Evaluation of New Criteria for Cavitation Inception in Diesel Injectors

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Abstract

Modern diesel injectors are characterized by high injection pressures wherein the flow inside the orifice and sac becomes turbulent and cavitation patterns are observed at the orifice exit. Traditionally cavitation inception in diesel injectors is based on the condition that local pressure drops below the vapor pressure of the fuel. While this criterion is seen to predict cavitation inception reasonably well, recent studies have shown that normal viscous stresses should be considered in addition to pressure, since a fluid element experiences stresses rather than the local pressure. This theory is applied to high Reynolds number flows in diesel injectors. The differences between traditional and total stress criteria to predict cavitation inception was found to be insignificant. The total stress criterion which is based on molecular viscosity was modified to include the effect of turbulent viscosity. For high injection pressure when the flow inside the injector is turbulent this new criteria based on turbulent viscosity significantly influenced cavitation inception regions. There is, however, a lack of quantitative experimental data for determining and validating an effective criterion for cavitation inception.

Introduction

Combustion of injected liquid fuel in diesel engines is dependent on the effective atomization to increase the surface area of fuel and hence achieve higher rates of mixing and evaporation. The reduction in fuel droplet size leads to higher volumetric heat release rates, prompt ignition, increased flammability limits, and lower engine emissions. During the past two decades there has been tremendous growth of interest in understanding the fundamental injection and atomization processes. The key to model the atomization process effectively lies in understanding the primary breakup of the liquid jet. Fundamentally, primary breakup in the region close to the nozzle orifice is strongly influenced by aerodynamics, cavitation, and turbulence effects from inside the injector [1,2,3]. First step towards modeling primary breakup is to understand the flow inside the nozzle since it provides boundary conditions, including turbulence and cavitation intensity, for spray models.

Cavitation refers to the formation of bubbles in a liquid flow when the local pressure drops below the vapor pressure of the fluid. Liquid to vapor transition can occur by heating the fluid at a constant pressure, known as boiling, or by decreasing the pressure at a constant temperature, which is known as cavitation. Cavitation has also been defined as "the liquid continuum rupture due to excessive stress" by Franc et al. [4]. Modern diesel engines are designed to operate at very high injection pressures (upto 3000 bar) leading to high injection velocities. Therefore, in a diesel injector nozzle, high pressure gradients and shear stresses can lead to cavitation, or the formation of bubbles. This can be beneficial to the development of the fuel spray, since the primary breakup and subsequent atomization of the liquid fuel jet can be enhanced. In addition, cavitation increases the liquid velocity at the nozzle exit due to the reduced exit area available for the liquid. Cavitation patterns extend from their starting point around the nozzle orifice inlet to the exit where they influence the formation of the emerging spray. The improved spray development is believed to lead to more complete combustion process, higher fuel consumption efficiency, and reduced exhaust gas and particulate emissions. However, cavitation can also decrease the flow efficiency (discharge coefficient) due to its affect on the exiting jet. Also imploding cavitation bubbles inside the orifice can cause material erosion thus decreasing the life and performance of the injector. Clearly an optimum amount of cavitation is desirable and it is im-

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portant to understand the sources and amount of cavitation for more efficient nozzle designs. Cavitation inception can be caused by "geometrical" and "dynamic" factors [5]. Geometrical parameters include the type of orifice (Valve Covered Orifice [VCO] or mini-sac), orifice inlet curvature, orifice length, ratio of inlet to outlet orifice diameter, and its surface roughness. Dynamic parameters include the imposed pressure gradient, injector needle lift and needle eccentricity. Improving our ability to predict cavitation inception is the major motivation for this research.

