and cracking reaction occurred at high temperature. The
418 latter decomposed the membrane and promoted the mass diffusion of light component, which
419 decreased the intensity of droplet micro-explosion.



420

421 **Fig. 6.** The evaporation processes of diesel-ABE blend droplets at different ambient

422

temperatures [32].

423 4.3. *Effect of concentration of light component*

424 The evaporation characteristics of biodiesel (BD) droplet mixed with n-propanol (P) at
425 ratios of 25%, 50%, and 75% at 673 K were studied by Huang et al. [74]. The results showed
426 that the micro-explosion of P25BD75 droplet occurred in the early stage of evaporation and had
427 the longest time and the highest intensity, while the micro-explosion of P75BD25 droplet
428 occurred in the latter stage of the evaporation. They concluded two conditions for the
429 occurrence of micro-explosion, i.e. overheating of light component inside the droplet and the
430 formation of an oil film on the droplet surface. When the concentration of light component was
431 small, it would quickly evaporate to form a heavy component oil film, leading to an early micro-
432 explosion. With the increase of light component concentration, generation rate of bubbles inside
433 the droplet enhanced and small bubbles coalesced to form larger ones, which strengthened
434 micro-explosion. When the concentration of light component was greater than that of heavy
435 component, the droplet diameter decreased rapidly due to the high content and fast evaporation
436 of light component, causing a later time for the internal heavy component to form an oil film.
437 At this time, significant light component has evaporated, resulting in a weaker micro-explosion.
438 Rosli et al. [78] compared diesel/gas-to-liquid (GTL) droplet in proportions of 20%, 50%, 80%,
439 and 100%. It was found that GTL50 droplet had the highest fluctuations in normalized diameter,
440 the strongest micro-explosion, the fastest evaporation rate, and the shortest lifetime. Han et al.
441 [62] studied biodiesel/ABE droplets with ABE proportions of 20%, 40%, 60%, and 80%. The
442 results showed that ABE60 droplet had the strongest micro-explosion, the fastest evaporation,
443 and the shortest lifetime. It was believed that the content of light components inside the droplet
444 when the oil film was formed determined the intensity of micro-explosion. ABE20 droplet did
445 not produce sub-droplets due to less light component, leading to less energy produced by bubble
446 burst. Coughlin and Hoxie [79] revealed that the strongest puffing occurred when
447 pentanol/soybean oil and butanol/soybean oil blended droplets had a 50%/50% mixing.

448 **Table 3** summarizes the studies on the influence of light component concentration on the
449 evaporation characteristics of miscible multi-component droplet. It can be seen that there is an
450 optimal light component concentration. When the light component concentration is less than
451 the optimal value, droplet puffing and micro-explosion are promoted with the light component
452 concentration, leading to an improved evaporation. When the light component concentration is
453 higher than the optimal value, droplet puffing and micro-explosion are suppressed with the
454 increase of the light component concentration, causing a worsened droplet evaporation. It is

455 worth noting that droplet evaporation may be the best when the light component concentration
 456 is around 50% due to the strongest puffing and micro-explosion [74, 78, 79].

457 **Table 3.** Effect of light component concentration on evaporation characteristics of miscible
 458 multi-component fuel droplet.

Refs.	Fuel components	Light component concentration	Key results
Xi et al. [50]	n-butanol + n-hexadecane	10%-50% of n-butanol	Increasing n-butanol concentration changed droplet nucleation from no to single and multiple bubbles, and evaporation from stable evaporation to partial breakup and micro-explosion.
Han et al. [66]	Diesel + ABE	10-80% of ABE	With the increase of ABE content, puffing frequency increased first and then decreased, and evaporation time decreased first and then increased. When ABE content was 40%-50%, puffing was the strongest.
Syam et al. [64]	Jet1 + ethanol	10-50% of ethanol	There was no puffing when ethanol was 10%. Many nucleation sites were generated inside the droplet and continuous puffing occurred when ethanol was 30%. Micro-explosion caused by puffing was the main phenomenon when ethanol was 50%.
Wang et al. [59]	FAME + ethanol	10%-40% of ethanol	Increasing ethanol concentration decreased micro-explosion delay time and droplet lifetime, and increased micro-explosion intensity.

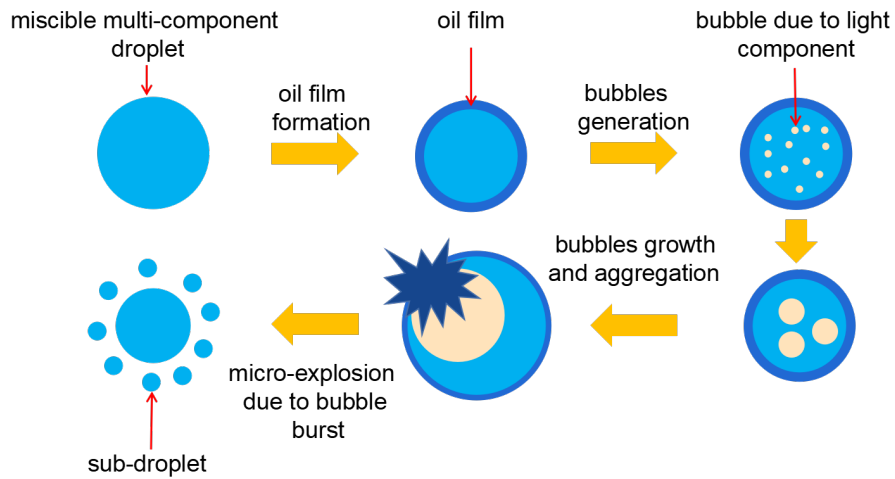
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460 4.4. Micro-explosion modes of miscible multi-component fuel droplet

