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NON-EVAPORATING LIQUID SPRAY SIMULATIONS WITH THE ETAB AND WAVE DROPLET BREAKUP MODELS

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Abstract

Non-evaporating diesel sprays have been simulated using the ETAB and the WAVE breakup models and have been compared with experimental data. The ETAB breakup model has been implemented into the commercial CFD-package Star-CD during this study. The model evaluation criteria include the spray penetration, the spray width, and the local droplet size. The comparisons have been made for various gas densities. The simulations showed good overall agreement with experimental data. However, the capability to predict the spray widths and droplet sizes could be improved for both models.

Introduction

The breakup of a liquid jet plays a fundamental role in the evolution of a diesel fuel spray. Due to the fact that many combustion systems involve sprays for supplying the fuel, the importance of accurately describing the fuel disintegration process is clear.

In this study, the Enhanced Taylor Analogy Breakup (ETAB) model by Tanner [1] and Tanner et al. [2], and the WAVE break up model by Reitz and Diwakar [3] are compared against experimental data. In the studies [1, 2] the ETAB breakup model has shown good performance under various conditions. In this study, the ETAB breakup model has been implemented into the commercial CFD-package Star-CD v3.150, and its performance has been compared with the Star-CD version of the WAVE breakup model.

In a previous study by Larmi et al. [4], the ETAB and WAVE models have been compared to experimental data, but the ETAB model results were obtained from KIVA code simulations and the WAVE model results were computed with Star-CD. Because the same code is used for both models in this investigation, the possible differences in the results due to different code implementations are eliminated.

The models are compared against measured spray penetration, droplet sizes, and spray width. The results show that both models are in good agreement with the measured data. However, especially the drop sizes as well as the spray widths could be predicted more accurately. In addition, the ETAB model has the benefit over the WAVE model that it automatically adjusts the pray angle according to changes in the gas density.

Spray Models

In the ETAB atomization and drop breakup model the disintegration of the liquid jet is simulated as a cascade of drop breakups where each breakup event follows experimentally observed breakup mechanisms (stripping or bag breakup). Thus, the initially large droplets undergo a series of breakups until the product droplets reach a stable condition. The actual drop breakup criterion is computed by means of the forced, damped harmonic oscillator of the standard TAB model [5, 6]. In addition, the radial product droplet velocities are determined from an energy conservation argument.

The WAVE breakup model [7, 8] is based on a linearized analysis of a Kelvin-Helmholtz instability of a stationary, round liquid jet injected into a quiescent, incompressible gas. The result is a general dispersion equation which relates the growth rate of an initial surface perturbation to its wavelength. The version used in this study is the Reitz-Diwakar model [3] which is available in Star-CD.

ETAB Model

In the ETAB breakup model, the rate of change of the droplet diameter is computed from

$$\frac{r}{a} = e^{-K_{br}\, t}, \tag{1}$$

where a and r are the radii of the parent and product drops, respectively. The breakup constant K_{br} depends on the breakup regime according to the Weber number as follows

$$K_{br} = \begin{cases} k_1 \omega & if \quad We \le We_t \\ k_2 \omega \sqrt{We} & if \quad We > We_t \end{cases}. \tag{2}$$

k_1 and k_2 are constants, ω is the drop oscillation angular velocity, and the transitional Weber number, $We_t = 80$. The deformation of the drop surface is computed from

$$y(t) = \frac{We}{12} + e^{\frac{-t}{t_d}} \left\{ \left[y(0) - \frac{We}{12} \right] cos\omega t + \left[\frac{\dot{y}(0)}{\omega} + \frac{y(0) - \frac{We}{12}}{\omega t_d} \right] sin\omega t \right\}, \tag{3}$$

and breakup occurs if the normalized drop distortion, *y(t)*, exceeds the critical value 1. Note that *y*=2x/a where x is the actual drop displacement of the drop equator. For a detailed explanation of ω and t_d, see [6].

After drop breakup, the product droplets are initially supplied with a velocity component perpendicular to the path of the parent drop with a value $v_\perp = A\dot{x}$, where $\dot{x}$ is the radial velocity of the drop surface and *A* is a constant determined from energy conservation criterion. The value of *A* is given by

$$A^2 = 5C_D/4 + 18(1 - a/r_{32})/We. \tag{4}$$

In Eq. (4) C_D is the aerodynamic drag coefficient and r_{32} denotes the Sauter mean radius, SMR. In the original TAB breakup model A =1, whereas in the ETAB model $A \approx 0.7$ for typical high-pressure injection conditions. This indicates that only 70% of the parent drop deformation velocity goes into the normal velocity component of the product droplets in the ETAB model as compared to the TAB model.

