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Review

Micro-Explosion Phenomenon: Conditions and Benefits

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Abstract: Adding water to fuel droplets is known to lead to puffing and micro-explosion. Puffing and micro-explosion lead to a rapid increase in the liquid fuel surface area. This, in turn, leads to an increase in the fuel evaporation rate and the formation of a homogeneous fuel vapor/air mixture. The latter is important for improving the efficiency of combustion technologies, including those used in internal combustion engines. The effects produced by puffing and micro-explosion lead to a reduction in fuel consumption, improved fuel/air mixing, and a reduction in harmful emissions. The contributions of puffing and micro-explosion to fire extinguishing have also been discussed in many papers. In this paper, we review the state of the art in the investigation of composite droplet micro-explosion and discuss the sufficient conditions for the start of puffing/micro-explosion as well as child droplet characteristics.

Keywords: composite droplets; emulsions; heating; evaporation; puffing; micro-explosion; critical conditions; child droplets

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1. Introduction

The study of threshold conditions, regimes, and behaviors of heterogeneous droplet breakup has been a trending topic of the latest research into the atomization of liquids with different component compositions. Just a few research findings on the behavior of secondary droplets during the micro-explosive breakup have been published so far, especially considering the heating schemes with convective, radiative, and mixed heat exchange. The component composition of secondary droplets is extremely difficult to predict reliably because the existing experimental setups, as well as hardware and software systems, have their limitations, and it is necessary to employ specialized tracking systems with a set of dye additives. The state of the art in world research indicates that the atomization of multi-component droplets is studied experimentally and theoretically in research centers and laboratories in Japan [1–9], Great Britain [10–20], Germany [21–23], the USA [24–39], Sweden [40,41], Italy [42], Israel [43], France [44–51], China [52–84], Malaysia [85–93], Saudi Arabia [94], Korea [95–100], India [101–110], Mexico [111], and Russia [10,112–156]. They obtained new data on droplet shapes, motion patterns, and dispersion using non-contact optical methods. It is important to study the atomization processes using optical techniques (PIV, PTV, IPI, SP, PLIF, LIP, two-color LIF, etc.), high-speed hardware and software systems, specialized tracer particles, and tracking software, and then to describe these processes in the form of physical and predictive mathematical models. In many modern papers dealing with micro-explosive atomization, the researchers focus on the experimental research of mechanisms and factors influencing the micro-explosive breakup behavior of droplets. They usually study mixed and immiscible liquids in a parent droplet [141,157]. Some researchers also deal with fuel-in-water emulsions [41], fuel blends in which micro-explosion occurs during combustion [158], as well as slurry fuels [133]. The main impact on the micro-explosive behavior comes from the following factors: ambient gas temperature [62,133], concentrations of gases dissolved in the liquid [5,9], size of the dispersed phase of water droplets in fuel-in-water

emulsions [42,159–164], component concentration ratio [16,83,104,165], concentration and size of solid particles [166–171], etc.

The key theoretical research findings are presented in Refs. [11,19,54,57,67,172] where the authors used their own in-house program codes. These models used experimentally established criteria to predict the time of breakup delay of multi-component droplets. Superheating of the inter-component interface [11], reaching the critical droplet size due to the vapor bubble growth [19,57,67], exceeding the critical thickness of the oil film [54], reaching the critical value of inertial forces acting on a droplet [172] can be used as such criteria. They make it possible to predict micro-explosion delays within the established boundaries with acceptable accuracy. These models have a number of assumptions and apply some constraints when predicting the breakup outcomes, the secondary droplet behavior in particular. With this in mind, it is necessary to create an experimental database, capable of describing the size and velocity distributions of secondary droplets resulting from the micro-explosion, controlling for the key factors (ambient temperature, component concentrations, and solid particle size), so that the resulting approximations could be used in models. It is especially important to develop these methods in the field of resource-efficient fuel technologies, thermal treatment, and gas-vapor-droplet heat carriers (Figure 1).

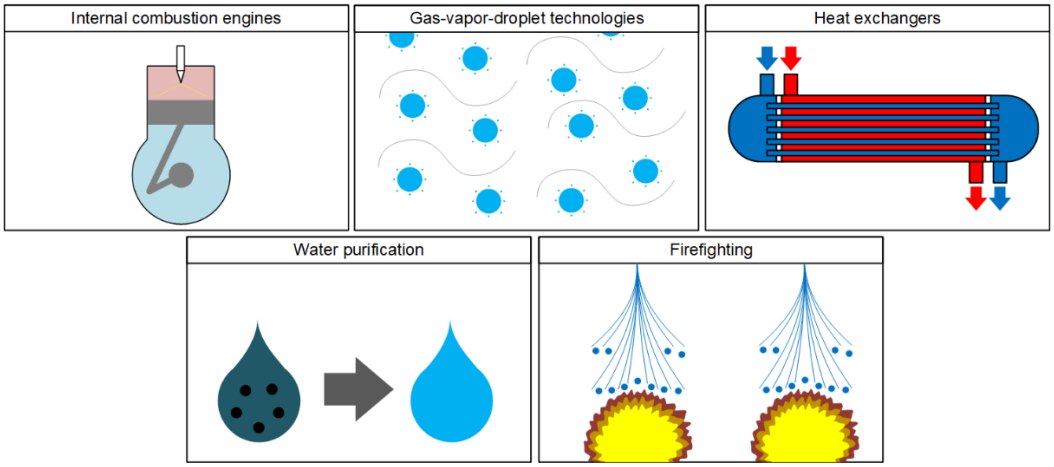

Figure 1. High-potential fields of use for the micro-explosive atomization of liquid droplets.

