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Modeling the atomization of high-pressure fuel spray by using a new breakup model

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A B S T R A C T

The main objective of this research is to develop a new breakup model and investigate the influence of cavitation, turbulence on processes of high-pressure diesel sprays. The model distinguishes between jet primary atomization and droplet secondary atomization. The primary atomization was simulated based on a modified turbulence induced atomization model taken into account the coupling effects of the relaxation of the velocity profile, cavitation and turbulent fluctuation based on the principle of conservation of energy. The growth time scale of surface waves was provided by Kelvin–Helmholtz (K–H) instability theory on an infinite length cylinder for an inviscid liquid jet. The time scale of initial surface waves based on K–H instability theory on an infinite plane jet is much larger than that based on infinite length cylindrical jet. Based on the present modified model, the weighting coefficients of turbulence and cavitation on the overall atomization can be distinguished clearly. There was remarkable variation in simulated spray shape with present models. It could be seen that the original turbulence induced atomization model results in a shorter spray penetration and smaller drops near the spray core than the modified model. When applying the turbulent weighting coefficient C_t in the determination of the spray angle, the resultant value of spray angle gradually drops due to the reduction of C_t. However, the spray angle increases with increasing the cavitation weighting coefficient C_{cav}. Comparing the experimental results (such as spray angle, tip penetration and spray shape) with the theoretical ones for different injection pressure, gives a reasonable agreement.

1. Introduction

The atomization of fuel spray plays a key role in the mixing of diesel fuel vapor and air, ignition, combustion, and the formation of pollutant emissions. The detailed understanding of the spray formation process has been recognized as an significant step for the increase of combustion efficiency and the reduction of pollutant emissions for D.I. Diesel engines.

Knowledge of atomization near the spray nozzle is important and basic to understanding the spray mechanisms, as characteristics in this region affect the atomization performance achieved further downstream. Despite lots of experimental investigations have been carried out [1–11], an in-depth and quantitative understanding of the near-nozzle spray region hasn't been achieved. But a vast amount of study show that internal flow in nozzle has an important influence on the spray characteristics [12–14]. Quantitative evaluation of spray construction in this region is nearly infeasible using most of conventional techniques (e.g., visible light methods) [15]. Numerical simulation and theoretical analysis are powerful tools of

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Nomenclature

α	nozzle diameter, m
L_t	integral length scale of turbulence, m
$L_{w,t}$	wavelength of surface instability, m
$L_{A,t}$	length scale of primary atomization, m
τ_t	turbulent time scale, s
U	liquid jet velocity, m/s
ρ_g	gas (ambient) density, kg/m^3
ρ_l	liquid fuel density, kg/m^3
ω	growth rate of instabilities, 1/s
r_p	radius of the product drop, m
δ	boundary thickness, m
θ	momentum thickness, m
α	spray cone angle, °
$\tau_{\exp,t}$	time for the exponential growth of instabilities, s
τ_w	wave growth time scale, s
$\tau_{A,t}$	time scale of atomization, s
$\tau_{spn,t}$	time required for the spontaneous growth of instabilities, s
$E_{boundary}$	kinetic energy of relaxation of the velocity profile, m^2/s^2
E_t	kinetic energy of turbulence, m^2/s^2
E_c	kinetic energy of cavitation, m^2/s^2
v_l	liquid kinematic viscosity, m^2/s
k	wave number of instabilities
σ	surface tension, N/m
c_d	discharge coefficient
Re	Droplet Reynolds number $2Ur_p/v_l$

Subscripts

x	x-direction
y	y-direction
l	liquid
g	gas
t	turbulent
c	cavitation

investigation of the atomization phenomena. Several theories have been proposed to explain the liquid core atomization, such as aerodynamic interaction with ambient gas, jet internal turbulence, cavitation inside the nozzle holes. Many researchers have focus on the effects of cavitation and turbulence on primary atomization. Arcoumanis et al. [16] numerically investigated the effects of nozzle flow and injection processes on the structure of diesel sprays. Huh and Gosman [17] developed a new phenomenological primary breakup model which considers the effects of turbulence on the jet breakup. Bianchi et al. [3] proposed a modified breakup model which included the effects of cavitation and turbulence in the KH model. S. Som developed a new primary breakup model named KH-ACT model. The new mode is modified to include the effects of cavitation and turbulence generated inside the injector. Rate of decrease in droplet radius scales with the ratio of length to time scale. The scales include aerodynamic-induced KH scale, cavitation and Turbulence scale. The largest ratio determines the dominant breakup process [18]. In Turner's study, the coherent liquid core is modeled as a liquid jet. The spray breakup is described using a composite model to separately address the disintegration of the liquid core into droplets and their further aerodynamic breakup. The jet breakup model uses the results of hydrodynamic stability theory to define the breakup length of the jet, and downstream of this point, the spray breakup process is modeled for droplets only [19]. But none of these theories alone can explain the complexity of the atomization phenomenon.

In an attempt to improve spray breakup predictions, many models have been proposed. The original TAB [20] spray breakup model was based on Taylor's analogy between an oscillating and distorting drop like a spring-mass system. Several studies [21–22] have revealed thought that the TAB model can produce excessive droplet breakup that is not in agreement with experimental data. This is attributed to the fact that cavitation and turbulence phenomena inside the injector nozzle and liquid core, experimentally shown to be of great importance to atomization [23–25], as well as non-linear droplet distortion effects are not accounted for in the TAB model. In the WAVE model [26–27], derived from a linear stability analysis of liquid jets, the breakup time is determined by surface instability of droplets as a function of the wavelength and the frequency of the Kelvin–Helmholtz wave. But WAVE model can't simulate the effects of nozzle internal flow (cavitation and turbulent fluctuations) on the jet atomization. In the turbulence induced atomization model [17] the jet internal