Study of Oil Droplet Ignition and its Induction for Pre-ignition under Different Environmental Conditions

Shubo Fei[1], Yunliang Qi[1, 2], Yingdi Wang[1], Huiqiang Zhang[3], Zhi Wang[1]
1. State Key Laboratory of Automotive Safety and Energy, Tsinghua University
Beijing, China
2. Graduate Aerospace Laboratories, California Institute of Technology
Pasadena, CA 91125, USA.
3.School of Aerospace Engineering, Tsinghua University
Beijing, China

1 Introduction

With the development of Gasoline Direct Injection (GDI) engine, an abnormal combustion phenomenon named as super-knock becomes one of the main limitation to its power density [1, 2], which would do a great harm to the engine with strong pressure oscillation [2]. It is reported by previous researchers that low speed pre-ignition (LSPI) is a necessary condition for super-knock [1, 3], and the lubricating oil droplet flying into the cylinder from the crevice between the piston and the cylinder wall is an essential induction factor for LSPI [4-11]. Therefore, lubricating oil droplet plays a critical role in the induction of pre-ignition and even super-knock, and performing detailed investigations on the ignition of lubricating oil droplet in a combustible ambient gaseous mixture is vital to the development of GDI engines. Long et al. [12], Ohtomo et al. [13], Takeuchi et al. [14] and Kassai et al. [15] performed investigations on lubricating oil droplet ignition under different environmental and initial conditions, focusing on the components of oil, the auto-ignition ability of oil droplet and the limitation for droplet to induce pre-ignition. So far, there is still a lack of detailed and systematic analysis on oil droplet ignition and its effect on pre-ignition induction of the ambient gaseous mixture. Furthermore, the optical diagnostics of pre-ignition process induced by a lubricating oil droplet is still insufficient. In this study, the investigations on lubricating oil droplet ignition in combustible ambient gaseous mixture under different environmental conditions are performed based on a rapid compression machine (RCM). The impacts of environmental pressure on the induction of pre-ignition by the oil droplet have been analyzed under different temperature conditions in this paper.

2 Experimental Settings

Experiments with respect to the ignition of lubricating oil droplet in the ambient gaseous mixture were performed based on a rapid compression machine [16]. As shown in Figure 1, the droplet is suspended on a tungsten wire in the combustion chamber. The oil sample here was taken from a synthesized gasoline engine oil in the market [17]. The ambient gaseous mixture consists of iso-octane and oxygen with stoichiometric ratio, as well as nitrogen and argon (used to adjust the temperature after compression).

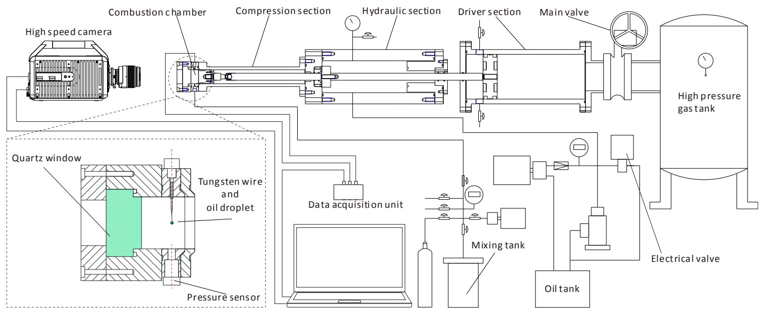
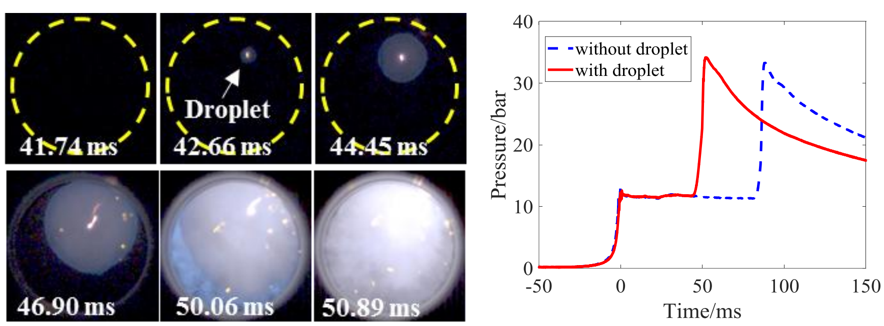


Figure 1. Sketch of Experimental system [16]