In contrast to puffing/micro-explosion phenomena, there are well-known combustion-induced rapid phase transition (CRPT) effects. Combustion-induced rapid phase transition (CRPT) [173–175] is also an important phenomenon in combustion theory, which is connected with explosion effects. Such effects are usually performed in $CH_4/O_2/N_2/CO_2$ mixtures [173–175]. Pressure dynamics during time have been found to reach peak values up to 20 times higher than adiabatic values (up to 240 bar) [173]. The use of such critical pressure in technology leads to severe fire and explosion safety issues [176,177] due to the increased reactivity of $CH_4/O_2/N_2/CO_2$ mixtures. The occurrence of high-pressure values has been addressed as a physical phenomenon: the water produced by combustion undergoes condensation at the walls of the vessel and, subsequently, rapid phase transition [178].

The aim of this review is to summarize the known research findings obtained by the world scientific community in the field of the micro-explosive breakup of liquid droplets exposed to intense heating. The focus is on studying the necessary conditions for stable droplet fragmentation and the characteristics of the resulting secondary liquid fragments. There are no available similar reviews in the literature. The significance of this research is summarizing a large amount of experimental and theoretical data in the field of puffing and micro-explosion phenomena from conditions to benefits as part of research in combustion teary.

2. Fragmentation Regimes and Critical Micro-Explosion Conditions

Secondary atomization of droplets in multi-component and multi-phase fuel flows is a promising approach to the development of technologies that can help reduce fuel consumption, anthropogenic emissions, and equipment wear, as well as stabilize fuel atomization in combustion systems [179–184]. The most effective secondary atomization methods are as follows: droplet/droplet collisions in intersecting fuel jets [185], droplet/solid surface (walls, meshes, rings, and ledges) collisions [186], puffing and micro-explosion [46,49,50]. A micro-explosion makes multi-component and multi-phase fuel droplets break up to form a cloud of child droplets, 1–100 μm in size [179]. This leads to multiple increases in the evaporation surface and chemical reaction area in a combustion chamber. Here, obtaining a fine mist by means of a micro-explosion is the optimal case from the perspective of saving both time and energy spent on droplet heating to fragmentation. In the first stages, specialists studied internal and external factors that affect micro-explosion conditions. It was established that the superheating of water at the water/fuel interface above the boiling point is the main reason triggering puffing and micro-explosion [141]. The research into composite droplet breakup outcomes is also an important objective (for instance, the size of the mist cloud and secondary fragments in it). Knowledge of the conditions that lead to the formation of child droplets with specific sizes and velocities is required for the optimal operation of process equipment [180,187,188]. The fragmentation of composite droplets is influenced by a key factor. For instance, the size of the dispersed phase in emulsions (micro-droplets of water in a drop of a combustible liquid) depends on the child droplet sizes and velocities, and, hence, on their momentum [164]. The size distributions of the child droplets obtained in the experiments are near-normal and symmetrical under the same conditions [164]. Refs. [46,49] mostly focus on the kinetic, thermal, and surface energy of child droplets. Tarlet et al. [46] determined the thermal energy distribution as a function of the number of forming child droplets and suggested that the distributions were logarithmic. Kinetic energy distributions of secondary fragments were established in Ref. [49], and their log-normal distribution was proposed. The micro-explosive breakup frequency of emulsions heavily depends on the parent droplet size and the size of the dispersed phase [89].

Experimental studies [46,50,147,150,156,160,189] are devoted to the processes of puffing/micro-explosion of slurry and emulsion droplets heated in high-temperature gas. The threshold temperatures at which this effect emerged were determined for several liquid and solid organic additives. The breakup of composite droplets was found to increase their evaporation surface by a factor of 12 to 15. To enhance the efficiency of thermal treatment technologies, it is essential to carry out experiments on the heating and evaporation modes of typical compositions. Of special interest are investigations seeking to improve fuel atomization in economic, environmental, and energy performance [47,190,191].

Figure 2 illustrates typical images showing the known regimes of fuel emulsion droplet heating, thermal expansion, evaporation, puffing, and micro-explosion. Each of the outcomes had its own special aspects. For instance, the monotonous evaporation regime was notable for the rapid heating and evaporation of the droplet without secondary fragments breaking off (Figure 2a). In the puffing regime, bubble nucleation mostly occurred locally rather than throughout the entire volume (Figure 2b). Bubble implosion was accompanied by droplet fragments breaking off the holder. The micro-explosion regime, notable for intense bubble nucleation throughout the entire volume, occurred at a higher gas temperature or with a higher concentration of the combustible liquid. At the initial stage, as the droplet was being heated, the surface remained virtually intact, but then there was a loud popping sound, and the droplet broke up instantaneously into an aerosol with detectable vapors. The vapors were detected using a special camera.