According to the traditional approach towards cavitation modeling, cavitation inception begins when the local pressure drops below the vapor pressure of the fuel at a given temperature. This criterion has been extensively used in the cavitation modeling community [6,7,8,9,10]. However, Winer and Bair [11] and Joseph [12] independently proposed that the important parameter for cavitation is the total stress that includes both the pressure and normal viscous stress. This was consistent with the cavitation experiments in creeping shear flow reported by Kottke et al. [13], who observed the appearance of cavitation bubbles at pressures much higher than vapor pressure. Thus a new criterion for cavitation inception was proposed by Joseph [12], based on the total stress that includes both the pressure and normal viscous stresses. These criteria were examined under laminar conditions in simplified geometries by Padrino et al. [14] and Dabiri et al. [15]. However, the flow inside modern injectors is known to be highly turbulent, with turbulent stresses prevailing over laminar stresses. We have further modified these criteria so that it can be used in both the laminar and turbulent cavitating flows, and evaluated its effectiveness to predict cavitation under realistic diesel engine conditions, which include realistic injection pressures and nozzle geometry. This forms the primary objective for this work i.e., to compare these criteria for predicting cavitation inception. The resulting change in nozzle exit conditions will also be characterized. We believe this is the first time that these new criteria have been evaluated under such conditions. Since primary atomization process is significantly influenced by cavitation and nozzle exit conditions, improved prediction capabilities can thus improve the predictive capability of spray models.

Physical and Computational Model

As a first step, 2D simulations will be performed and difference between these criteria will be characterized. The single orifice simulated for the full-production HEUI 315B mini-sac nozzle used in the present study is shown in Figure 1(a). The nozzle has six cylindrical holes with diameter of 169 μm at an included angle of 126°. Assuming the flow to be symmetric across all the nozzle orifices only a single orifice was simulated at steady state by considering the flow to be two-dimensional. The computational domain (single orifice) used in the simulations is indicated by a marked box. Authors acknowledge that there may be differences between the 3-D and 2-D flow characteristics since the throttling area near the orifice inlet is much larger for the 2-D case. However, the fact that the mean flow is two-dimensional lends confidence to the 2-D approach. In fact, future studies will involve assessing these criteria for 3D nozzle flows and comparing the predictions between these approaches. The base grid generated is shown in Figure 1(b). A structured mesh was created with a total of 18,040 cells (grid1), with 7200 cells (120x60) in the nozzle orifice block itself. A high mesh density is used in the sac region and in the nozzle orifice in order to capture the large pressure and velocity gradients in these regions. The boundary locations imposed, needle contour, as well as the sac and nozzle orifice regions.

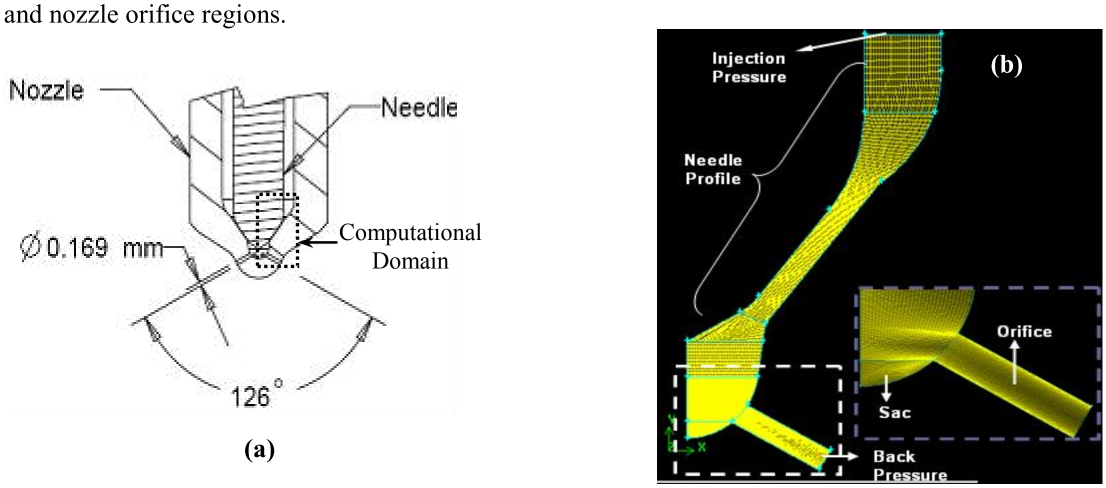

Figure 1. (a) Schematic of 6-hole full-production mini-sac nozzle. Only two holes are seen in this cross-sectional slice. (b) Grid generated for cavitation simulations.