461 **Fig. 7** illustrates the micro-explosion process of a miscible multi-component fuel droplet.
 462 Shen et al. [80] pointed out that micro-explosion of miscible multi-component fuel droplet was
 463 induced by vigorous bubble nucleation and rapid bubble growth of the light components.
 464 Similarly, many researchers [52, 62, 70, 74] believed that the evaporation of light components
 465 on the droplet surface leads to the formation of an oil film of heavy components [66], which
 466 inhibits the outward diffusion and evaporation of light components inside the droplet. Then the
 467 light components overheat and nucleate to produce bubbles when the droplet temperature is
 468 higher than their boiling points. The pressure in the bubble increases with the continuous
 469 evaporation of light components and bubble aggregation. Due to the pressure difference
 470 between the inside and outside of the bubble and the flow in the droplet, the bubble moves
 471 towards the edge of the droplet, stretching the oil film on the air-droplet interface and reducing
 472 its surface tension [59]. Droplet micro-explosion occurs once the bubble pressure is higher than
 473 the sum of surface tension of the thinnest part of oil film and ambient pressure. Rao et al. [81]

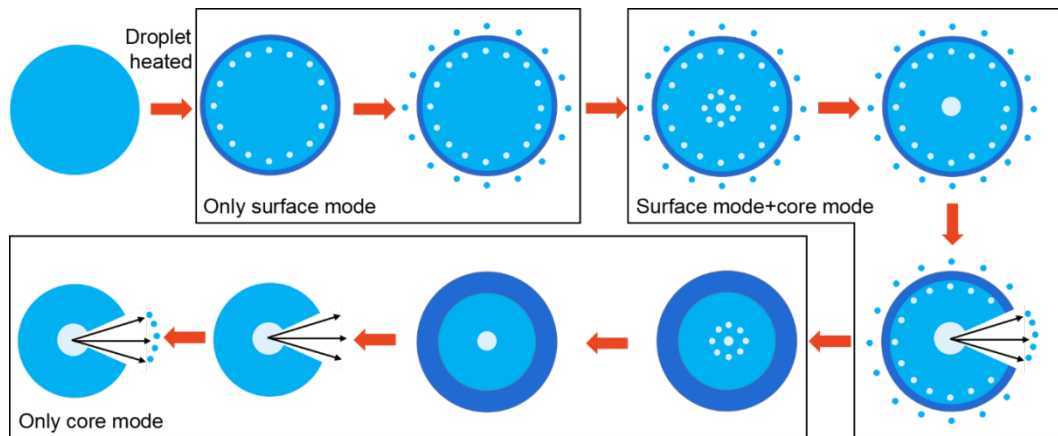
474 divided bubble growth into three periods. The first period was the growth of a single large
475 bubble with small bubbles coalescing. The second period was the growth of two or more large
476 bubbles merged by small bubbles, and the growth of larger bubbles coalesced by large bubbles.
477 In the third period, due to the bubble growth, droplet stretched in all directions, the oil film
478 thinned, and the droplet surface folded, resulting in Plateau-Rayleigh instability and capillary
479 wave propagation. Wang et al. [65] reported that the droplet always vibrated after generating
480 bubbles. They explained that it was due to rapid change of mass distribution in the droplet that
481 was attributed to the bubble movement and aggregation. Zhou et al. [82] reported that the
482 diameter of bubbles had a greater effect on micro-explosion than the number of bubbles. They
483 also agreed that bubble coalescence, growth and rupture caused micro-explosion. Meng et al.
484 [76] found that bubble position affected micro-explosion, and micro-explosion intensity was
485 high only when the bubble was located near the center. Faik and Zhang [83] also reported that
486 the micro-explosion caused by bubble rupture inside the droplet was more intense than the
487 micro-explosion on the droplet surface. In fact, the bubble takes a long time from generation to
488 rupture, so the bubble position tends to deviate from the center of the droplet before rupture,
489 leading to a relative small degree of droplet breakup. As a result, the micro-explosion process
490 of miscible multi-component droplet usually occurs repeatedly until the bubble formed by
491 evaporation of the remaining light components cannot break the oil film.

492 The bubbles can be released through the oil film with a little pressure when the surface
493 tension of oil film is small, so that large vapor bubbles cannot be accumulated inside the droplet,
494 resulting in a small degree of droplet breakup. Zhang et al. [52] proposed two evaporation
495 modes: surface and core modes. Surface mode meant that many micron-sized sub-droplets were
496 ejected from the droplet surface during the evaporation process, while the core mode meant that
497 there were many small bubbles inside the droplet. Due to the small surface tension of oil film,
498 larger bubbles formed by aggregation of many small bubbles were still relatively small, which
499 lead to local explosion of droplet, as shown in **Fig. 8**.



500

501 **Fig. 7.** Schematic diagram of micro-explosion of a miscible multi-component droplet.



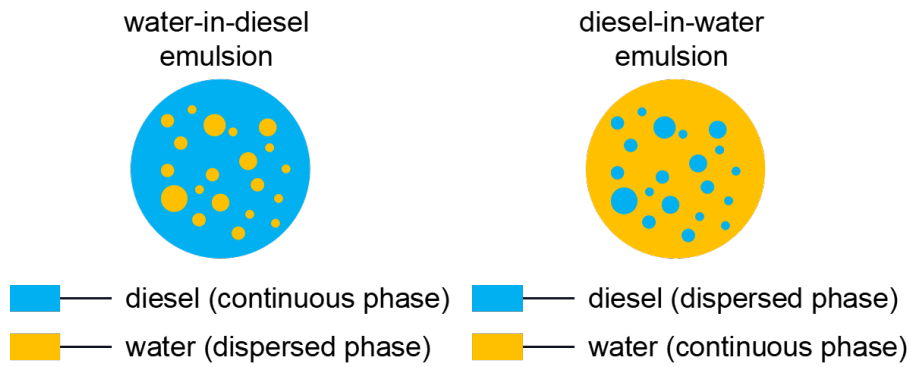
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503 **Fig. 8.** Schematic diagram of surface and core evaporation modes of a biodiesel-butanol
504 droplet [52].

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506 **5. Evaporation characteristics of liquid-liquid immiscible multi-component fuel droplets**

507 Liquid-liquid immiscible multi-component fuel refers to a temporarily stable mixture of
508 two or more immiscible liquid components mixed by high speed stirring or ultrasonic under the
509 action of emulsifier, such as diesel-water and diesel-ethanol emulsified fuels. Their
510 microstructure is that one component is distributed in other continuous component in the form
511 of discrete droplets. Taking diesel-water as an example, there are two emulsion forms, i.e.
512 water-in-oil and oil-in-water, as shown in **Fig. 9**. Water-in-oil emulsified diesel has water as the
513 dispersed phase and pure diesel as the continuous phase, while oil-in-water emulsified diesel is
514 the opposite.