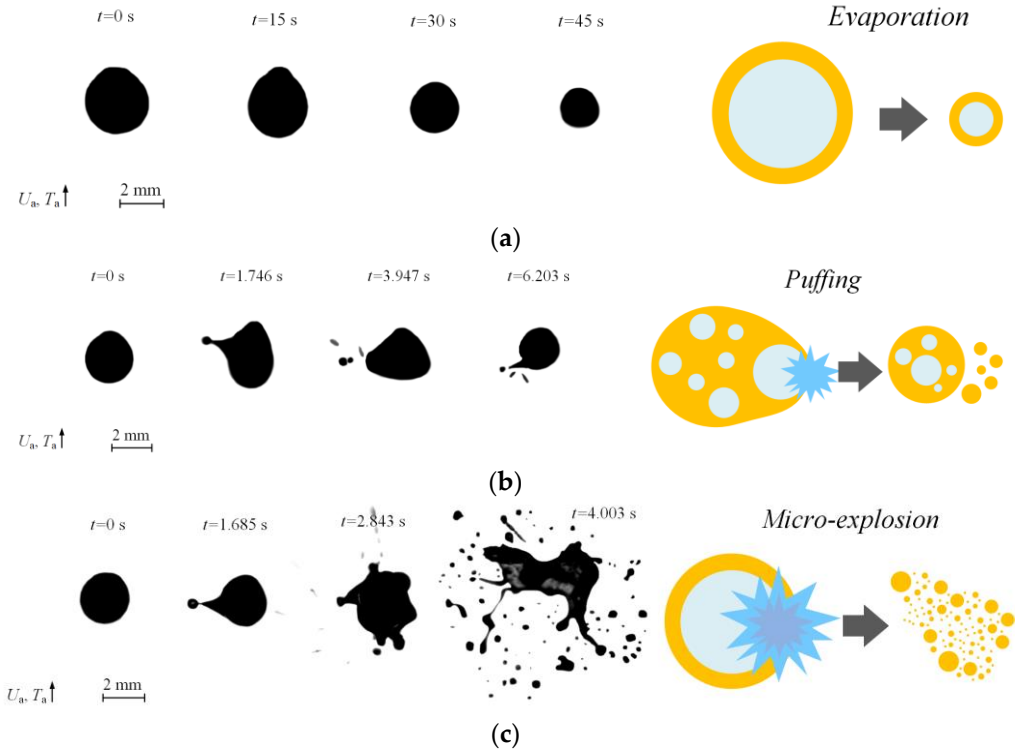

Figure 2. Typical images and schemes of fuel emulsion droplet heating, expansion, evaporation, puffing, and micro-explosion regimes (U_a = 3 ± 0.1 m/s, R_{d0} = 1.2 ± 0.1 mm, η_f = 90 ± 5%) obtained using the method described in Ref. [116]: (**a**)—evaporation without fragmentation (T_a = 473 ± 5 K), (**b**)—puffing (T_a = 573 ± 5 K), (**c**)—micro-explosion (T_a = 673 ± 5 K).

Figure 3 highlights the temperature ranges in which different modes of two-liquid droplet heating, evaporation, puffing, and micro-explosion occurred. The transient areas are shaded where two outcomes were observed with different repeatability.

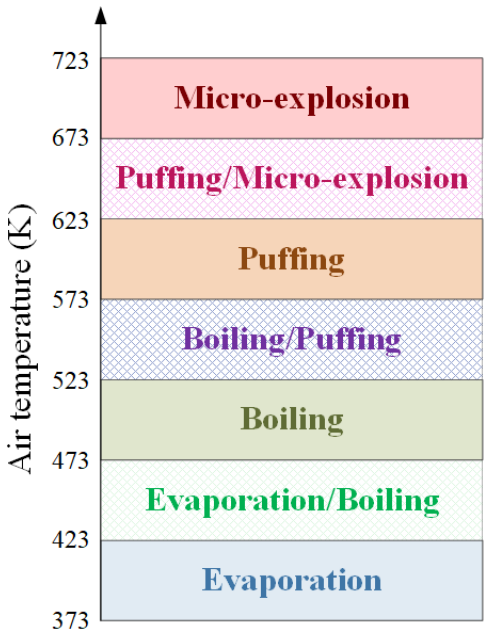

Figure 3. Temperature ranges of micro-explosion regimes of two-liquid droplets (95% of distilled water/5% of kerosene, V_d = 15 ± 1 µL, U_a = 2 ± 0.1 m/s) singled out by analyzing the research findings from Ref. [141].

