Simplified model for predicting the onset of multicomponent droplet microexplosion

2017/08

Xinyi Huang[1,2], Pavan Bharadwaj Govindaraju[1], Matthias Ihme[1],

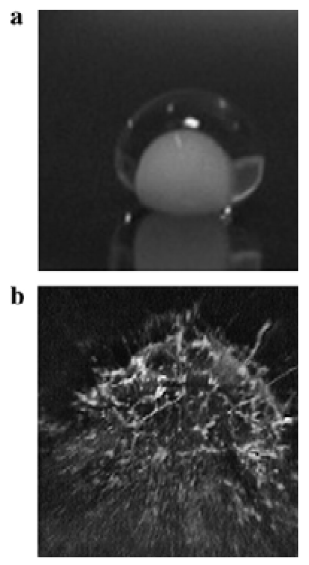
1 Department of Mechanical Engineering, Stanford, 2 School of Aerospace Engineering, Tsinghua University

Microexplosion: enhancing combustion efficiency

Microexplosion is a phenomenon that might happen during the evaporation or combustion of multicomponent droplets, especially emulsified droplets.

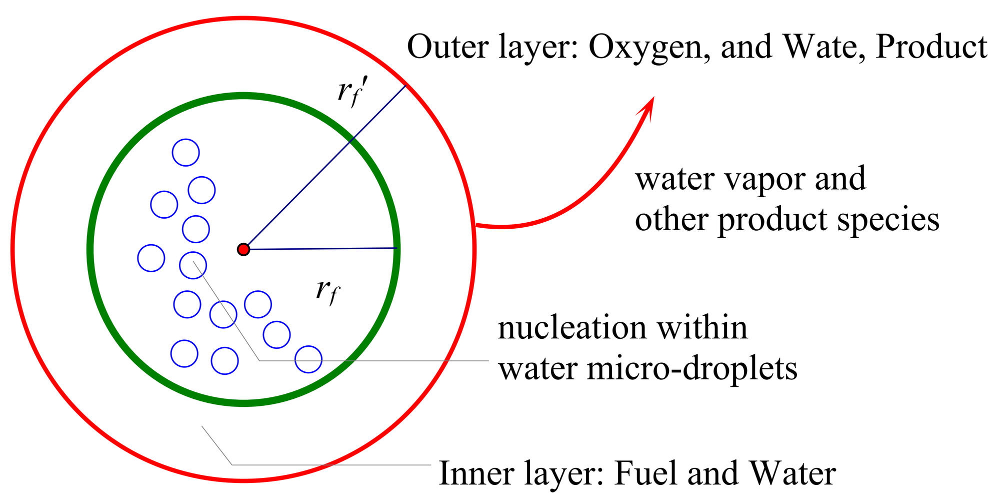
Microexplosion can help both to enhance the efficiency of combustion, and to reduce the emission of soot and NO_x. Thus, the application of emulsified fuel is both **efficient** and **environmentally friendly**.

A simplified prediction model of the onset of the microexplosion will be helpful for internal combustion engine designer to improve the efficiency of the combustors.