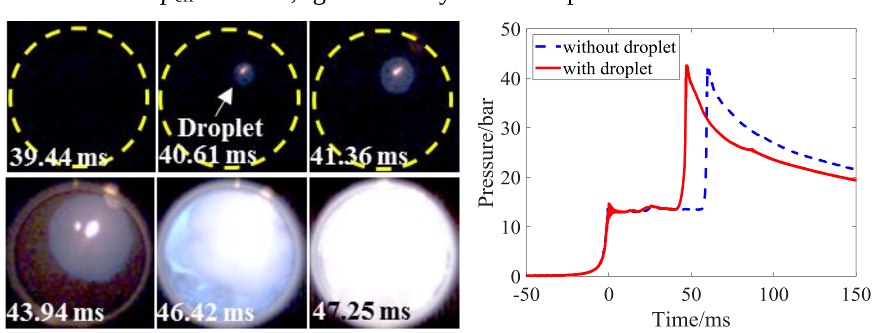
The effective pressure and effective temperature are used here to describe the thermal state in the combustion chamber at the end of compression (set as '0' of time coordinate) [16, 17].

3 Results and Discussions

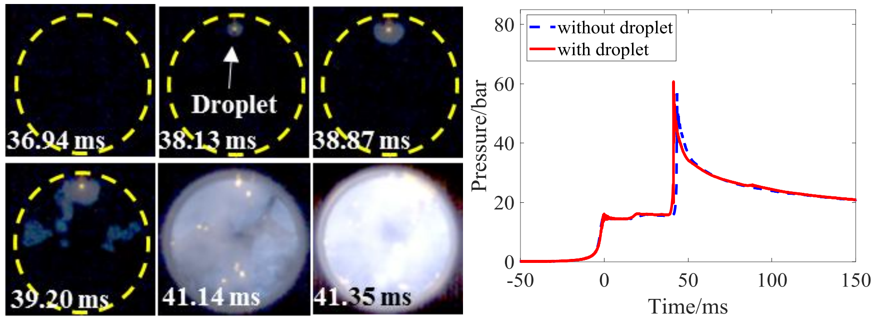
Figure 2 (A) to (C) show the ignition processes and the corresponding pressure traces under the conditions that the effective temperature is 680 K, with the effective pressure varying from 12 to 16 bar. Under the situations of (A) and (B), the flame front generates around the droplet and propagates towards the unburnt gas. There would be a sequential auto-ignition in the end gas at the end of flame propagation. With the increase of environmental pressure, the ignition delay of the ambient gaseous mixture without an oil droplet decreases while that with an oil droplet keeps almost the same. As a result, the pre-ignition induction by oil droplet would be more inconspicuous with the increase of pressure, which is shown in Figure 4.



A. p_{eff} = 12 bar, Ignition delay with a droplet = 50.13 ms



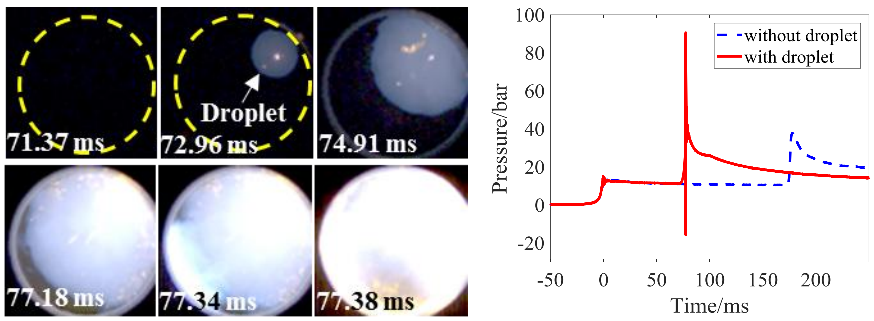
B. p_{eff} = 14 bar, Ignition delay with a droplet = 46.41 ms



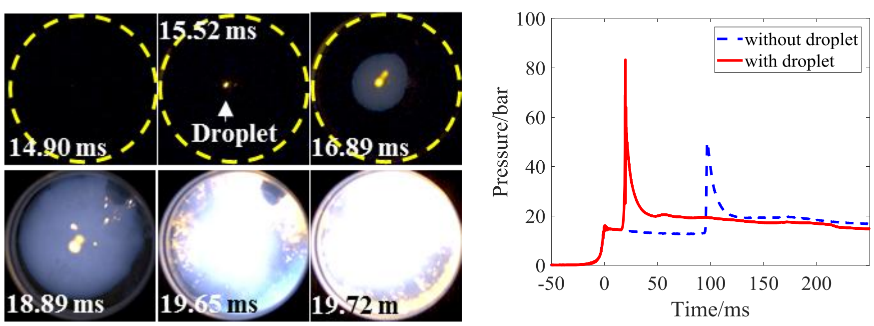
C. p_{eff} = 16 bar, Ignition delay with a droplet = 41.23 ms