The main physical mechanism of two-liquid droplet breakup involves water superheating before the droplet fragmentation. The two-liquid droplet temperature fields obtained experimentally by the PLIF method [141,192] demonstrate that at the water/fuel interface, water reached its boiling point (i.e., 373.15 K). The combustible liquid temperature near the water/fuel interface could reach 383–393 K. This illustrates the superheating effect at the water/fuel interface, which leads to puffing and micro-explosion. At the same time, cases are known [141,192] when a two-liquid droplet is heated throughout its volume to a temperature of 353–363 K, evaporates monotonously, and does not atomize (i.e., maintains its integrity). The local superheating of two-liquid droplets is what activates low-temperature vaporization centers [193,194] and ultimately leads to droplet destruction. The latter is accompanied by visual effects producing a fine aerosol.

According to the published research findings on micro-explosive breakup [4,45,48,51,88,135,141,156], a group of factors (concentration of liquids, original droplet size, and the heat flux supplied to the droplet surface) has a decisive influence on the main characteristics: duration of the process and child droplets size and number. In the case of emulsion droplets, the following is also considered important [163,187,195]: the size of the dispersed-phase droplets (water droplets within a flammable liquid, for instance, kerosene and Diesel fuel) as well as the type and concentration of the stabilizer.

3. Characteristics of Secondary Fragments

Research into the outcomes of the micro-explosive breakup of composite fuel droplets, such as the sizes of secondary droplets and the aerosol cloud incorporating them, is yet another major objective when studying the patterns of micro-explosive breakup. In particular, the size of the parent droplet influences the features of dispersion. However, the size of the parent droplet only marginally affects the size of child droplets [89]. Antonov et al. [130] investigated the impact of the holder material, energy supply scheme, component concentrations, as well as parent droplet size and type on the characteristics of child droplets. The results obtained demonstrate that the child droplets produced from the fragmentation of composite droplets are smaller in size than those produced from the fragmentation of emulsion droplets of the same original size and composition [130]. It was also experimentally established [130] that the heating scheme and original parent droplet size affect the child droplet characteristics more than any other factors under study. The initial temperature of the water inside the two-fluid droplet also affects the child droplet characteristics [117]. According to the research findings, the smallest child droplets size and hence the greatest free surface area of the liquid increase can be obtained under conditions of the minimum initial temperature of the water and maximum heating temperature [117]. The fragmentation mode (puffing or micro-explosion) is the key factor influencing the size and number of the child droplets. Micro-explosion usually produces a large number of child droplets with minimum size, whereas the child droplets generated by puffing are much fewer in number but larger in size [130,141]. The typical differences in the distributions of child droplets produced by puffing and micro-explosion were presented in [119]. Just like parent droplets, child droplets undergo puffing and micro-explosion as well as cascade secondary atomization [196]. The summarized research findings on how the rheological properties of water-in-diesel emulsions affect the child droplet characteristics can be found in Ref. [115]. It was established that the child droplet characteristics depend heavily on the surface tension and viscosity of a multi-component liquid. By varying these parameters of liquid components, one can intensify the micro-explosion efficiency by 6–7 times [115].

Some experiments [16,73,82,104,165,197,198] focus on the main ignition and combustion characteristics of multi-component fuel. The emphasis here is on child droplet size and velocity in an aerosol cloud: they heavily depend on the breakup regime, heating temperature, oxygen content in the ambient gas, as well as component concentration [73,76,82,86,104,165,199,200]. Avulapati et al. [165] established that the probability of large fragments being produced (several-fold larger than the smallest child droplets) is insignificantly higher during micro-explosion than during puffing. According to the

research findings in Ref. [104], abrupt explosion mode produces the smallest child droplets. The child droplets characteristics produced by ejection and bubble rupture are smaller than those produced by micro-explosion [76]. The ambient gas temperature does not only affect the breakup regime but also the size of the emerging child droplets. So, Refs. [119,129] Show that the average size of child droplets decreases with an increase in temperature, which leads to a significant increase in the free surface area of the water and fuel after the breakup. The size of child droplets also depends on the composition of the initial droplet [104]. The child droplet number, size, and velocity can also be affected by the concentration and structure of solid particles. Ojha et al. [197] present the distributions of child droplet velocities as a function of their diameters. According to the findings [197], the child droplet velocities increase, and their sizes decrease with an increase in the proportion of solid additives. By adding solid coal particles to the fuel, one can intensify the micro-explosive breakup of composite droplets [116]. The smaller the solid particles, the smaller the average size of child droplets resulting from puffing/micro-explosion. An increase in the heating temperature does not only change the child droplet size but also their component composition: with an increase in the gas temperature from 523 to 823 K, the average proportion of water-only child droplets produced from composite droplets goes down from 27% to 3% [201]. Research findings of characteristics of secondary fragments are summarized in Table 1.