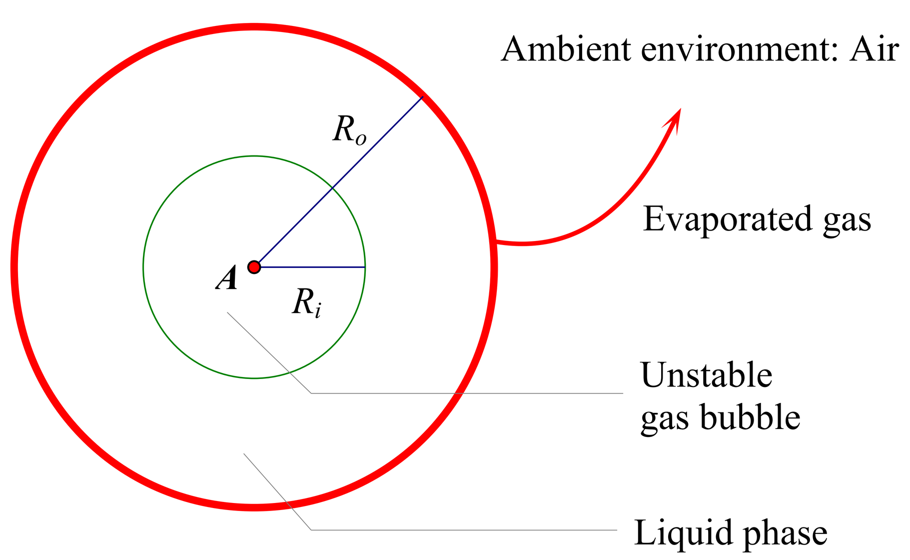


T. Kadota et al.(2007)

Former models



1. Based on superheat criterion, Law(1978) [3] developed a model for water emulsified droplets. Mainly, microexplosion will happen if the temperature exceeds a certain value.



2. Based on linear perturbation analysis, Zengbing Yang(2000) [2] developed a model for multicomponent droplets. Mainly, microexplosion will happen if the accumulating perturbation reaches a threshold.

Instability analysis and Model building

To build the model, we based on the instability analysis of Chia-fon Lee and their group's work. There will be a gas bubble formed by nucleation inside the multicomponent droplet before microexplosion, which has been experimentally observed in many work. Microexplosion usually happens instantaneously, which leads to the instability of the bubble dominating the breakup of the droplet.

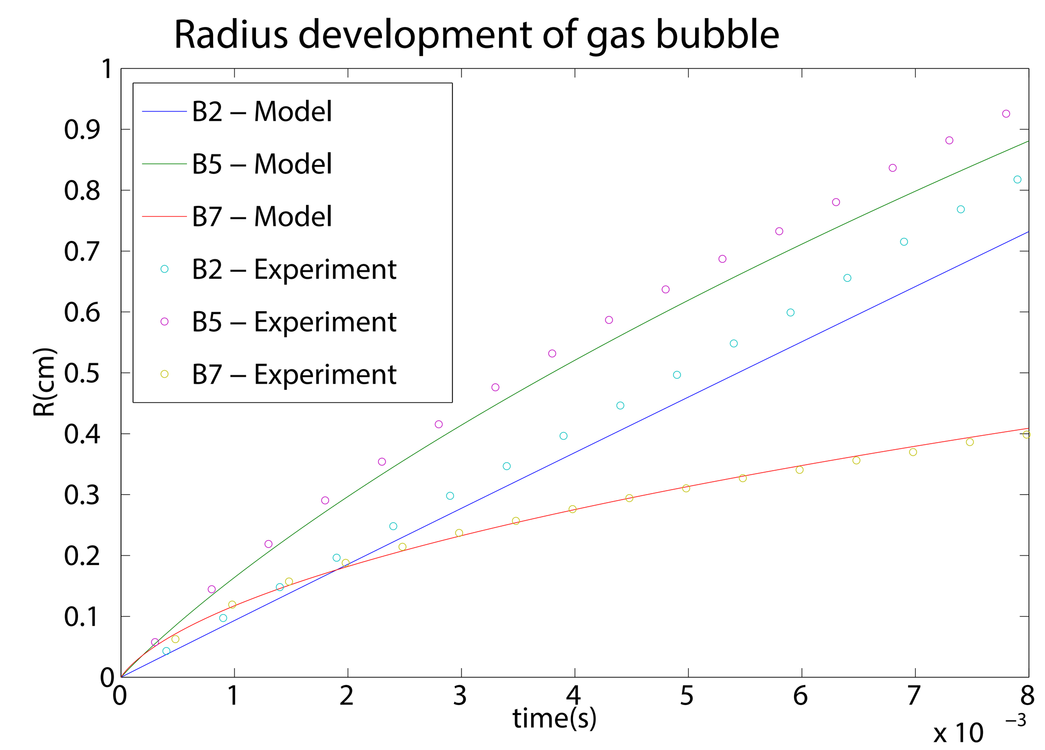
Zengbing Yang and Chia-fon Lee have developed a complete theory for this breaking process, which mainly consists of the bubble growing and the perturbation accumulation. The temperature solving process is complicated, and we wish to reduce such cost and give a simple modeling.