The commercial CFD software FLUENT v6.2 was used to perform the numerical simulation of flow inside the nozzle. FLUENT employs a mixture based "full cavitation model" proposed by Singhal et al. [16]. More details about the model can be found elsewhere [16,17,18]. The two-phase model considers a mixture comprising of liquid fuel, vapor, and a non-condensable gas. While the gas is compressible, the liquid and vapor are considered incompressible. The mixture is also modeled as incompressible. In addition, a no-slip condition between the liquid and vapor phases is assumed. Then the mixture properties are computed by using the Reynolds–Averaged continuity and momentum equations [16,17,18]. This "full cavitation model" in FLUENT has been previously validated against Winklhofer et al. data [19] employing the traditional criterion of cavitation by several researchers [18,]. In the current study we do not present any validation since extensive validation can be found elsewhere [20,21]. The flow is considered isothermal, which is justified based on previous experimental studies, which indicate that the temperature difference between the fuel inlet and exit is typically not more than 10K [22]. The pressure values are specified at the inlet and outlet boundaries. Properties of both liquid and vapor phases are specified.

Results and Discussion

According to the traditional criterion, cavitation occurs when the local pressure drops below the vapor pressure of the fuel at a given temperature i.e., when $-p + p_v > 0$. This criterion can be represented in terms of a cavitation index (K) as:

$$K_{Classical} = \frac{p - p_b}{p_b - p_v} < -1 \Rightarrow Cavitating \tag{1}$$

The formulation for the new criterion is summarized below.

Maximum tension criterion: $-p - 2\mu S_{11} + p_v > 0$

Minimum tension criterion: $-p + 2\mu S_{11} + p_v > 0$

The new criteria can be expressed in terms of the modified cavitation index as:

$$K_{\max} = \frac{p + 2\mu S_{11} - p_b}{p_b - p_v} < -1 \Rightarrow Cavitating \tag{2}$$

$$K_{\min} = \frac{p - 2\mu S_{11} - p_b}{p_b - p_v} < -1 \Rightarrow Cavitating \tag{3}$$

where the strain rate S_{11} is computed as:

$$S_{11} = \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2} \tag{4}$$

Under realistic Diesel engine conditions where flow inside the nozzle is turbulent, turbulent stresses prevail over laminar stresses. Accounting for the effect of turbulent viscosity the new criteria is further modified as:

$$K_{\text{max-turb}} = \frac{p + 2(\mu + \mu_t) S_{11} - p_b}{p_b - p_v} < -1 \Rightarrow Cavitating \tag{5}$$

$$K_{\text{min-turb}} = \frac{p - 2(\mu + \mu_t) S_{11} - p_b}{p_b - p_v} < -1 \Rightarrow Cavitating \tag{6}$$

In order to evaluate this new criterion in realistic diesel injectors, we performed simulations using the nozzle described earlier (cf. Fig. 1). To the best of our knowledge, this is the first time that this new criterion has been evaluated under realistic diesel engine conditions. Simulations were performed for a peak injection pressure of 1367 bar and an injection pressure of 100 bar with a constant back pressure of 1 bar at full needle open position. Figures 2 and 3 present 'K' contours computed using the traditional criterion based on local pressure, as well as the new criteria based the minimum and maximum total stresses incorporating the effects of molecular and turbulent viscosity. Note for all these criteria, the cavitation region is characterized by 'K' less than -1.