Avulapati et al. [16] showed that there are two modes of micro-explosion: with a stronger and weaker vapor discharge. They differ significantly in concentrations and vaporization rates. The droplets produced during a strong vapor discharge are smaller in size, but their relative velocities are higher. Smaller child droplet sizes improve their intermixing with the ambient air and intensify their evaporation, which is important for the development of liquid and slurry fuel ignition, combustion, and evaporation technologies. Combustion processes are often characterized by the normalized diameter [165] and the droplet normalized square diameter [79,104,197]. These functions are used to illustrate the fragmentation modes, which help determine the evaporation and combustion rate, as well as the fragment disruption intensity and velocity relative to the parent droplet surface.

Recent papers in the field of child droplet behavior (in particular, [114]) focus on studying and analyzing the joint effects during the heating, evaporation, and micro-explosion of a group of composite droplets. When droplets in a fuel aerosol undergo puffing/micro-explosion, the resulting child droplets interact with parent and child droplets [114] with the following outcomes: droplets collide with each other to form smaller fragments with the subsequent micro-explosion of the latter; one droplet breaks up into secondary fragments that interact with adjacent droplets (chain-like fragmentation of neighboring droplets due to high kinetic energies and velocities of secondary fragments); puffing occurs together with micro-explosion; droplets collide in the bounce and separation regimes with the subsequent redistribution of the combustible and noncombustible liquids. Figure 4 schematically shows the joint effects of the micro-explosion breakup of composite droplets in a fuel aerosol. These effects have a significant influence on the droplet size in the aerosol, so they are important to consider when designing process equipment. The density of multi-component droplet arrangement in an aerosol also significantly affects the child droplet characteristics. The temperature and aerodynamic traces emerging during evaporation reduce the temperature of the flow behind the droplet. This prolongs the breakup delay time and leads to changes in the fragmentation regime [120]. By varying the distance between parent droplets, i.e., the density of their arrangement in an aerosol cloud, one can control the sizes of secondary fragments of each parent droplet [120]. Fuel fragments fill the combustion chamber most effectively when the distance between parent droplets exceeds 8–10 of their radii.

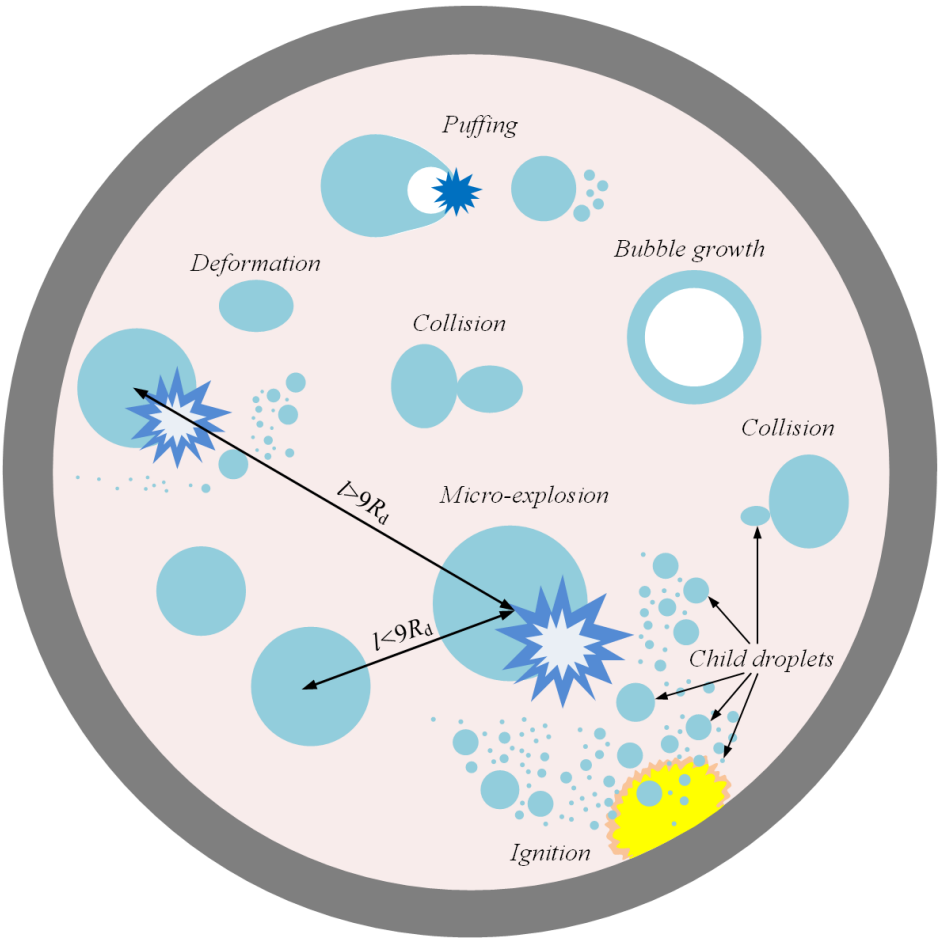

Figure 4. Joint effects of micro-explosive atomization of multi-component droplets in a model chamber based on the analysis of research findings [114].

Table 1. Known data on the characteristics of droplet micro-explosion for different liquids.

