DILATION STABILITY ANALYSIS OF EVAPORATING LIQUID–GAS INTERFACE AND SIMULATION OF PRIMARY ATOMIZATION OF EVAPORATING SPRAY

P. Zeng*, H. Pitsch, B. Binninger & N. Peters
Institute for Combustion Technology, RWTH Aachen University, Germany

Summary Spray combustion is mostly accompanied by high ambient temperature and intense heat release, the effect of liquid–gas interface evaporation on the droplet formation process is the focus of current study. In this paper, firstly, the linear stability of small perturbations on the interface due to dilation is theoretically studied. Secondly, primary atomization of turbulent liquid jets, where breakup into liquid droplets occurs, is numerically simulated.

INTRODUCTION

Liquid fuel direct injection has excelled many other technologies in internal combustion engine developments. Substantial improvements of engine performance are achievable through multiple-injection, rate shaping, etc. During fuel injection, the primary atomization process firstly determines the spray characteristics, such as the fuel drop size and velocity distributions. The evaporating spray then immediately affects the fuel-air mixture, and the resulting mixture ultimately controls engine performance and pollutant emissions. Figure 1 shows the effect of liquid–gas interface evaporation on primary atomization and spray formation. The main purpose of this paper is to study the dilation stability due to interface evaporation and to show the simulation results of primary atomization of evaporating spray.

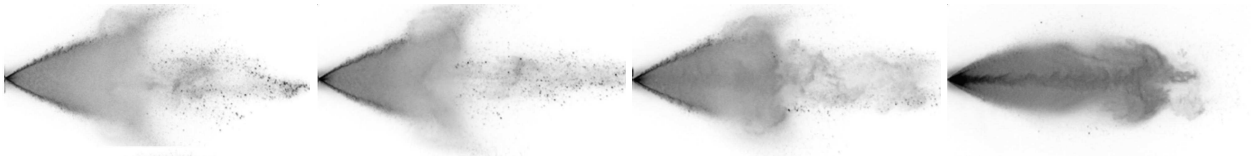

Figure 1. Experiment pictures of gasoline direct injection with different liquid temperature [1]. From left to right, T_{liquid} = 323K, 343K, 363K, 381K. As T_{liquid} increases, the liquid–gas interface evaporation during primary atomization intensifies, leading to different droplet size and velocity distributions as well as the following gaseous mixture formation.

DILATION STABILITY ANALYSIS ON EVAPORATING LIQUID–GAS INTERFACE

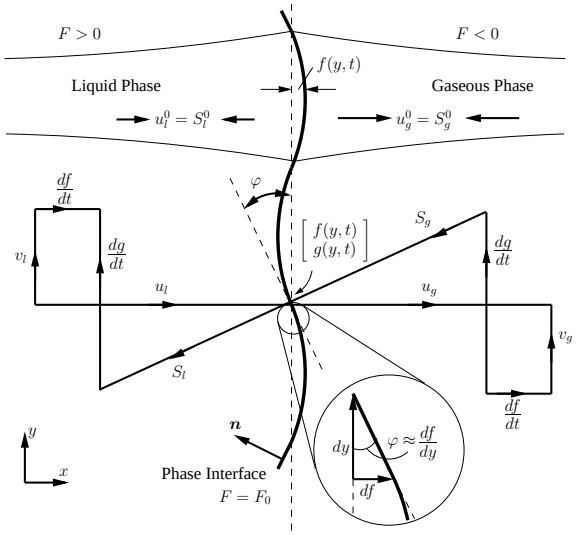

Figure 2. Gas expansion $u_g^0 = (\rho_l/\rho_g)u_l^0$, and kinematic boundary condition at Liquid–Gaseous phase interface element $\left[f(y,t), g(y,t)\right]^T$. Surface regression velocity S due to evaporation cancels the interface propagation velocity u, $S_l = u_l^0$ and $S_g = u_g^0$, maintaining the position of the interface front.

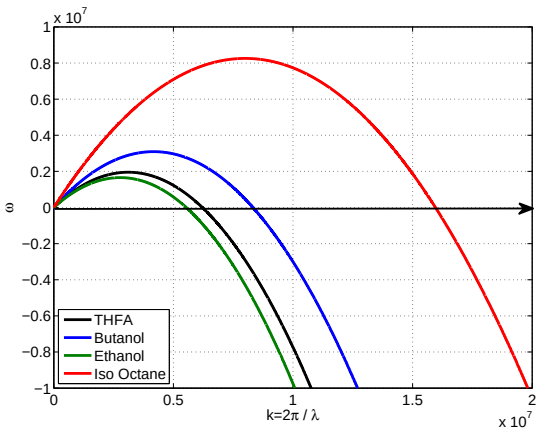

Figure 3. Using the dispersion relation Equ. (1) and the injection conditions list in Tab.1, maximum instability occurs for $k_{\max} = 2\pi/\lambda_{\max} = 0.25 \times 10^7 [\mathrm{m}^{-1}]$, which gives a wave length $\lambda_{\max} \approx 2.5 \times 10^{-6} [\mathrm{m}]$. At the injection conditions list in Tab.1, the spray droplet diameters are in the order of several micrometers as well [2]. Note that Iso Octane has the smallest density ratio γ, but highest surface regression velocity S_l.