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Fig. 9. Microstructures of diesel-water emulsified fuels.

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The evaporation process of immiscible multi-component fuel droplet is similar to that of miscible multi-component fuel droplet. There are also puffing and micro-explosion phenomena, both of which are the result of the first evaporation of light components in the droplet due to the difference in boiling points between components [51]. The evaporation characteristics of diesel blended 10% ethanol droplet were studied by Han et al. [84]. They divided the droplet evaporation process into three stages at 623 K: transient heating, fluctuation evaporation and equilibrium evaporation. In the first stage, droplet expansion due to heat absorption was larger than droplet contraction due to surface evaporation, causing the slow increase of droplet d^2/d_0^2 to the maximum value. In the second stage, the droplet diameter fluctuated because ethanol was superheated and nucleated to produce bubbles, which continued to grow until the droplet surface tension was overcome, leading to puffing and micro-explosion. The third stage was mainly the evaporation of pure diesel, so the evaporation process roughly followed the d^2 law. When the temperature rose to 723 K, the fluctuation evaporation stage was more violent due to the increase of heat supplied to the droplet by environment, resulting in a rapid increase of bubble nucleation rate.

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Kim et al. [85] divided the evaporation process of n-decane droplet mixed with 20% water into three stages: droplet heating, droplet inflation/puffing and pure evaporation. In the droplet heating stage, the d^2/d_0^2 of droplet increased first and then decreased since the droplet thermal expansion rate was first larger and then less than the surface evaporation rate. In the droplet inflation/puffing stage, water evaporation on droplet surface caused droplet puffing, while water evaporation inside the droplet resulted in droplet inflation. As the temperature rose, the droplet inflation gradually changed to puffing and the puffing probability increased. It was due to the higher rate of water vapor production that enhanced bubble expansion and the lower droplet surface tension that facilitated droplet breakup. Moreover, they also investigated the

541 impact of ambient pressure on droplet evaporation. The results reported that the generation and
542 growth of bubbles were inhibited by the pressure, because the boiling point of water increased
543 and some vapor dissolved in the droplet when ambient pressure was higher, leading to decreases
544 of probability and intensity of puffing. The pure evaporation stage was mainly the evaporation
545 of n-decane that followed d^2 law. In addition, they found that ambient temperature had greater
546 influence on droplet evaporation rate and lifetime than ambient pressure. The probability and
547 strength of puffing increased with the temperature, which greatly improved droplet evaporation
548 rate and shortened droplet lifetime.

549 Since it promotes the generation of small droplets ($<5 \mu\text{m}$) and increases the evaporation
550 surface area, micro-explosion of immiscible multi-component droplet is the main reason for
551 faster droplet evaporation. Compared with other droplet secondary atomization technologies,
552 micro-explosion can obtain the smallest sub-droplet size and the largest evaporation surface
553 area ratio [86], which increases the spray volume and promotes spray evaporation [87].
554 Therefore, micro-explosion has attracted significant research attentions for liquid-liquid
555 immiscible multi-component fuel droplet. The studies on micro-explosion of liquid-liquid
556 immiscible multi-component fuel droplet are summarized in **Table S2**.

557 Different to miscible multi-component fuel droplet, immiscible multi-component fuel
558 droplet undergoes an aggregation process of dispersed phase before micro-explosion, which is
559 a key factor for the occurrence of micro-explosion [88]. The breakup characteristics of
560 kerosene/water emulsion droplet was studied by Watanabe et al. [89]. They reported that the
561 coalescence of dispersed water droplets led to the occurrence of micro-explosion and the droplet
562 color changed from milky white to transparent. Syed et al. [90] divided the micro-explosion
563 process of water-in-palm oil into four distinct stages. The first stage was emulsion separation,
564 in which the droplet shape did not change significantly but the color changed from milky white
565 to transparent. In the second stage, small water particles merged into larger ones, and some of
566 the unmerged water particles evaporated on the droplet surface, resulting in the occurrence of
567 puffing. The third stage was bubble growth, during which the merged water particles vaporized
568 to produce bubbles, leading to droplet expansion. In the fourth stage, bubbles burst which
569 caused droplet micro-explosion. Suzuki et al. [91] found that accelerating coalescence process
570 of dispersed water droplets increased the occurrence probability of micro-explosion by using
571 methylene blue to dye the water particles in the droplet. **Table 4** summarizes the studies on the
572 internal parameters of emulsion droplet before micro-explosion. It can be seen that the
573 temperature of dispersed phase exceeds its boiling point before micro-explosion, meaning that

574 the dispersed phase has a certain level of superheat and metastable state. Therefore, more
 575 aggregation of dispersed phase leads to larger dispersed droplets and superheat, whose
 576 evaporation releases more energy and thus increases the occurrence probability and intensity of
 577 micro-explosion [89, 92-94].

578 This section reviews the effect of various factors on micro-explosion of liquid-liquid
 579 immiscible multi-component fuel droplet. Moreover, the mechanisms of micro-explosion of
 580 liquid-liquid immiscible multi-component fuel droplet are concluded and micro-explosion
 581 modes are proposed.

582 **Table 4.** Studies on internal parameters of emulsion droplet before micro-explosion.

Refs.	Droplet components	Research aims	Key findings
Strizhak et al. [95]	N-tetradecane + water	Temperature until micro-explosion	The temperature of water reached 100-125 °C before micro-explosion.
Volkov and Strizhak [96]	Oil/kerosene/gasoline/waste turbine oil/waste transformer oil + water	Explosive disintegration of water emulsion droplets	Temperature at phase interface before droplet breakup reached 100-125 °C; Temperature difference between phase interface and water droplet center determined the number of sub-droplets after micro-explosion.
Moussa et al. [97]	N-tetradecane + water	Conditions of micro-explosion of emulsified fuel droplet	Maximum temperature of water droplets reached ~130 °C. Atomization (micro-explosion or puffing) was related to temperature, size and position of the trigger droplet. When one of these parameters was not optimal, it could be compensated by the others.
Antonov et al. [98]	Transformer oil + water	Temperature and convection velocity until micro-explosion	The threshold temperature and average convective velocity were 100-120 °C and 2.5-3 mm/s before micro-explosion, respectively.

