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Full Length Article

Modelling thermal effects in cavitating high-pressure diesel sprays using an improved compressible multiphase approach

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ABSTRACT

In this study, the influence of in-nozzle phenomena including flow separation, cavitation, turbulence and hydraulic flip on the morphology of the spray emerging from a convergent-divergent-convergent diesel injector is investigated numerically. Non-linear equations of state for the liquid diesel, diesel vapour and chamber gas are employed for the simulation of high pressure diesel injection and atomisation processes. A modified multiphase mixture energy equation which takes into account enthalpy of phase change due to cavitation is integrated into a previously developed compressible, multiphase Volume of Fluid Large Eddy Simulation. The mass transfer source terms are modelled using a modified Schnerr and Sauer cavitation model. The numerical method is validated by comparing simulated mass flow rates, momentum fluxes, effective injection velocities and discharge coefficients at different injection conditions against published experimental data obtained using the same injector. Favourable comparison between simulations and experimental measurements is achieved with minor discrepancies attributable to unknown experimental uncertainties and assumptions made in numerical modelling. Calculation of in-nozzle flow and primary spray breakup reveals that interfacial instabilities generated due to in-nozzle flow separation, cavitation and liquid-wall shear contribute greatly to the jet fragmentation. The increase in sensible enthalpy due to wall shear induced viscous heating together with enthalpy of condensation increase the surface temperature of the exiting jet. Comparison of the flow physics before and after the onset of hydraulic flip indicates that wall shear is one of the main mechanisms inducing most of the energy for jet breakup. This modelling shows that vapour production at nozzle entrance remains after the onset of hydraulic flip, limiting the extent of ambient air influx. In addition, the onset of hydraulic flip causes production of near nozzle shockwaves as a result of significantly increased injection velocity attributable to minimised wall shear. This aspect needs more experimental evidence and simulations to confirm and validate.

1. Introduction

It is well understood that the atomisation characteristics of diesel sprays have a profound impact on the air-fuel mixing process and thus the combustion efficiency and pollutant formation. The preliminary factors governing the quality of atomisation include in-nozzle flow separation, cavitation, turbulence and liquid-gas interaction when the spray enters the combustion chamber. At high injection pressures, atomisation of the diesel spray is found to be enhanced especially when cavitation occurs in injector nozzles [1].

In fuel injector nozzles, high pressure gradients caused by flow contraction and acceleration at the nozzle inlet can initiate flow separation. This reduces the effective flow area and creates a recirculation zone in which static pressure can decrease to, or below, fuel vapour pressure [2,3]. The onset of cavitation then generates vapour in the flow just downstream of the nozzle inlet, which in turn decreases wall shear on the flow. Consequently, wall shear reduction leads to increase in maximum flow velocity in the nozzle. Further downstream where local pressure recovers, condensation and collapse of cavities restore the flow effective area and wall shear, which then decrease axial flow velocity [4]. Depending on the relative length of the cavities and nozzle, vapour bubbles may persist and collapse in the jet outside of the nozzle exit [5]. Collapse of cavities within the jet enhances jet breakup intensity, further increasing the spray dispersion angle [6,7]. Moreover, there are situations where flow separation and accumulation of cavities can result in complete detachment of fluid flow from the nozzle wall [8]. In those cases, ambient gases are drawn into low pressure regions of the nozzle, causing formation of mixtures composed of liquid, vapour and ambient gas near the nozzle wall [9]. In addition, the occurrence of complete flow detachment in the nozzle eliminates wall shear on the

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Nomenclature

Abbreviations

ASOI	After start of injection
LES	Large Eddy Simulation
SGS	Sub Grid Scale
MULES	Multi-Dimensional Universal Limiter with Explicit Solution
PISO	Pressure Implicit with Splitting of Operator
VOF	Volume of Fluid
RHS	Right hand side
PR	Peng-Robinson