As expected, 'K' contours based on the classical criterion (cf. Figs. 2 and 3) coincide with vapor fraction contours (not shown), indicating that the cavitation index can be used to determine the vapor fraction distribution at the orifice exit. Cavitation criteria based on molecular viscosity (K_{max}, K_{min}) show negligible difference with the classical criterion for both injection pressures. In fact, the average '*K*' values at the nozzle exit do not show any difference between the three criteria ($K_{Classical}$, K_{max}, K_{min}). Since spray development outside the nozzle depends on the average vapor fraction at the nozzle exit, it is not expected to be modified significantly using the new criteria based on molecular viscosity. These results are consistent with those of Dabiri et al. [15], who reported that the differences between the criteria in terms of the possible cavitation regions become less significant at high Reynolds numbers (i.e., at high injection pressures).

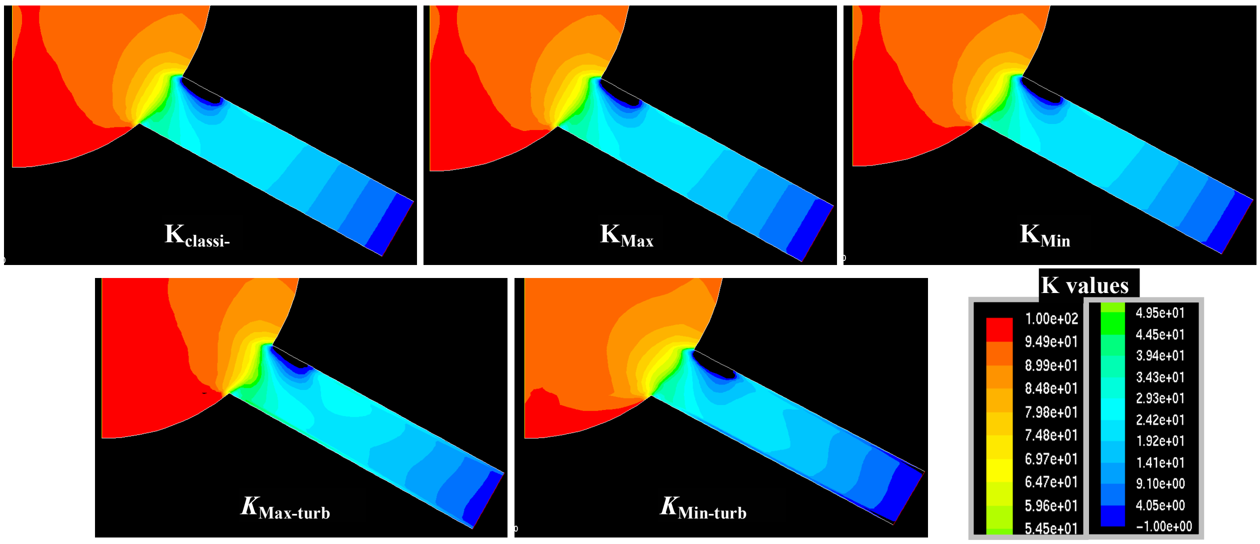

Figure 2. 'K' contours computed for injection pressure of 100 bar and back pressure of 1 bar using the different cavitation inception criteria for the nozzle orifice described in Fig. 1. Only the nozzle orifice and sac regions are shown.