583

584 *5.1. Effect of droplet size of dispersed phase*

585 The size of dispersed phase affects its aggregation. The aggregation of the dispersed phase
 586 is inhibited due to the high Laplace pressure when the diameter of dispersed phase is small. As
 587 the diameter increases, the size distribution of dispersed phase inside the droplet becomes
 588 heterogeneous, leading to a larger difference in Laplace pressure and a larger van der Waals
 589 force between the dispersed phase [93]. This promotes the dispersed droplets to merge into
 590 larger droplets [88, 99], thereby facilitating the occurrence of micro-explosion.

591 Califano et al. [100] showed that larger dispersed water droplets aggregated faster. They
592 believed that micro-explosion was related to phase separation and proposed two micro-
593 explosion modes. One was that larger water droplets formed by the aggregation of dispersed
594 water droplets evaporated to cause micro-explosion, and the other was that many small water
595 droplets evaporated simultaneously to cause micro-explosion. Ismael et al. [101] found that the
596 high pressure and shear flow of the emulsified fuel in the injection device led to smaller size of
597 dispersed phase, resulting in a decrease in aggregation of water droplets and postponing the
598 occurrence of micro-explosion. A higher injection pressure increased the micro-explosion delay
599 time. Shen et al. [93] also reported that the dispersed water droplets were more likely to
600 aggregate into large ones when their diameters increased, so that more water remained in the
601 droplet before micro-explosion. This increased the energy released by evaporation of water,
602 thus enhancing the probability of catastrophic micro-explosion of diesel/water emulsion droplet.
603 Mura et al. [102] showed that the number of sub-droplets generated by micro-explosion
604 increased first and then decreased with the increase of water droplet diameter in sunflower
605 oil/water droplet. It was believed that a higher degree of phase separation promoted micro-
606 explosion. Large water droplets exploded before phase separation occurred, while medium
607 water droplets had sufficient time for phase separation and water droplets aggregated into larger
608 ones by convection, causing stronger micro-explosion. For small water droplet, the phase
609 separation was limited by the energy required to overcome the pressure that the curved interface
610 exerted on the molecules inside the water droplet (Laplace pressure), resulting in a low degree
611 of phase separation. They also found that the temperature before micro-explosion with large,
612 medium and small water droplets was 95, 200 and 134 °C, respectively [99]. Droplet with
613 medium water droplets had the strongest micro-explosion due to the highest degree of superheat.
614 Therefore, there is an optimal dispersed phase size for micro-explosion. Micro-explosion is
615 strengthened with the increase of the dispersed phase size until the optimal size, and further
616 increase of dispersed phase size will weaken the micro-explosion.

617

618 *5.2. Effect of dispersed phase and emulsifier concentrations*

619 When preparation conditions of emulsion (i.e. stirring time and emulsifier content) are
620 unchanged, the size of the dispersed phase increases with its concentration. This accelerates the
621 aggregation of dispersed phase, thereby promoting the occurrence of micro-explosion.
622 However, if the concentration exceeds a certain value, the light dispersed phase will transform

623 into the continuous phase and the heavy continuous phase will transform into the dispersed
624 phase. Then the evaporation and diffusion of light components are not restrained, which makes
625 it difficult for micro-explosion to occur.

626 Shen et al. [93] found that the droplet only occurred puffing, a few small droplets were
627 ejected from the droplet surface and the entire droplet could not be broken when the water
628 content was 5%. These were attributed to low energy released by the evaporation of water. As
629 the water content increased, local micro-explosion occurred. When the water content was 20%,
630 the dispersed water droplets merged into a large one, whose explosive evaporation caused
631 catastrophic micro-explosion and produced many sub-droplets. The effect of ethanol
632 concentration on puffing and micro-explosion of ethanol/hexadecane droplet was investigated
633 by Shen et al. [80]. The results showed that the dispersed phase aggregated when the
634 concentration of ethanol was 20%. It evaporated quickly once the droplet temperature exceeded
635 the superheat limit of the dispersed phase, releasing abundant energy in a short time and causing
636 the droplet to explode violently. When the ethanol concentration was 40%, the degree of
637 aggregation of dispersed phase was decreased and puffing occurred. When the ethanol
638 concentration was 60%, n-hexadecane accumulated inside and ethanol surrounded the outside.
639 The ethanol evaporated first to satisfy the d^2 law, and then the n-hexadecane evaporated. There
640 was weak puffing at the late stage of evaporation process, because a small amount of ethanol
641 was wrapped in n-hexadecane. Madan et al. [103] obtained similar conclusions from
642 experiments on the puffing and micro-explosion of diesel blended with ethanol droplets. They
643 reported that there was only puffing in most of the droplets when ethanol content was less than
644 10%. When ethanol content was 10%-40%, micro-explosion occurred and the droplet did not
645 expand before micro-explosion. No micro-explosion occurred when ethanol content was greater
646 than 40%.

647 The function of an emulsifier is to reduce the interfacial tension between the continuous
648 and dispersed phases, so that the dispersed phase can be stably distributed in the continuous
649 phase in the form of dispersed droplets. Hence, a higher emulsifier concentration increases
650 emulsion stability and reduces aggregation of dispersed phase and energy released by the
651 evaporation of dispersed phase, causing a change from micro-explosion to puffing [104]. The
652 impact of emulsifier content on puffing and micro-explosion characteristics of biodiesel/water
653 droplet was investigated by Khan et al. [105]. The results showed that 5% and 10% emulsifier
654 experienced micro-explosion while 15% emulsifier did not. A higher emulsifier concentration
655 decreased the size of dispersed phase and delayed the occurrence of micro-explosion [104, 106].