*Corresponding author. E-mail: p.zeng@itv.rwth-aachen.de

As Fig.2 shows, the steady liquid–gaseous phase interface is a $y-z$ plane, separating the liquid phase $x<0$ and the gaseous phase $x>0$. The interface front is propagating in the positive x direction with constant values u_l and u_g for the liquid and gaseous phases. The time-dependent two dimensional velocity perturbations, u^1,v^1 and the pressure perturbation p^1 can be introduced by using a small value ϵ ($0<\epsilon\ll 1$). u^0, v^0, p^0 are the zero$^{\text{th}}$ order terms, and they denote the steady planar flow field. Following the procedure of linear stability analysis of the interface perturbation, a particular solution $\exp(iky+\omega t)$ is introduced, where k is the wave number, connected with the wave length λ by $k=2\pi/\lambda$, and where i is the imaginary unit, $\exp(iky)$ therefore makes the perturbation periodic in y direction. Different from k, which is a real parameter, the time exponential term $\exp(\omega t)$ can be complex. its parameter ω play the role of an eigenvalue of the problem. Stability of the interface perturbation is determined by the real part of ω. If nontrivial solutions of the perturbations equations on the phase interface, subject to certain boundary conditions, correspond to positive values of the real part of ω, the interface is unstable. And we can find the dispersion relation as

$$\omega=\frac{kS_l}{\gamma+1}\left[\sqrt{\gamma^4+\gamma(\gamma+1)\left(\gamma-\frac{k\sigma}{\rho_l S_l^2}-1\right)}-\gamma^2\right] \tag{1}$$

Fig.3 shows that, for the TMFB fuel injections[a)], maximum instability occurs for $k_{\text{max}}=2\pi/\lambda_{\text{max}}=0.25\times 10^7[\text{m}^{-1}]$, which gives a wave length $\lambda_{\text{max}}\approx 2.5\times 10^{-6}[\text{m}]$. At the injection conditions list in Tab.1, the spray droplet diameters are in the order of several micrometers as well.

SIMULATION OF PRIMARY ATOMIZATION

Simulation of turbulent atomization has been performed both without and with interface evaporation, see Fig. 4. The detail numerical methods can be found in [3, 4].

Table 1. Liquid Fuel Injection Conditions

Liquid Fuel	ISO Octane	Ethanol	Butanol	THFA
Liquid Reynolds Number	$63{\cdot}10^3$	$35{\cdot}10^3$	$18{\cdot}10^3$	$12{\cdot}10^3$
Liquid Weber Number	$338{\cdot}10^3$	$384{\cdot}10^3$	$352{\cdot}10^3$	$230{\cdot}10^3$
Surface Regression S_l [m/s]	7.35	2.5	3.1	2.6
Density Ratio γ	23	26	27	35
Surface Tension σ [N/m]	0.018	0.022	0.024	0.037

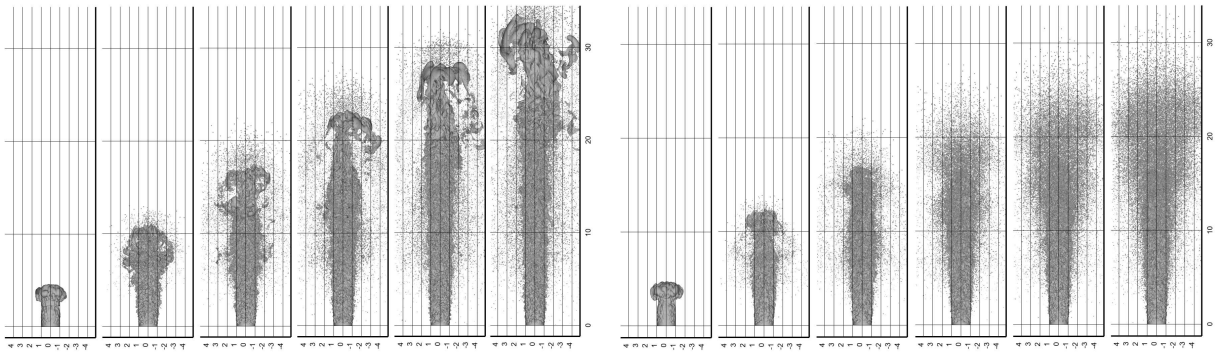

Figure 4. Snapshots of primary breakup without(left) and with (right) interface evaporation. The corrugated surface is the phase interface, the spheres are detached droplets tracked by Lagrangian model. There is a liquid core with elongated ligaments near the injector nozzle. Under the injection condition given above, the liquid core length is around 2 mm. Beyond that point, the primary breakup is complet, leaving only particles in the flow field. As expected, with interface evaporation, the atomization process is intensified.

References

[1] Schmitz I., Ipp W. and Leipertz A., *SAE 2002.*

[2] Reddemann, Mathieu, Martin and Kneer *Atomization and Spray 2011*.

[3] Herrmann M., *J. Comput. Phys.* 227:2674-2706 (2008).

[4] Zeng, Sarholz, Iwainsky, Binninger, Peters, and Herrmann, *Lecture Notes in Computer Science: Recent Advances in Parallel Virtual Machine and Message Passing Interface*, Springer-Verlag, 2009.

[a)] Acknowledgement: This work was performed as part of the CoE "Tailor-Made Fuels from Biomass"-TMFB, funded by the Excellence Initiative of the German federal and state governments.