Bubble Growth: Rayleigh-Plesset equation

$$\rho_\ell\left[R_i\frac{d^2R_i}{dt^2}+1.5\left(\frac{dR_i}{dt}\right)^2\right]$$
$$= P_{gi}-P_\ell-\frac{2\sigma}{R_i}-\frac{4\mu}{R_i}\frac{dR_i}{dt}-\frac{4\kappa}{R_i^2}\frac{dR_i}{dt}.$$

This is the growth equation of the bubble. This is directly derived from the momentum equations of the droplet. The driving force is the difference of pressure P across the interface.

Using Mikic's solution[5], the growth of the bubble can be well predicted.



Perturbation Growth: Linear instability analysis

$$(\Delta-\Delta^2-\psi_o\Delta)\Omega^2+(-1+\Delta^4+\psi_o)We_o^{1/2}\Omega$$
$$+2\Delta^2+2\Delta^{-2}-3\psi_i\frac{We_i}{Ma_i^2}\frac{\Omega}{\Omega+3We_i^{1/2}}\Delta^2=0$$

$$\Omega=\sqrt{\frac{\rho_\ell\overline{R_i}^3}{\sigma}}\omega,\quad We_o=\frac{\rho_\ell\overline{V_o^2}\overline{R_i}}{\sigma},\quad We_i=\frac{\rho_\ell\overline{V_i^2}\overline{R_i}}{\sigma},$$

$$Ma_i=\frac{\overline{V_i}}{c},\quad \Delta=\frac{\overline{R_o}}{\overline{R_i}},\quad \psi_o=\frac{\rho_{go}}{\rho_\ell},\quad \psi_i=\frac{\rho_{gi}}{\rho_\ell}.$$

With the linear instability analysis of the droplet, we can get perturbation equation. Solving this cubic equation, its roots show the growth rate of the perturbation. The accumulation of the perturbation give a criterion for the onset of microexplossion. One criterion developed by Yang[1] follows.

$$K(t)=\frac{R_{o0}e^{\int_0^t\omega dt}}{R_o-R_i}$$

When *K(t)* reaches a certain value, it implies the onset of the microexplosion.

Pros and cons of the model

Making the assumption that the dynamics of the bubble is slightly related to the temperature makes it possible to calculate the growth of the bubble directly. If given appropriate temperature profile, the calculation process could be a lot easier than what is in Yang's thesis[2].

It is also clear that if the temperature is uncertain in a large range, the model will be unreliable. It needs a lot of experimental data to verify it.

Future work on expanding the model

1.The gas bubble growth is proved to fit the experiment, while there is still a lot of work to do on building the perturbation model. The roots of cubic equation are greatly sensitive to the parameters, so to prove the robustness is an important work of the model building.

2.All bubble properties will influence the parameters, and that is tightly related to temperature. We would like to develop a 1-dimension temperature model, which can give a correct profile of temperature and thus bubble properties are better estimated.

3.Also, the model is meant to fast and correctly predict the onset of microexplosion, so how to make it a model widely applicable to all kinds of droplets with various components is a big aim.

Reference

1. Zeng, Y., & Chia-fon, F. L. (2007). Modeling droplet breakup processes under micro-explosion conditions. *Proceedings of the Combustion Institute*, 31(2), 2185-2193.
2. Zeng, Y. (2000). *Modeling of multicomponent fuel vaporization in internal combustion engines* (Doctoral dissertation, University of Illinois at Urbana-Champaign).
3. Law, C. K. (1977). A model for the combustion of oil/water emulsion droplets. *Combustion Science and Technology*, 17(1-2), 29-38.
4. Kadota, T., Tanaka, H., Segawa, D., Nakaya, S., & Yamasaki, H. (2007). Microexplosion of an emulsion droplet during Leidenfrost burning. *Proceedings of the Combustion institute*, 31(2), 2125-2131.
5.Mikic, B. B., Rohsenow, W. M., & Griffith, P. (1970). On bubble growth rates. *International Journal of Heat and Mass Transfer*, 13(4), 657-666.

Acknowledgement

I would like to express my thanks to Peter Ma, Yu Lv, Xiang I.A. Yang, Qing Wang, Kevin Grogan and all those who have given precious suggestions and kind help.

I also appreciate Tsinghua University and Stanford University for the support.