Figure 2. Ignition processes and pressure traces under the conditions that T_{eff} = 680 K and V_0 = 0.1 μL

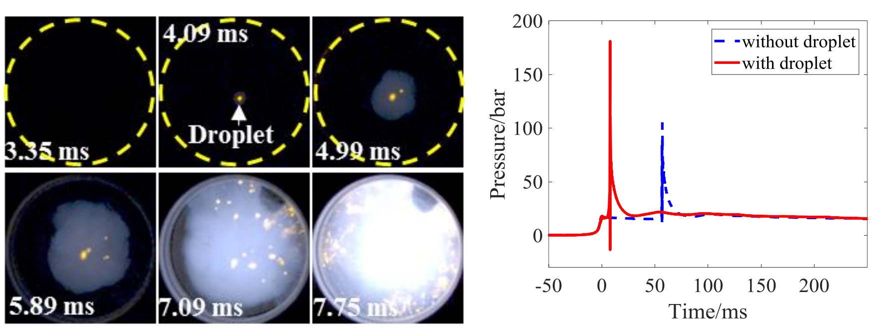
Figure 3 (A) to (E) show the ignition processes and the corresponding pressure traces under the conditions that the effective temperature is 740 K, with the effective pressure varying from 12 to 20 bar.



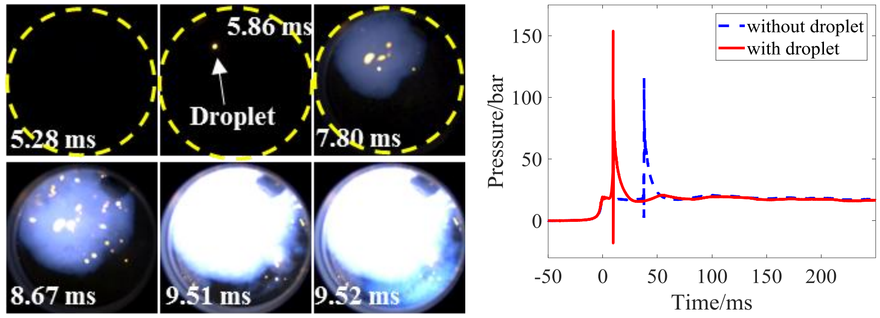
A. peff = 12 bar, Ignition delay with a droplet = 77.34 ms



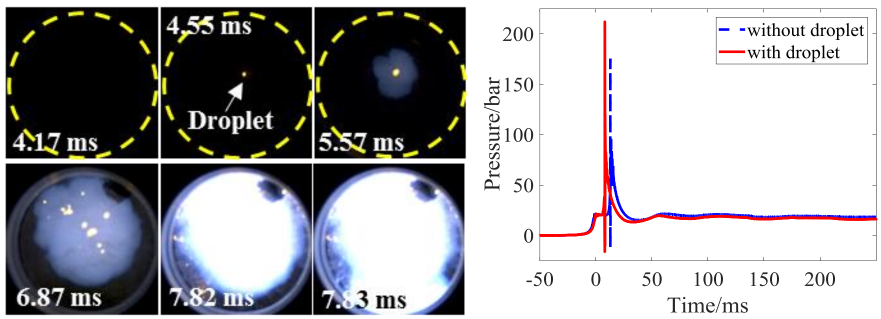
B. p_{eff} = 14 bar, Ignition delay with a droplet = 19.66 ms



C. p_{eff} = 16 bar, Ignition delay with a droplet = 7.82 ms



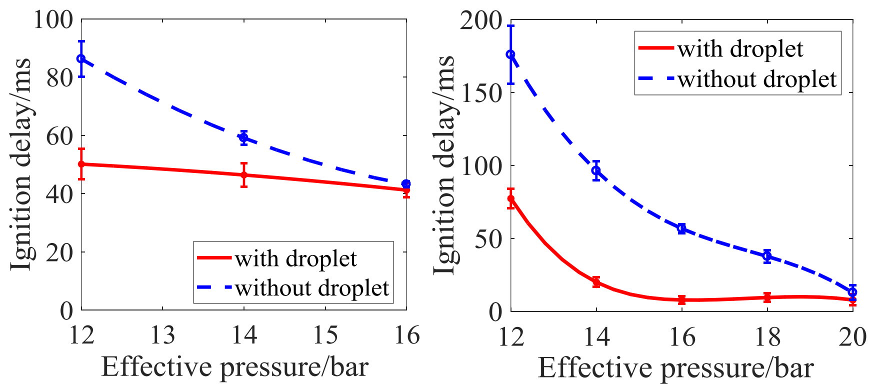
D. p_{eff} = 18 bar, Ignition delay with a droplet = 9.50 ms