Symbols

ρ	Density $[kg/m^3]$
t	Time $[s]$
Δt	Time step size$[s]$
U	Velocity $[m/s]$
p	Static pressure $[Pa]$
τ	Shear stress tensor
σ	Surface tension $[N/m]$
κ	Surface curvature
$\bar{n}$	Unit vector normal to liquid-gas interface
δ	Dirac function
α	Phase volume fraction
ψ	Compressibility
μ	Dynamic viscosity $[Pas]$
k	Sub-grid-scale kinetic energy $[m^2/s^2]$
I	Identity tensor
ε	Sub-grid-scale turbulent dissipation
υ	Kinematic viscosity $[m^2/s]$
V	Volume of a computational cell $[m^3]$
Δ	Sub-grid length scale $[m]$
h	Sensible specific enthalpy $[J/kg]$
λ	Thermal conductivity $[W/(m.\ K)]$
$\dot{m}^+$	Condensation rate $[kg/s]$
$\dot{m}^-$	Vaporisation rate $[kg/s]$
C_a	Interface compression factor
C_v	Coefficient for vaporisation
C_c	Coefficient for condensation
p_v	Vapour pressure $[Pa]$
rR_b	Inverse of average nuclei diameter $[1/m]$
n	Cavitation nuclei/bubble density $[1/m^3]$
η	Kolmogorov length scale $[m]$
W	Characteristic length $[m]$
Δp	Pressure difference$[MPa]$
Q	Q criterion
ΔH	Enthalpy of phase change $[J/kg]$
C_p	Constant pressure heat capacity
K	Kinematic energy $[J/kg]$
H'	Pressure dependent specific enthalpy $[J/kg]$
R	Gas constant
v_m	Molar volume $[m^3/mol]$
Z	Compressibility factor
ω	Acentric factor
$\dot{m}_f$	Mass flow rate $[kg/s]$
$\dot{M}_f$	Momentum flux $[kg{\cdot}m/s^2]$
u_{eff}	Effective injection velocity $[m/s]$
C_d	Discharge coefficient
A_o	Nozzle cross-sectional area $[m^2]$
D	Nozzle diameter $[m]$
d	Diameter $[m]$
$\dot{m}$	Mass transfer rate $[kg/s]$
a_p	Diagonal coefficient of velocity matrix

Subscripts

l	Liquid phase
v	Vapour phase
g	Gas phase
i	Phase index
sgs	Sub-grid-scale
nuc	Nuclei
inj	Injection
$i{-}j$	Phase pairs
r	Reduced
c	Critical

Superscripts

$ideal$	Ideal fluid
$real$	Real fluid

liquid jet. Thus, production of interfacial instabilities is minimised and spray atomisation is suppressed, which decrease the spray dispersion width [9]. Despite the advantage that cavitation can potentially enhance atomisation, conditions triggering the generation of in-nozzle cavities such as high injection pressure and the use of sharp nozzle inlets are often achieved at the cost of reduced longevity of fuel injectors. At high injection pressures, cavitation caused by high flow inertia and flow separation were found to erode the sharp nozzle entrance of a square throttle in time of the order of 200 µs in Greif et al.'s work [10]. This promotes the use of a rounded nozzle inlet which not only maintains a desired discharge coefficient but also improves the durability of fuel injectors by suppressing cavitation. However, suppression of cavitation due to the decrease in the extent of the recirculation zone eliminates the benefit that allowing cavitation could potentially improve atomisation and air/fuel mixing. Alternatively, cavitation can be initiated at several nozzle diameters downstream of the rounded entrance by adding a convergent-divergent section to the nozzle [11,12]. The resultant venturi effect can lead to sufficiently low pressure for cavitation to occur.

Due to the extremely small size of injector holes which have an average length of 1 mm and a diameter varying from 100 µm to 300 µm for most automotive diesel engines, experimental investigations of the in-nozzle phenomena and their effects on the subsequent jet breakup are challenging. Although useful information has been obtained from large scale replicas of fuel injector nozzles, the scale effects have been recognised to contribute significantly to the deviation in cavitation morphology between enlarged and real-scale injector nozzles [5,13]. For instance, cavitation structures differ from enlarged-scale nozzles (clouds of bubbles) to real-scale nozzles (cavitation pockets). On the other hand, the scale limitation encountered in experimental investigations of flow physics in a real-scale cavitating fuel injectors can potentially be overcome using numerical models.

As far as two-phase models are concerned, attempts have been made by Ghiji et al. [14,15] and De Villiers et al. [16] to link in-nozzle turbulence with early breakup of the diesel spray using an incompressible Volume of Fluid (VOF) approach. However, the absence of a phase change model results in the omission of the effects of cavitation on the spray evolution. Inclusion of compressibility effects and phase change through the implementation of a Tait equation of state and a cavitation model has enabled the capturing of extreme pressure peaks triggered by collapse of cavities in Koukouvinis et al.'s work [17]. A more advanced compressible approach adopting an energy equation based on sensible