To account for the droplet surface stripping near the nozzle exit, the initially injected parcels have been equipped with a power law size distribution according to

$$g(r) = \frac{n+4}{r_0} \left(\frac{r}{r_0} \right)^{n+3}, \tag{5}$$

where r_0 is the nozzle radius and $n = 0.5$ has been determined computationally to fit experimental data [2]. Eq. (5) gives a mass distribution where most of the injected fuel mass is in the large droplets. Table 1 gives the values of the ETAB model constants.

WAVE Model

The WAVE breakup model, as implemented in Star-CD, gives the rate of change of the droplet diameter as

$$\frac{d D_d}{d t} = -\frac{(D_d - D_{d,stable})}{\tau_b}, \tag{6}$$

where D_d is the instantaneous droplet diameter and τ_b is the characteristic time scale of the breakup process. The diameter of the droplets are changing as they approach a stable droplet diameter $D_{d,stable}$. The characteristic time scale is computed differently according to the breakup regime involved. The bag breakup regime is determined from

$$We = \frac{\rho |u - u_d|^2 D_d}{2\sigma_d} \ge C_{b1}, \tag{7}$$

where C_{b1} is the critical Weber number, ρ is the density, u is the gas velocity, u_d is the droplet velocity, and σ_d is the drop surface tension. In the bag breakup regime the characteristic time is computed from

$$\tau_b = \frac{C_{b2}\,\rho_d^{0.5}\,D_d^{1.5}}{4\sigma_d^{0.5}}. \tag{8}$$

The stripping breakup regime is determined from

$$\frac{We}{\sqrt{Re_d}} \geq C_{s1}, \tag{9}$$

where C_{s1} is a model constant, and Re_d is the droplet Reynolds number. Now the characteristic time scale is computed from

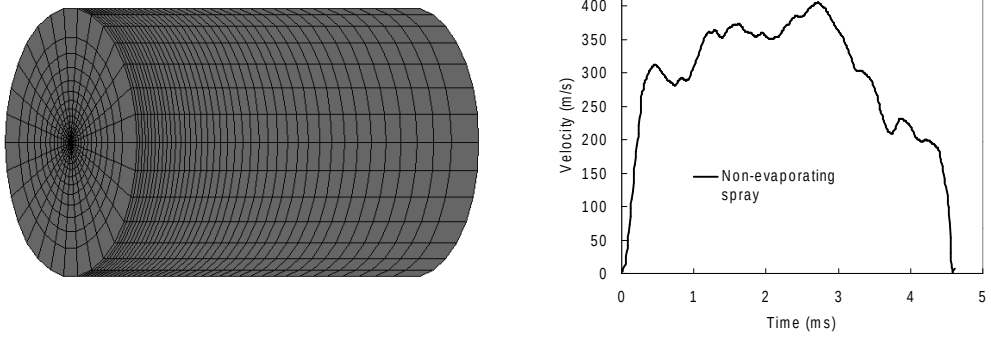
$$\tau_b = \frac{C_{s2}}{2}\left(\frac{\rho_d}{\rho}\right)\frac{D_d}{|u-u_d|}, \tag{10}$$

where C_{s2} is a model constant. The values of the different constants are given in Table 1.

The WAVE breakup model, in contrast to the ETAB model, has no radial velocity component given to the product droplets after drop breakup. Therefore it is necessary for the user to give the correct initial spray cone angle and in this study a value of 25 degrees has been used. The initial drop size distribution used is the same as described above within the ETAB model.

ETAB model constant	Explanation	Value used	Default value		WAVE model constant	Explanation	Default value
C_α	Initial jet breakup angle	4.5	1.56		C_{b1}	Bag breakup We	6
C_λ	Jet breakup length	5.5	5.5		C_{b2}	Bag breakup time	3.14159
k_1	Bag break up regime	0.2222	0.2222		C_{s1}	Stripping breakup We	0.5
k_2	Stripping breakup regime	0.2222	0.2222		C_{s2}	Stripping breakup time	20
n	Exponent of the initial size distribution	0.5	0.5		n	Exponent of the initial size distribution	0.5

Table 1. ETAB and WAVE breakup model constants.



A) B)

Figure 1. A) The polar mesh used in the spray computations. The diameter of the mesh is 10cm and the length is 15cm. The nozzle is located on the axis and 0.5mm from the left-hand side wall. The mesh has 14, 30, and 40 cells in the radial, azimuthal, and axial directions, respectively (a total of 16800 cells). The cell size near the nozzle hole is close to 1mm. B) Calculated fuel injection velocity at the nozzle hole exit.