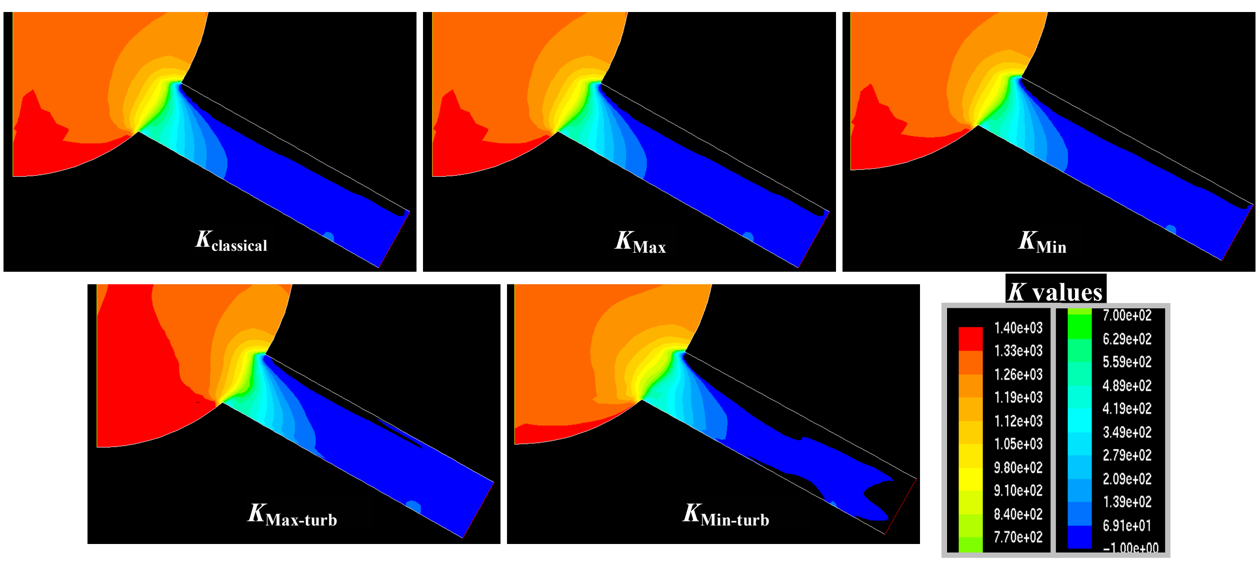

Figure 3. 'K' contours computed for injection pressure of 1367 bar and back pressure of 1 bar using the different cavitation inception criteria for the nozzle orifice described in Fig. 1. Only the nozzle orifice and sac regions are shown.

Incorporating the criteria based on turbulent viscosity, at an injection pressure of 100bar (cf. Fig. 2), minor differences are observed between the maximum tension ($K_{max\text{-}turb}$) and minimum tension criteria ($K_{min\text{-}turb}$). The minimum tension criterion indicates marginally larger cavitation pockets. However, this minimum tension criterion is a necessary but not sufficient condition, implying possibility for cavitation inception. In contrast, '*K*' contours corresponding to the maximum tension criterion ($K_{max\text{-}turb}$) indicates marginally reduced cavitation pockets compared to those for the traditional criterion. The differences among these turbulent viscosity based criteria become more pronounced at high injection pressures (cf. Fig. 3). While the minimum tension criterion predicts significantly larger cavitation pockets, the maximum tension criterion shows smaller pure vapor regions. Thus, an important observation here is that under realistic high-pressure diesel engine conditions, the turbulent viscosity based criteria for cavitation inception modifies the vapor fraction distribution inside the nozzle. This can be explained by the fact that while molecular viscosity is independent of Reynolds number, turbulent viscosity increases as the injection pressure or Reynolds number is increased. Cavitation experiments under realistic diesel engine conditions (high injection and back pressures) with real injectors (not scaled up) are necessary for validating such criteria. Unfortunately, according to the best of our knowledge, such quantitative information is missing, which inhibits a detailed evaluation of these criteria.

Conclusions

We have reported a comprehensive investigation on the criterion for cavitation inception for a single orifice of HEUI 315B diesel injector. The mixture approach based model in FLUENT v6.2 software has been employed. A new criteria for cavitation inception based on the total stress has been implemented, and its effectiveness in predicting cavitation has been evaluated under realistic diesel engine conditions. For high Reynolds number flows, minor differences in cavitation inception regions are observed between these criteria. Accounting for the effect of turbulence significant differences between these criteria were noted. However, due to the death of quantitative experimental data under diesel engine conditions detailed evaluation of these criteria was not feasible.

Nomenclature

p	local pressure
p_v	vapor pressure of fuel
p_b	back pressure
$K_{Classical}$	classical criterion for cavitation
μ	molecular viscosity
$K_{\max}, K_{\min}$	criteria for cavitation based on molecular viscosity
S_{11}	rate of strain tensor
u, v	velocities in x, y direction respectively
μ_t	turbulent viscosity
$K_{\text{max-turb}}, K_{\text{min-turb}}$	criteria for cavitation based on turbulent viscosity

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