References	Composition	Factors Covered
[16]	Diesel fuel–Biodiesel–ethanol emulsion	- Fragmentation regimes
[165]	Diesel fuel–Biodiesel–ethanol blends	- Component concentrations
[104,199]	Ethanol/Jet A-1 blends Butanol/Jet A-1 blends Acetone-butanol-ethanol (ABE)/Jet A-1 blends	- Component concentrations - Type of combustible component - Fragmentation regimes
[86]	GTL–Diesel fuel blends	- Component concentrations - Fragmentation regimes
[200]	Biodiesel-acetone-butanol-ethanol (ABE) blends	- Component concentrations - Heating temperature - Fragmentation regimes
[46,49,164]	Water-in-sunflower oil emulsion	- Diameter of the dispersed water - Surface and kinetic energies

Table 1. *Cont.*

References	Composition	Factors Covered
[89]	Water-in-Diesel fuel emulsion	- Parent droplet size - Water content
[130]	Two-components and emulsion droplets (Diesel fuel, rapeseed oil, water)	- Energy supply scheme - Holder material - Component concentration - Parent droplet size - Parent droplet type
[117]	Two-component rapeseed oil/water droplets	- Initial water temperature
[115]	Water-in-Diesel fuel emulsion	- Viscosity, interfacial, and surface tension
[197]	Jet A-1 with boron particles	- Concentration of solid particles - Structure of solid particles
[119,129]	Two-component and emulsion rapeseed oil/water droplets	- Ambient gas temperature
[116]	Composite droplets (rapeseed oil, water, coal microparticles)	- Concentration, size, and type of solid coal particles
[79]	Biodiesel/ethanol blends	- Ethanol content - Heating temperature - Gas flow
[56]	two-components and emulsion droplets (Diesel fuel, rapeseed oil, water)	- Joint effects during micro-explosion

Research findings are most often presented using the probability density of child droplet size and velocity distribution in a certain unified form (for instance, [202,203]). Zhao et al. [204] present that log-normal or gamma normal distributions describe the probability density of fragment size distribution. The fragment size distributions as a function of the fragment number or volume fraction are typical of atomization-related research [205]. Research findings can also be presented as dimensionless functions. For instance, parent and child droplet velocities can be presented as a function of normalized time [206].

Research into child droplet characteristics (size, number, velocities, trajectories, temperature, and component composition) during micro-explosion is one of the vital tasks and a major logical link in the development of the multi-component fuel phase transition theory. Today, there is no unified theory of child droplet generation during micro-explosion. To gain a deeper insight into phase transitions and to introduce these effects into liquid and slurry fuel combustion technology, it is necessary to develop mathematical models that will predict child droplet characteristics depending on the factors above.

4. Current Models of Micro-Explosive Droplet Fragmentation

Most of the models of micro-explosive phenomenon use commercial software packages with built-in specialized numerical methods. Combined application of DNS (discrete numerical simulation) [18,19,165] and VOF (volume of fluid) [15,20,207] methods is the most popular numerical approach to the solution of the micro-explosive breakup of two-liquid droplets in a gas. In-house program codes are also widely used by scientists for the investigation of the micro-explosion of two-liquid droplets [10,11,113,208]. Several hypotheses have been formulated on the physical patterns of the micro-explosive droplet

breakup [18,19,57,113,116,165,209]. Wang et al. [210] experimentally established that micro-explosion occurs after the appearance of one or two large vapor bubbles near the center (core) of the droplet. The difference in the component volatiles directly affects the bubble occurrence. The bubble occurs in a droplet if the droplet is heated to the boiling point of the least volatile component [210]. Li et al. [211] established that the superheating degree affects bubble generation inside the droplet and further breakup. The breakup was found to occur because bubbles expand inside a droplet, and its surface tension decreases due to superheating [132]. High-velocity convective flows at the liquid/liquid interface serve as another breakup mechanism [135], which triggers the interface disruption followed by the droplet breakup. The first and, at the same time, quite simple model of the micro-explosive breakup of typical two-liquid droplets was based on the water/fuel interface superheating above the boiling temperature as the criterion of the said breakup [11]. When heated, the least volatile component (water) concentrates in the core of the droplet. It is superheated to temperatures sufficient for bubble nucleation, thus triggering the droplet breakup [11].

The widely used models of the micro-explosive breakup, for example, [18,19,57,165,209], have some limitations related to the input experimental data affecting the numerically obtained results. In addition, these models do not consider some effects and processes in the absence of definite experimental data or due to the complexity of the calculation. Some processes and factors (see Ref. [11] for the main ones) hinder the development of more complex and generalized models of two-liquid droplet micro-explosive breakup, including the links between breakup mechanisms and outcomes. For these reasons, it is of great interest to theoretically study the heating, evaporation, swelling, and micro-explosive breakup of liquid droplets using the most typical threshold conditions of breakup (secondary atomization) [18,19,57,165,209]: superheating of the water/fuel interface above the explosive boiling temperature, critical size (radius) of a bubble before the breakup, and exceeding the pressure in the vapor film.