656 The puffing frequency increased as the size of dispersed phase decreased and the content of
657 emulsifier increased. This was consistent with the observation of Shen et al. [94] that puffing
658 and micro-explosion occurred at high and low emulsifier concentrations, respectively.

659

660 *5.3. Effect of initial droplet size*

661 Most of researchers found that there was no micro-explosion phenomenon in liquid-
662 liquid immiscible multi-component droplet when initial droplet size was relatively small. Khan
663 et al. [107] confirmed that the initial droplet diameter affected the frequency and delay time of
664 puffing and micro-explosion of diesel emulsified with water droplet and the size of the produced
665 sub-droplets. Watanabe et al. [89] reported that puffing and micro-explosion occurred when
666 initial droplet diameters were 0.7 and 1.2 mm, respectively. Kim et al. [85] observed no micro-
667 explosion in a small n-decane/water droplet (0.9 ± 0.1 mm) because water evaporation was
668 completed before its aggregation. Fu et al. [108] suggested that emulsified fuels in real diesel
669 engines would not experience micro-explosion due to the very small droplets. However, Hsieh
670 et al. [92] reported that the droplet size had insignificant effect on the micro-explosion strength
671 of n-hexadecane/water droplet. They attributed it to the fact that there was only one water
672 droplet in the emulsion droplet. The change in droplet size would not significantly influence
673 the contact surface area between water droplet and n-hexadecane oil film, leading to little
674 impact of droplet size on the strength of micro-explosion. Therefore, for a droplet containing a
675 large amount of dispersed phase, the droplet size may have a significant effect on the occurrence
676 of micro-explosion and need to be further studied.

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678 *5.4. Effect of other factors*

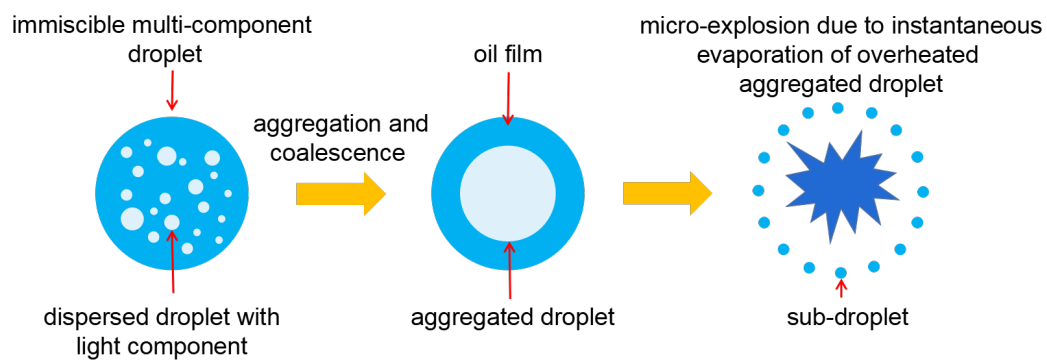
679 Other factors include ambient temperature, initial dispersed phase temperature, fluid
680 properties and impurities. The influence of heating temperature and fluid properties on micro-
681 explosion rate of emulsion droplet was studied by Moussa et al. [109]. The results showed that
682 micro-explosion rate enhanced with the ambient temperature. This was because the deactivation
683 of emulsifier accelerated phase separation under a high temperature, which enhanced the
684 aggregation of dispersed phase and thus promoted the occurrence of micro-explosion. In
685 addition, lower impurities and fuel viscosity resulted in higher micro-explosion rate. The
686 presence of impurities would reduce the level of metastable state of water droplets and a higher

687 viscosity increases the resistance of aggregation of water droplets, thereby inhibiting the
 688 occurrence of micro-explosion. Shen et al. [93] found that the probability of micro-explosion
 689 of diesel/water droplet increased with ambient temperature and catastrophic micro-explosion
 690 gradually transformed to partial micro-explosion. This trend was related to the larger
 691 temperature gradient in the droplet when ambient temperature was high, so the inner water
 692 droplets did not evaporate when the surface water droplets evaporated, resulting in less energy
 693 released by the micro-explosion. Antonov et al. [110] investigated the impact of initial water
 694 core temperature on breakup of emulsion droplet. They reported that a lower initial temperature
 695 increased the initial temperature difference between water core and combustible component,
 696 shortened the micro-explosion delay time, and enhanced the strength of micro-explosion. If the
 697 initial temperature was reduced from 353 to 273 K, the average size of the sub-droplets was
 698 reduced by 80% to 90%.

699

700 *5.5. Micro-explosion modes*

701 Existing studies showed that micro-explosion of liquid-liquid immiscible multi-
 702 component droplet had two modes, namely instantaneous and bubble micro-explosion modes.
 703 For the instantaneous micro-explosion mode, dispersed small droplets of light component
 704 aggregate to form one larger droplet. When the temperature exceeds the overheating limit of
 705 light component, the light component evaporates instantaneously and the released energy
 706 breaks droplet completely [80], as illustrated in **Fig. 10**. In this mode, there is no expansion
 707 before micro-explosion and micro-explosion occurs in a very short time. After a micro-
 708 explosion, there is almost no droplet left. The number of produced sub-droplets is large and the
 709 size is small, which is more conducive for rapid droplet evaporation to form a uniform mixture,
 710 thereby improving engine performance.



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712 **Fig. 10.** Schematic diagram of instantaneous micro-explosion of a liquid-liquid immiscible

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multi-component droplet.