E. p_{eff} = 20 bar, Ignition delay with a droplet = 7.86 ms

Figure 3. Ignition processes and pressure traces under the conditions that T_{eff} = 740 K and V_0 = 0.1 μL

Under this temperature condition, the introduction of oil droplet would not only shortens the ignition delay of the ambient gaseous, but also induces or enhances pressure oscillation during combustion. The ignition delay of gas phase with an oil droplet would first decrease and then keeps almost constant with the increase of the pressure, while that without a droplet keeps decreasing until it becomes almost the same as that with an oil droplet, which is also shown in Figure 4.



A. T_{eff} = 680 K B. T_{eff} = 740 K

Figure 4. Statistical data of ignition delay under different effective pressure conditions

With the effective pressure increasing to 16 bar, the induction of pre-ignition by oil droplet would be restrained under 680 K because the ignition delay of the ambient gaseous mixture with a droplet keeps almost constant. However, there would still be a remarkable induction of pre-ignition by the droplet under 740 K due to the decrease of ignition delay with a droplet. Under the latter temperature condition, the limitation of pressure on pre-ignition induction by oil droplet is extended from 16 bar to 20 bar. The different pressure-dependence mechanisms of pre-ignition induction by oil droplet under different temperature conditions could be attributed to the redistribution of physical and chemical delay of oil droplet under different environmental conditions. Under relatively low temperature condition, although the increase of pressure shortens the ignition delay of the mixture consisting of oil vapor and the ambient gas, it also prolongs the time for the preparation of oil vapor by restraining the evaporation of droplet [18]. Thus, the ignition delay with oil droplet keeps almost constant with the increase of pressure under 680 K. When the temperature increases to 740 K, the evaporation of droplet is enhanced, which make the effect of shortening chemical delay by the increase of pressure become dominate under relatively low-pressure conditions, instead of its restraining towards evaporation. With the further increase of pressure, the restraining of evaporation by pressure becomes strong enough again, and the ignition delay of the ambient gaseous mixture with an oil droplet might be close to its lower limit, resulting in the stabilization of ignition delay of the ambient gaseous mixture with an oil droplet.

4 Conclusions

Investigations on lubricating oil droplet ignition in the ambient gaseous mixture under different environmental conditions are performed based on a rapid compression machine. The impacts of pressure on the induction of pre-ignition in the ambient gaseous mixture by the oil droplet have been analyzed under different environmental temperature conditions. The conclusions are drawn as follows.

1. The introduction of lubricating oil droplet would decrease the ignition delay of the ambient gaseous mixture. Furthermore, the effect of pre-ignition induction shows different pressure–dependence mechanisms under different environmental temperature conditions.

2. Under a relatively lower temperature (680 K) condition, the ignition delay of the ambient gaseous mixture without an oil droplet decreases with the increase of pressure, while that with an oil droplet keeps almost constant. As a result, the pre-ignition induction of the ambient gaseous mixture by the oil droplet would be more inconspicuous with the increase of pressure.

3. Under a relatively higher temperature (740 K) condition, the values of ignition delay of the ambient gaseous mixture with/without an oil droplet both decrease with the increase of pressure when the pressure is in a relatively lower range (12-16 bar). On the other hand, the ignition delay of the ambient gaseous mixture with an oil droplet keeps almost constant while that without an oil droplet continue to decrease with the increase of pressure when the pressure is in a relatively higher range (16-20 bar). Consequently, when the pressure is relatively low, the effect of pre-ignition induction by oil droplet remains stable with the increase of pressure. However, it becomes weaker with the increase of pressure when the pressure is relatively high, when the environmental temperature is 740 K.

4. The different pressure-dependence mechanisms of pre-ignition induction by the oil droplet under different temperature conditions could be attributed to the trade-off effect of environmental pressure on droplet evaporation and chemical reaction in the gas phase.

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