The physical and mathematical models of heat transfer before micro-explosion using several criteria (the criterion of the critical nucleation temperature at the water/fuel interface, the exceeded threshold pressure in the vapor film as the criterion, the critical bubble size (radius) as the criterion) are presented in Ref. [126]. The first model is based on the assumption that a two-fluid drop consists of a spherical water droplet in the center and a fuel film enveloping it.

The heat and mass transfer conditions in a two-liquid droplet in the second model are described in a similar way to the statement of the first model. The main difference was in the balance of forces acting on the droplet being heated due to the surface tension, water vapor pressure, and ambient gas pressure. When the pressure in the vapor film at the water/fuel interface exceeded the surface tension and ambient gas pressure, this was regarded as the criterion of micro-explosion.

The critical bubble size (radius) criterion is used in the third model. The assumption used in the model is that the vapor bubble is located in the center of the water core, and fuel envelops it. The Eulerian method based on a fixed uniform mesh was used to solve the problem. The interface was tracked using continuous Eulerian markers by means of the VOF method [207]. The gas and liquid phases are regarded as a single multi-component medium. The spatial distribution of phases in the computational domain is obtained by means of a special function of the marker $F(x, y, z, t)$. The volume fraction of a phase in a computational cell is taken as 1 if the cell is filled with the phase and as 0 if the cell is empty. If the interface crosses the cell, then $0 < F(x, y, z, t) < 1$.

The micro-explosion criterion for a model based on the critical bubble size (radius) implies tracking the threshold bubble radius R_{bubble}. The critical value of R_{bubble} is set from the experiments. As a rule, a mesh is added to the videograms for continuous monitoring of the bubble size. The use of the critical bubble size (radius) as the criterion of micro-explosion is valid for spherical droplets and when the bubble is located in the center according to the scheme of the solution space. The criterion of the critical bubble size is associated with the liquid film around it (δ_f) reaching a critical thickness.

The experimental conditions affect the emerging droplet shape, which may be spherical or ellipsoidal. As a result, it is sensible to consider the droplet shape and initial location of nucleation in it when modeling the micro-explosive fragmentation. In most of the experiments, droplets deformed rapidly when traveling in a gas and consecutively took the shapes of a prolate ellipsoid, sphere, oblate ellipsoid, and sphere (i.e., they underwent deformation cycles). Thus, to approximate the modeling results to the experimental data, the characteristics were calculated with varying shapes observed in the experiments, and the resulting values were averaged. The droplet shape has a significant impact on the integral micro-explosion characteristics not only because the critical values of the liquid film thickness are reached faster when a droplet with a bubble becomes prolate or oblate. It also heavily depends on the growth of the aerodynamic drag force. In particular, the values of the aerodynamic drag coefficient for the spherical and ellipsoidal droplet shapes differ by 1.4–1.7 times [208]. The higher the inertia acting on the droplet, the more intensely its surface deforms in a gas. Liquid heating enhances this deformation [208]. These conditions intensify the micro-explosion of heated parent and child droplets even more.

5. Relevant Objectives and Solutions

The component composition, size, velocities, trajectories, and other characteristics of secondary droplets produced during micro-explosive fragmentation have not yet been studied comprehensively (Figure 5). In particular, according to published experimental data, the conditions for modes of the breakup of two-liquid droplets were established: evaporation (T_a = 300–400 K), puffing (T_a = 400–600 K), and micro-explosion (T_a = 600–1500 K) [141]. The most promising modes for the intensification of heat and mass transfer processes are puffing and micro-explosion. These modes of breakup lead to an increase in the droplet evaporation surface area by tens and hundreds of times. It has been established that when droplets are heated on a substrate, the times to puffing/micro-explosion and the number of secondary fragments are significantly less than in the air flow and in a muffle furnace [140]. Under heating conditions on the substrate, the increase in the droplet evaporation surface area did not exceed 10–20 times. The times to puffing/micro-explosion correspond to a high gas temperature (above 1000 K), small parent droplet sizes (below 500 μm), and a high concentration of combustible liquid (above 90%) [12]. Despite the list of complex and interesting experimental results, it is necessary to create an extensive experimental database on the micro-explosions of heterogeneous liquid droplets especially to separate modes of breakup using nondimensional criteria. The database should contain secondary droplet characteristics (number, size, component composition, velocities, trajectories, shape, collision outcomes in a flow, as well as joint effects), their dependences on the parent droplet parameters, atomization conditions (pressure, flow rate, jet type), and spray heating (heating scheme and rate, temperature, pressure) to use generalized experimental dependences for mathematical modeling. It is still a relevant task to develop mathematical models simulating the micro-explosion of parent droplets based on classical nucleation theory, kinetic nucleation theory, density functional theory, and heterogeneous nucleation theory, that would predict the secondary droplet characteristics. Now there is only simple classical models [113,123,126] of puffing/micro-explosion phenomena related to main conditions (the critical nucleation temperature at the water/fuel interface, the exceeded threshold pressure in the vapor film, the critical bubble size (radius)). Unfortunately, such models could not predict the child droplets after the breakup of parent droplets. The way to decide these problems is by using direct numerical simulations [6,14,19,20] or molecular dynamics models [1]. However, in these cases, there are certain requirements to mesh quality and sizes that are not absolutely clear at the moment.