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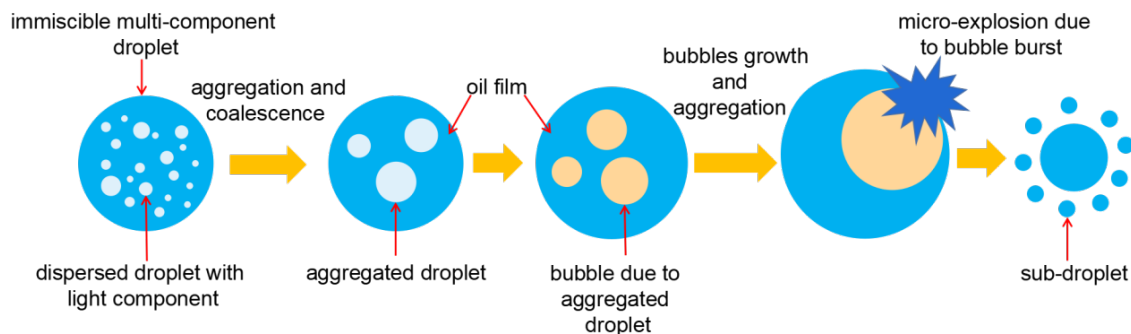
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For the bubble micro-explosion mode, the light component evaporates inside the droplet to generate bubbles when the energy released by the instantaneous evaporation of the aggregated light component is insufficient to break the droplet (e.g. aggregation is relatively small or droplet surface tension is large) [101]. As shown in **Fig. 11**, the bubble ruptures and the micro-explosion occurs when the bubble gradually grows to a point where the bubble pressure is larger than the sum of droplet surface tension and ambient pressure, which is similar to the micro-explosion of miscible multi-component droplet. Swelling is observed before micro-explosion. The intensity of micro-explosion depends on the bubble position. Zhang et al. [111] reported that droplet only experienced puffing and partial micro-explosion when the bubble was close to droplet surface, while overall micro-explosion occurred when the bubble was located in the droplet center. Since it takes a long time from bubble generation to rupture, the degree of droplet breakup is relatively small compared to instantaneous micro-explosion. Therefore, the micro-explosion process tends to repeat until the bubble formed by dispersed phase cannot break the droplet.



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Fig. 11. Schematic diagram of bubble micro-explosion of a liquid-liquid immiscible multi-component droplet.

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6. Evaporation characteristics of liquid-solid immiscible multi-component fuel droplets

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With the development of technology in recent years, it is possible to produce nanoparticles with special properties. These particles are mostly metal with sizes between 10-100 nm and have high energy release rate and oxidation heat. Adding them to liquid fuel in a certain proportion to form a nanofluid fuel can improve the fuel thermal physical properties, including volumetric energy density and evaporation rate, which can shorten the ignition delay and

738 thereby increase the combustion and heat release rates. Meanwhile, it can also reduce pollutant
739 emissions [112]. Hence, many researchers have experimentally investigated the evaporation
740 characteristics of nanofluid fuels to obtain the optimal conditions that promote evaporation
741 when using nanoparticles. On the one hand, nanoparticles absorb thermal radiation [113], which
742 improves the heat transfer inside the droplet and accelerates evaporation [114, 115]. On the
743 other hand, the accumulation of particles on droplet surface reduces its evaporation rate [116].
744 It is worth noting that nanoparticles can also cause micro-explosion [117], leading to droplet
745 breakup and promoting the evaporation. The evaporation process of nanofluid fuel droplet is a
746 result of the combined effect of the three mechanisms mentioned above.

747 This section discusses the effect of different factors on the evaporation characteristics of
748 nanofluid fuel droplets. The related studies are summarized in **Table S3**. In addition, the
749 mechanisms and modes of micro-explosion of nanofluid fuel droplets are also discussed.

750

751 *6.1. Effect of ambient temperature and nanoparticle concentration*

752 Ambient temperature is a decisive factor affecting the micro-explosion of nanofluid fuel
753 droplet. When the temperature is relatively low, the droplet evaporates smoothly and there is
754 no micro-explosion. However, micro-explosion occurs when the temperature is relatively high,
755 which facilitates the evaporation of droplet. Nanoparticles concentration affects the competitive
756 relationship between the absorption of thermal radiation and the particle aggregation. The
757 former dominates when the particle concentration is relatively low, resulting in the
758 enhancement of droplet evaporation rate. The latter plays a dominant role when particle
759 concentration is relatively high, leading to lower droplet evaporation rate. The concentration of
760 nanoparticles also influences the micro-explosion process.

761 The evaporation characteristics of diesel droplet with different ceria concentrations
762 (0.05%-5%) at 673 and 873 K was studied by Wang et al. [118]. They found that the droplet
763 evaporation process was divided into transient heating and equilibrium evaporation at 673 K.
764 The lifetime of nanofluid droplet was longer than that of pure diesel, because the aggregation
765 of nanoparticles formed a porous spherical shell that inhibited fuel evaporation. However, the
766 droplet evaporation process at 873 K was divided into three stages, namely transient heating,
767 fluctuation evaporation and equilibrium evaporation. There was micro-explosion which broke
768 the particle aggregation and increased the droplet evaporation surface area. Consequently,

769 droplet evaporation rate was improved and droplet lifetime was reduced [63]. Wang et al. [118]
770 also reported that there was an optimal particle concentration for droplet evaporation.

771 Gan and Qiao [119] reported that droplet evaporation deviated more obviously from the
772 d^2 law without micro-explosion under the condition of high particle concentration, low ambient
773 temperature, weak convection and high boiling point of the fuel. They believed that this was
774 the result of the aggregation of particles in the droplet. If the particle aggregation time was
775 shorter than or equal to the droplet lifetime, larger aggregates would be formed in the droplet
776 evaporation process, which inhibited the diffusion and evaporation of fuel components, thereby
777 reducing the evaporation rate. If the aggregation time was longer than the droplet lifetime, the
778 particle aggregates were smaller and had less impact on droplet evaporation. However, there
779 was no deviation of evaporation from the d^2 law under conditions that were conducive to reduce
780 droplet lifetime. Javed et al. [54] reported that micro-explosion occurred at the late evaporation
781 stage of kerosene droplet added with ligand-protected aluminum nanoparticles at 973 K, which
782 accelerated the evaporation. A higher nanoparticles concentration advanced the micro-
783 explosion time. When the temperature was higher than the melting point of particles at 1073 K,
784 some particles gathered on the droplet surface melted, which supplied additional heat of fusion
785 to the droplet and greatly enhanced the evaporation rate.