Computational Issues

The mesh used in this study is shown in Fig. 1 with additional information. The mesh independence has been established previously in [4] for the same mesh as used in this study. The computations are made with the RNG k-ε turbulence model where the model constant C_3 has been changed to a value of -1.0, as is discussed in

[9]. The initial values given for the k and epsilon are 0.01 m^2/s^2 and 1.0 m^2/s^3, respectively. In all simulations the droplet coalescence model of O'Rourke [10] is used. The time step size is 1μs and during every time step 8 computational drops are introduced. The initial spray cone angle used for the ETAB model is 10 degrees whereas a value of 25 degrees has been used for the WAVE model. Note that the radial expansion in the ETAB model is controlled by the model constant C_α listed in Table 1.

The initial injection velocity profile, which is very important for the accurate description of the spray evolution, was calculated with a one-dimensional transient code developed at the Helsinki University of Technology (HUT) [11]. The measured fuel injection pressure was used as input data for the velocity calculations. Fig. (1) shows the calculated velocity profile used for the non-evaporating spray simulations.

Experiments

A constant volume measurement chamber, filled with nitrogen at room temperature, was used in the experiments that were conducted at HUT. The chamber pressures were ranging from 1.06MPa to 3.5Mpa and, accordingly, the gas densities used in the experiments (and in the simulations) were either 20 kg/m^3 or 39 kg/m^3.

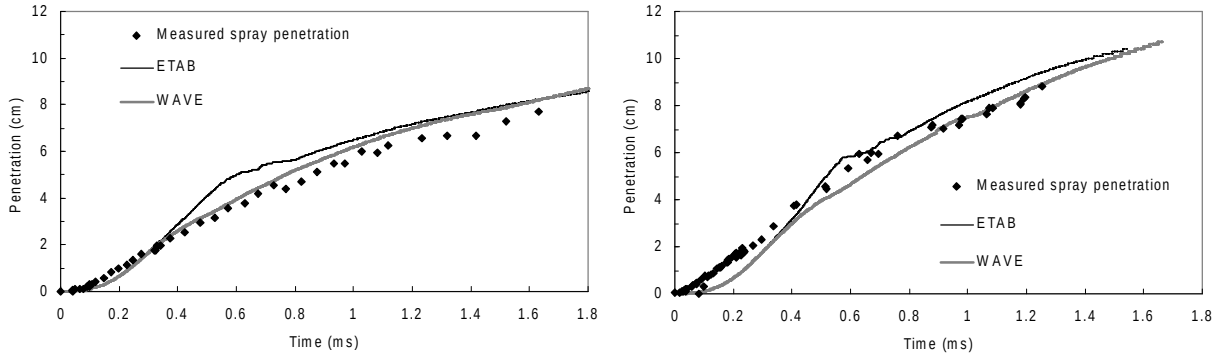
The fuel used in this study was marine fuel oil (MFO) with density 858.8 kg/m^3 (at 15°C), viscosity 8.04 mm^2/s (at 30°C), and surface tension 30.4 mN/m (at 20°C). The total mass injected is 0.125157 g (from one nozzle hole). Table 2 shows the experimental and computational cases.

The width of the spray was analyzed using 20 different images from a fully developed spray at 62mm downstream from the nozzle. The droplet sizes were also measured at 62mm from the nozzle but at different radial distances from the spray axis (6, 8, and 10mm). Each SMD value has been averaged over 20 different sprays and the measurement was made from a fully developed spray, i.e., typically later than 1.0ms after the start of fuel injection. The spray tip penetration was analyzed using 20 to 50 images which were taken at various injection times.

Case	Cam Speed (r/min)	Gas density (kg/m^3)	Fuel quality
1	500	39	MFO
2	500	20	MFO

Table 2. Experimental and computational cases.

Results

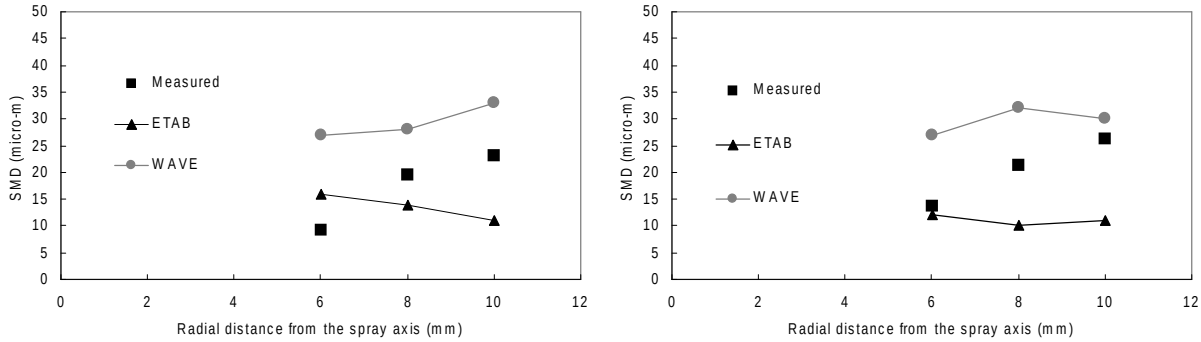


A) B)

Figure 2. Measured and computed spray penetration in A) Case 1, 39 kg/m^3, B) Case 2, 20 kg/m^3.