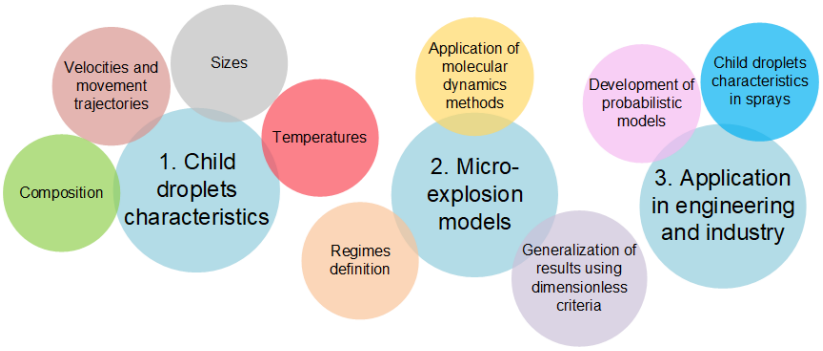

Figure 5. Schematic representation of promising trends in the development of science and technology related to micro-explosions.

Fundamentally, it is necessary to understand how to separate the puffing and micro-explosion regimes using the modeling methods of molecular dynamics and experimental data to create a complex multi-component model of explosion and evaporation controlling for various factors (fast depressurization and fast heating) with a minimum number of empirical constants, as well as to summarize the research findings using dimensionless parameters (Reynolds, Weber, Ohnesorge, Jacobi, and Bond number, etc.). It seems relevant to introduce in-house codes to commercial software packages, for example, Ansys Fluent, Comsol Multiphysics, Matlab, Mathematica, and OpenFOAM (Figure 5).

From a practical standpoint, it is important to transition to the use of micro-explosion in power plants, airplane engines, ground-based power systems, etc. (Figure 5). This will require: (i) creating a database with the characteristics of secondary fragments produced by the micro-explosion of a small array of neighboring parent droplets arranged in a spray according to different schemes (the experimental methods and setups should be adjusted to identify the component composition, size, velocity, and other secondary droplet characteristics); (ii) developing probabilistic models simulating micro-explosions of droplets in sprays controlling for coalescence, bounce, separation, and disruption of neighboring parent and child droplets.

6. Conclusions and Perspectives

(i) Micro-explosion is a momentary breakup of a parent heterogeneous droplet into an array of secondary fragments with a size ranging from several dozens to several hundreds of micrometers. The breakup is caused by the boiling of the internal water core or several cores. Researchers typically focus on water as the inert liquid and Diesel fuel (or dodecane), kerosene (or decane), and Biodiesel (or rapeseed oil) as combustible liquids. The analysis of the experimental data helped us establish the temperature conditions for the occurrence of three droplet behavior regimes: evaporation (T_a = 300–400 K), puffing (T_a = 400–600 K), and micro-explosion (T_a = 600–1500 K). Puffing and micro-explosion are of the greatest interest in terms of intensifying the heat exchange processes since they can increase the droplet evaporation surface area by dozens and hundreds of times.

(ii) Research into the characteristics of child droplets produced during the puffing/micro-explosion of multi-component fuel droplets plays an important role in the further technological and industrial use of these effects. Controlled puffing/micro-explosion effectively fills the combustion chamber with fuel fragments with the required characteristics (size, velocity, temperature, and component composition), which provides the optimal operation of the process equipment and reduces its wear. According to the experimental data, child droplet characteristics depend on a number of factors, in particular, the parent droplet size, component composition and rheological properties of the multi-component fuel, fragmentation regime, as well as the scheme of the energy supply to the droplet. To introduce the micro-explosion effects into power technology, it is necessary to develop mathematical and physical models simulating the generation of child droplets.

(iii) Three classes of mathematical models are singled out, simulating the heat and mass transfer in a droplet under the conditions prior to the micro-explosive breakup. The models are based on using the following criteria: superheating of the water/fuel interface above the explosive boiling point of the noncombustible liquid (water) and the threshold radius reached by the bubbles emerging in droplets. These models can predict the transient conditions (threshold temperatures and heating times) between three heating and evaporation regimes for two-liquid droplets: evaporation without breakup, puffing (partial fragmentation), and micro-explosion. The predictive models of droplet micro-explosion can be made more complex to explore the breakup outcomes in detail, i.e., when studying the number, velocities, trajectories, size, momentum, and component composition of secondary droplets.

(iv) Despite the large number of papers in the field of puffing/micro-explosion, there are many open issues and research challenges. In particular, fundamentally, it is necessary to understand how to separate the puffing and micro-explosion regimes, and from a practical standpoint, it is important to transition to the use of micro-explosion in power plants, airplane engines, ground-based power systems, etc.

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