786 Tanvir et al. [113] reported that the evaporation rate of ethanol droplet with graphite
787 nanoparticles was higher than that of pure ethanol droplet in the early evaporation stage, but
788 lower in the late evaporation stage. It may be due to fact that the absorption of radiation energy
789 of particles dominated in the early evaporation stage, while particle aggregation was dominant
790 in the late evaporation stage that reduced the effective evaporation surface area. The
791 evaporation characteristics of jatropha vegetable oil/diesel droplet with a low particle
792 concentration at the level of ppm at 873 K were studied by Wang et al. [120]. The results showed
793 that no micro-explosion occurred and there was an optimal particle concentration for facilitating
794 droplet evaporation. They suggested that nanoparticles at a ppm level was better than a
795 percentile level in enhancing droplet evaporation. Although the droplet with the percentile level
796 of particle concentration could experience micro-explosion, the particles inside the droplet
797 aggregated to form a spherical shell in the later stage of evaporation, which suppressed the
798 droplet evaporation. Wang et al. [36] found that the average droplet evaporation rate of diesel
799 droplet with cerium oxide nanoparticles was enhanced as particle concentration increased from
800 0.05% to 0.25% at 873 K. The micro-explosion delay time was reduced by 24.1% and 47.1%,
801 and the micro-explosion intensity was increased by 37.5% and 49.5%, respectively when

802 compared to diesel. However, the evaporation rate in the steady evaporation stage was reduced
803 due to particle aggregation. The results reported in Wang et al. [117] and Ferrão et al. [121] also
804 demonstrated that intensity of droplet micro-explosion became larger with the increase of
805 nanoparticles concentration. This could be explained by the reason that increasing particle
806 concentration strengthened the heterogeneous nucleation, which generated more bubbles [36].

807

808 *6.2. Effect of other factors*

809 There are also other factors affecting the evaporation characteristics of nanofluid fuel
810 droplet, such as surfactant, type, size and shape of particle. The influence of surfactant on the
811 evaporation of heptane droplet with the addition of aluminum nanoparticles was investigated
812 by Javed et al. [55]. They reported that surfactant formed a thin layer on droplet surface at low
813 temperatures, which retarded the diffusion of fuel components. When nanoparticles were added,
814 there was a thick and porous shell on the droplet surface due to accumulation of particles bonded
815 with adsorbed surfactant, which further inhibited the droplet evaporation. However, it was
816 difficult to form a dense and porous shell at high temperature as a result of decomposition of
817 surfactant. The depression of fuel diffusion was weakened, which thus improved the
818 evaporation rate. The impact of particle type on the evaporation of deionized water droplet was
819 studied by Chen et al. [122]. The results showed that droplet evaporation with 0.05% Ag
820 nanoparticles and 1% surfactant was larger than that of pure deionized water droplet. However,
821 droplet evaporation with 0.05% Fe₂O₃ nanoparticles and 1% surfactant was smaller than that of
822 pure deionized water droplet. This may be because the ability to absorb radiation is different
823 for different particles, so that the competitive relationship between promoting and inhibiting
824 effects of particles on evaporation was changed. Ghamari and Ratner [114] studied the impact
825 of carbon shape (nanoparticles, nanotubes and nanoplatelets) on the evaporation of aviation fuel.
826 They reported that carbon nanotubes had the best effect on promoting droplet evaporation.
827 Ferrão et al. [121] found that the size of aluminum nanoparticles had insignificant effect on
828 droplet lifetime and micro-explosion strength of hydro-processed vegetable oil.

829

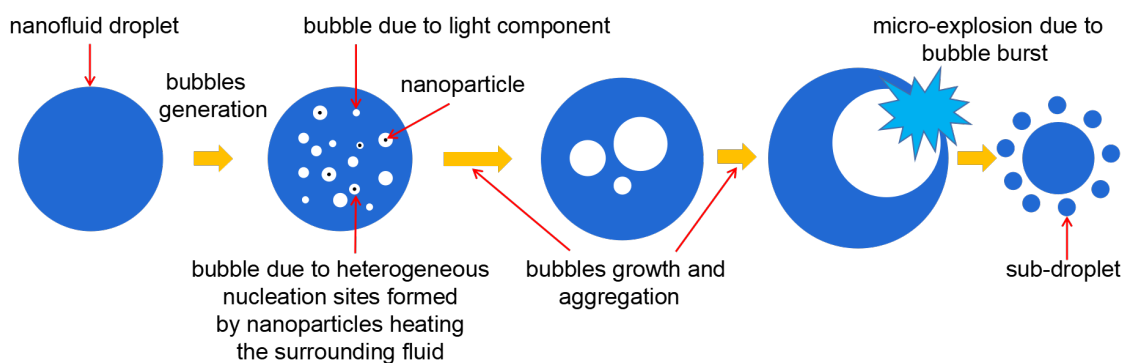
830 *6.3. Micro-explosion modes*

831 **Table 5** summarizes the mechanisms of micro-explosion of nanofluid fuel droplet. Micro-
832 explosion of nanofluid fuel droplet is caused by the rupture of bubbles generated inside the

833 droplet, which is the same as the micro-explosion of miscible multi-component fuel droplet.
 834 However, the sources of bubbles are different. There are two bubble sources in the nanofluid
 835 fuel droplet. The first one is from the evaporation of light components, and the other is produced
 836 by heterogeneous nucleation sites due to the heating of nanoparticles on the surrounding fluid.
 837 Small bubbles merge into larger ones under the van der Waals force, surface tension and droplet
 838 internal flow. The bubble bursts once the bubble pressure is larger than the sum of droplet
 839 surface tension and ambient pressure, leading to the distortion and breakup of the droplet, as
 840 shown in **Fig. 12**.

841 **Table 5.** Mechanisms of micro-explosion of nanofluid fuel droplet.

