Gas-droplet flows in fire safety engineering

K.N. Volkov[1] and V.N. Emelyanov[2]

[1]Faculty of Science, Engineering and Computing, Kingston University, London, SW15 3DW, United Kingdom

[2]Faculty of Power Engineering, Baltic State Technical University, Saint Petersburg, 190005, Russia

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Presenting author email: k.volkov@kingston.ac.uk

Interaction of laser pulse with gas-droplet mixtures plays an important role in different applications including environmental monitoring of high-risk industrial objects and enclosed spaces, and laser ignition of volumetric explosion for application to fire mitigation. For the optimization of technological processes and for keeping the environment free from droplets, a detailed knowledge of the interaction of laser pulse with individual droplets is necessary. The physical and mathematical models of optical breakdown on individual droplet and up-to-date numerical methodology for computer modeling are developed, and laser-induced breakdown on liquid droplet is studied.

A chain of processes leading to explosion and optical breakdown of individual droplet was developed (Figure 1). These processes depend on optical properties of droplet and ratio of droplet radius to radius of laser spot.

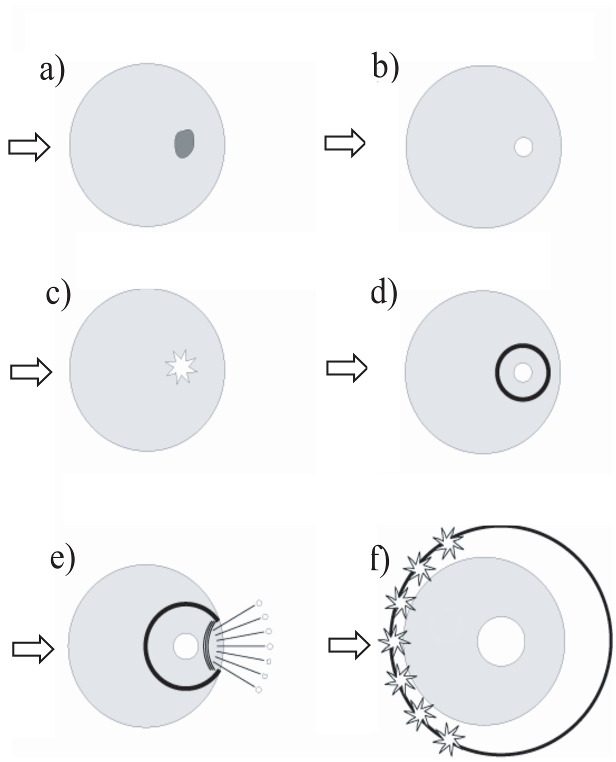

Figure 1. Optical breakdown on liquid droplet.

The laser radiation focuses inside a droplet near its shadow side (fragment a). In this region, overheating conditions arise, and liquid is in meta-stable state in which its temperature exceeds the temperature of saturated vapour at given temperature. Internal vapour cavity is formed, and liquid boils off in this cavity (fragment b). Increase in pressure in the vapour cavity creates conditions for internal micro-breakdown. Free electrons are generated as a result of isothermal ionization. It leads to collisions of electrons with ions and atoms and electron–electron collisions. Internal micro-plasma spot is appeared and absorbs laser radiation (fragment c). Further increase in pressure in the vapour cavity forms shock wave expanding inside droplet (fragment d). Expansion of shock wave induces thermal ionization of surrounding gas on shock wave front (fragment e). Free electrons that have appeared on shock wave front induce chain mechanism of breakdown, receiving their energy due to reverse drag effect (fragment f). The cascade ionization process is significant at high pressure and longer laser pulse because under these conditions, electron-atom or electron-ion collisions have sufficient time to occur during the laser pulse.

Sub-models describe heating, evaporation, appearance of free electrons due to thermal ionisation on front of shock wave, development of electron avalanche due to reverse drag effect. Heating model is based on solution of unsteady heat diffusive equation. To compute optical properties of particle (e.g., absorption efficiency of laser radiation), semi-empirical data are used. The equations describing electron avalanche include the equation of heating of vapor aureole of particle due to electron–atom collisions, the equation of warming-up of electrons, the ionization kinetic equation of vapor as a result of electron impact, and the equation of particle mass. The plasma is considered as an ideal gas. The Euler equations are used for the simulation of gas dynamical processes in the droplet. A simple model of one-step chemical reaction is used in order to reproduce combustion of individual droplet.

The time of optical breakdown is a result of the competition between 3 factors: (i) time of heating a droplet to the temperature of explosive transformation (at low pulse energy, the large droplets do not have enough time for being heated, and the small droplets exchange heat intensively with the surrounding), (ii) intensity of the shock wave contributing to the thermal ionization of vapour (for massive droplets, the intensity of shock wave is low), (iii) time of development of an electron avalanche. Increase in droplet radius leads to increase in time of droplet heating and decrease in degree of ionization. No electron avalanche develops at low intensity of laser pulse, and threshold value of optical breakdown increases.