Figure 2 shows the measured and computed spray tip penetrations with the ETAB and WAVE breakup models in the cases 1 and 2. Both models are generally in good agreement with the measurements. There is a slight knee in the penetration length of the ETAB model close to injection time of 0.6ms in both cases. This is a computational artifact due to the Star-CD implementation and it is currently under investigation.

Figure 3 has the measured and computed droplet sizes, taken 62mm downstream of the nozzle hole, at different radial locations from the spray axis in the cases 1 and 2. Both models seem to be relatively close to the measured drop sizes. However, a general trend seems to be that the WAVE model overestimates the droplet sizes whereas the ETAB model slightly underestimates them. Close to the spray axis the ETAB predictions are excellent but further away from the axis the droplets become somewhat too small.



A) B)

Figure 3. Measured and computed droplet SMD in A) Case 1, 39 kg/m^3, B) Case 2, 20 kg/m^3.

In Figure 4 the measured and computed spray widths, taken 62mm downstream of the nozzle hole, are shown. The spray angle for the computational cases are determined between 1.5 and 1.8 ms after the start of fuel injection. During this time the spray width does not change noticeably. Both models are seen to underestimate the spray width.

Figure 5 shows the computed sprays at 1.5ms with both breakup models for the cases 1 and 2. The computational mesh is shown in the same figure and it should be pointed out that the axial cell distribution is shown correctly but because the plots show the outer wall of the mesh, the radial cell distribution is much too coarse in the figure.

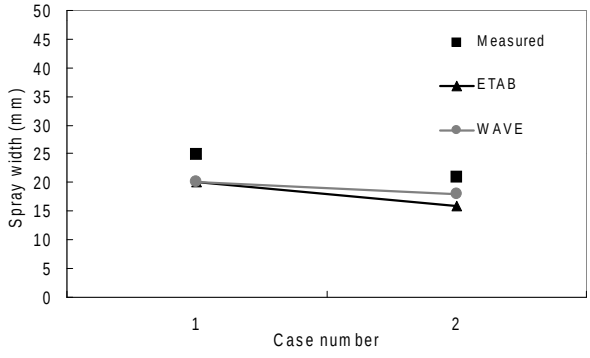


Figure 4. Measured and simulated spray widths.

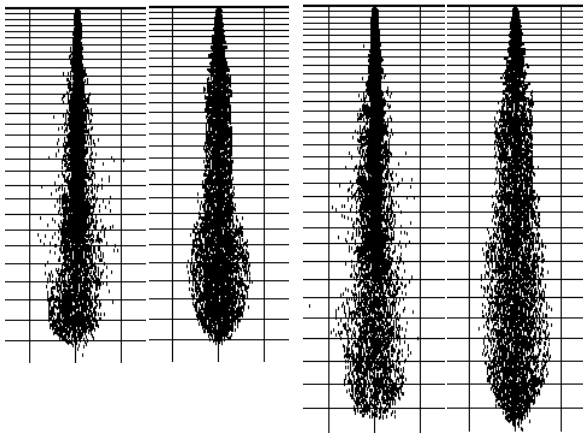


Figure 5. Sprays shown at 1.5ms for the Case 1, 39 kg/m^3, left, and for the Case 2, 20 kg/m^3, right. First and third figures from the left-hand side are computed with the ETAB breakup model, and second and fourth figures with the WAVE breakup model.

Conclusions

The ETAB droplet breakup model has been implemented into the commercial CFD-package Star-CD and its performance has been evaluated for non-evaporating sprays. The computations have been compared with the WAVE breakup model and with the experimental data taken in the high-pressure constant-volume chamber at Helsinki University of Technology. The ETAB model has the advantage over the WAVE model that it adjusts the spray angle automatically to gas density.

Both models compare well with the measured spray penetration data. The knee seen in the penetration data of the ETAB model is due to the Star-CD implementation and it is currently under investigation.

The results of this study show that the ETAB model performs well in Star-CD for non-evaporating sprays. As is generally accepted, different breakup model parameters require adjustments to different injection systems, fuels and nozzle types. Accordingly, further testing of the ETAB model in Star-CD with different fuels and nozzles is required. Also, the model performance has to be evaluated for evaporating and for reacting sprays.

Acknowledgements

Part of this research has been conducted during the corresponding author's visit to Michigan Technological University from January to December 2001. Support for this research has been provided by the National Technology Agency (TEKES), the Academy of Finland, the Technical Research Centre of Finland (VTT Processes), and by the NSF grant EIA-9871133.

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