Refs.	Droplet components	Nanoparticles	Mechanisms of micro-explosion
Javed et al. [54]	kerosene	Aluminum	Heterogeneous nucleation sites were formed by temperature of aluminum nanoparticles exceeding the boiling point of kerosene and evaporation of overheated light components, leading to bubble burst and micro-explosion.
Wang et al. [118]	Diesel	Ceria	Bubble rupture was produced by heterogeneous nucleation sites that were formed by nanoparticles' heating on surrounding liquid and the evaporation of light components, leading to micro-explosion.
Dai et al. [123]	Diesel	Cerium oxide	The burst of bubble produced by heterogeneous nucleation sites and evaporation of light components led to micro-explosion.
Wang et al. [36]	Diesel	Cerium oxide	The temperature of nanoparticles was higher than the liquid temperature, which formed a local hot spot and became a heterogeneous nucleation site to generate bubbles. The burst of bubbles caused micro-explosion.
Ferrão et al. [121]	Hydro-processed vegetable oil	Aluminum	Particles accumulated on droplet surface formed a local hot spot, which induced nucleation to produce bubbles. The rupture of bubbles caused micro-explosion.



842

843

Fig. 12. Schematic diagram of micro-explosion of a nanofluid fuel droplet.

844

845 **7. Challenges and future research directions**

846 In spite of significant experimental investigations on the evaporation characteristics of fuel
847 droplets, there are still many research gaps that should be addressed, which are concluded as
848 follows:

- 849 • All current experimental methods for fuel droplets have their own disadvantages, as
850 discussed in section 2. Therefore, researchers have to choose a relatively appropriate
851 method according to their research purposes. In the case that existing methods are difficult
852 to improve, advanced numerical methods are needed to eliminate the effect of external
853 conditions on droplet evaporation.
- 854 • The tested droplet size is generally at the millimeter level, while the spray droplet size in
855 real engines is at the micrometer level. Thus the evaporation characteristics of the fuel
856 droplets may be different. However, the preparation and measurement of an isolated micron
857 droplet is very difficult, which could be evaporated very quickly (within 50 ms) [65].
858 Therefore, advanced simulation methods are needed to investigate evaporation
859 characteristics of micron droplets. To achieve this, the experimental data on evaporation
860 characteristics of millimeter droplets are very valuable for verifying and optimizing the
861 numerical models.
- 862 • Most of the experiments on multi-component fuel droplet evaporation were conducted
863 under atmospheric pressure and static conditions. For in-cylinder direct injection engines,
864 fuel is generally injected at the end of the compression stroke when the pressure is higher
865 than atmospheric pressure and the ambient gas is turbulent, which may cause different
866 droplet evaporation characteristics. Future studies are needed to investigate droplet
867 evaporation under elevated pressure and turbulent conditions.
- 868 • Due to experimental limitations, there is a lack of studies on droplet internal behavior. The
869 microscopic mechanism of droplet evaporation has not been clearly understood. There are
870 few studies on the effect of initial size of multi-component fuel droplet on micro-explosion.
871 However, there is no consensus in the existing studies, which needs further investigations.
- 872 • Current studies only concerned one droplet in isolation, but did not combine it with jet
873 spray research. Optimizing fuel spray and combustion based on the evaporation
874 characteristics of fuel droplets can provide useful guidance for better fuel utilization in real
875 engines.

876

877 **8. Conclusions**

878 Investigating the evaporation characteristics of a fuel droplet is of great significance for a
879 cleaner and more efficient use of fuels in engines. This paper critically reviews the current
880 experimental studies on the evaporation characteristics of a fuel droplet in different fuel
881 components. The major conclusions are summarized as follows:

882 (1) There are three research methods for fuel droplet evaporation, including suspension, flying
883 drop and levitation. Each method has its own advantages and disadvantages, leading to
884 different applications. Among them, suspension and levitation methods are the most widely
885 applied due to their simple setups and convenient measurements.

886 (2) The evaporation process of a single-component fuel droplet is divided into two stages:
887 transient heating and equilibrium evaporation. Droplet evaporation are affected by the fuel
888 boiling point, latent heat of evaporation and other physical and chemical properties (e.g.
889 mass diffusivity). The droplet evaporation rate increases with the initial droplet diameter
890 and droplet lifetime increases with the ambient pressure. Turbulence promotes droplet
891 evaporation, but the degree of impact is weakened with the increase of turbulence intensity.

892 (3) There are puffing and micro-explosion phenomena in the evaporation process of miscible
893 multi-component fuel droplet, which breaks up the droplet to increase the evaporation
894 surface area and thus the droplet evaporation. A larger difference in the boiling points of
895 components and a higher ambient temperature are favorable for puffing and micro-
896 explosion, thereby improving the droplet evaporation. There is an optimal concentration of
897 light component at around 50% for droplet evaporation.

898 (4) Liquid-liquid immiscible multi-component droplet also has puffing and micro-explosion
899 phenomena that promote droplet evaporation. The micro-explosion is related to the
900 aggregation and superheat of dispersed phase. Greater aggregation and overheat increase
901 the probability and intensity of micro-explosion. There is an optimal size and concentration
902 of dispersed phase for micro-explosion. Increasing the emulsifier concentration and fluid
903 viscosity reduce the probability of micro-explosion. Reducing impurities and initial
904 temperature of the dispersed phase are conducive to the occurrence of micro-explosion.
905 The initial droplet size may have an effect on micro-explosion, which needs a further
906 research.

- 907 (5) Nanoparticles could either enhance or reduce the evaporation of liquid-solid immiscible
908 multi-component fuel droplet, which are determined by their materials, shape, and
909 concentrations. Nanoparticles with a stronger ability to absorb heat radiation may facilitate
910 droplet evaporation, while the effect of particle size is not obvious. There is an optimal
911 concentration of nanoparticles for droplet evaporation.
- 912 (6) Future studies need to develop more advanced experimental and numerical methods to study
913 droplet evaporation and its internal behavior under real engine conditions. Meanwhile,
914 studies on fuel droplet evaporation should be combined with fuel spray and combustion to
915 provide guidance for improving engine performance.

916

917 **Declaration of Competing Interest**

918 The authors declare that they have no known competing financial interests or personal
919 relationships that could have appeared to influence the work reported in this paper.

920

921 **Supplementary Information**

922 Additional information about evaporation of miscible multi-component fuel droplets
923 (Table S1), micro-explosion of liquid-liquid immiscible multi-component fuel droplets (Table
924 S2), and evaporation of nanofluid fuel droplets (Table S3).

925

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