CFD investigation of fuel property effect on cavitating flow in generic nozzle geometries

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Abstract

This paper reports a numerical study of the effect of fuel property and fuel temperature change on mechanical cavitating flow in generic nozzle geometries. The work was based on the commercial CFD code ANSYS CFX11.0. The liquid and the vapor phase were treated as a homogeneous mixture with a transport equation for the volume fraction of the vapor phase. The cavitation induced inter-phase mass transfer was calculated by a Rayleigh-Plesset-Equation based cavitation model. First, model parameter calibration was carried out and the results were validated against experimental results. Then, investigations were carried out for the effects of three important properties, namely the fuel vapor saturation pressure, density and viscosity, on cavitation behavior. Simulations were carried out by varying each of the parameters and keeping the other constant in the same time and by varying the temperature for the fuel n-heptane. Their influences on the discharge coefficient, critical cavitation point, vapor volume fraction distribution, and flow velocity development in the nozzle throttle were evaluated.

Introduction

The thermodynamic properties of Diesel or gasoline fuels in the market can vary a lot, because the compositions of the fuels can be very different from oil company to oil company, and even from refinery to refinery, and from production time to production time. Recently, the automotive industry is seeing a big trend in application of regenerative fuels or blending of mineral fuels with high percentage of renewable fuels. Some material parameters of these new fuels such as density, viscosity and vapor saturation pressure differ very much from the traditional mineral fuels. In addition, fuel properties are affected by operating temperature and pressure. As an example, the fuel viscosity in cold start phase can be doubled compared to the normal operating conditions. Therefore, two points are of practical importance for the direct injection technology development and validation. One is the fuel property under real engine operating conditions. The other is about the effect of fuel properties on the hydraulic flow, atomization of an injection nozzle and mixture formation in engine.

The present numerical study is to investigate the fuel density, viscosity and vapor saturation pressure on the cavitating flow behavior in fuel injection nozzle by using generic rectangular throttle geometries. First, numerical simulation was carried out for a model Diesel fuel. The results were compared to experimental data available at Continental Automotive GmbH for model validation purpose. Then the investigation was realized by varying one of the parameters and keeping the other unchanged in order to get a clear conclusion about the effect of each parameter. With the background of gasoline direct injection technology development, simulation was also carried out for n-heptane at various temperatures. Their effects on the discharge coefficient, critical cavitation point, vapor volume fraction distribution, and the velocity development in the throttle were evaluated.

Mathematical Model of Cavitating Flow

The work was based on the commercial CFD code ANSYS CFX11.0. The liquid and the vapor phase were treated as a homogeneous mixture with a transport equation for the volume fraction of the vapor phase. The cavitation induced inter-phase mass transfer was calculated by a Rayleigh-Plesset-Equation (RPE) based cavitation model. A pressure 100 bar was assigned assigned at inlet in all cases, while the outlet pressure was varied from 90 to 10 bar. By assuming stationary and symmetrical flow, simulation was performed based on ¼ th of the throt-tle geometry to achieve a good compromise between quality and computational effort.

Results and Discussion

The first case of investigation was based on model Diesel. The numerical mass flow rate at various injection pressures (Δp) agree well with the measurement data (Fig.1a), whereas there is some delay in cavitation inception and the critical cavitation point in CFX simulation. At throttle entrance ($l/d < 1$) part of the central velocity profiles direct above the boundary layer overshoots the Bernoulli velocity $V_0 = \sqrt{2 * \Delta p / \rho_l}$ for flow acceleration (Fig.1b). Overshoots also occur in the center region of the throttle in the case of Δp = 80 bar, where the flow

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becomes choked in the throttle due to strong cavitation (Fig.1c).

Surprisingly, increase of vapor saturation pressure (cavitation threshold) from 0.035 bar (model Diesel) to 0.8 bar (model gasoline fuel), no essential difference in flow and cavitation behavior was predicted. This difference becomes insignificant due to the high pressure gradient in the throttle.

Reduction of viscosity enhances cavitation with a much higher dynamic pressure level and a lower static pressure in the throttle and with a slight increase in the nozzle exit velocity and mass flow rate at the same injection pressure. The critical cavitation point was predicted at lower Δp. This indicates the strong effect of the Reynolds number. In the similar sense (Reynolds number effect), increase of fluid density was found to increase mass flow rate, discharge coefficient, but to reduce average injection velocity. These results are consistent with the recent literature [1-3]. In addition, the vapor volume fraction distribution displayed in Fig. 2 for four different fluid densities indicates that there is a Re threshold for cavitation inception.

Compared with the model Diesel, n-heptane has a lower density and a much lower viscosity. This leads to a much higher Reynolds number, higher injection velocity, lower injection mass, much more enhanced cavitation under the same injection pressure. Increase of the temperature from 20°C to 70°C, the viscosity of n-heptane decreases by about 40 % while the density decreases by about 5%. The final effect is a reduction in mass flow rate and much stronger cavitation due to the increasing Reynolds number.

As can be expected, a nozzle with sharp edge at entrance was predicted to cause much stronger cavitation than a nozzle with rounding inlet rounding. This effect is very dominant. In this case, the effect of the fuel properties was found to be much less significant than in the case of inlet rounding.

Conclusions

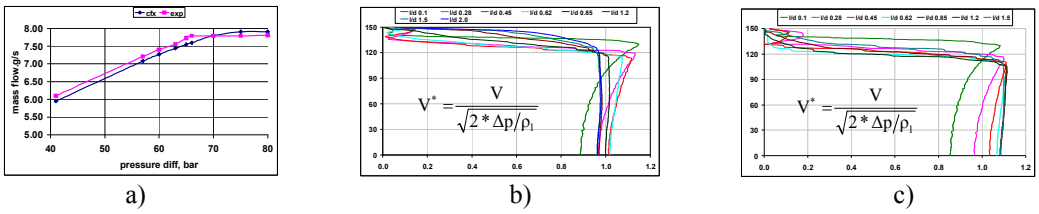
In summary, the present investigation has dealt with the fuel property effect on mechanically induced cavitation. The outcomes can be summarized as follows. Reduction of viscosity enhances cavitation with a slight increase in the injection velocity and mass flow rate at the same injection pressure. Increase of fluid density was found to increase the mass flow rate, discharge coefficient, but to reduce the injection velocity. The saturation vapor pressure does not have a significant effect on cavitation due to the very high pressure gradient in the throttle of the injection nozzle. Compared with the model Diesel fuel, the case of n-heptane has a much stronger cavitation. The fuel temperature has a significant effect on cavitation due to the density and viscosity change under different temperature. All these results indicate a strong effect of Reynolds number on cavitation phenomenon. In addition, it was found that cavitation was much strong in a nozzle without inlet rounding. In this case the fuel property effect is less obvious than in nozzle with inlet rounding.

References

[1] L. Perković, D. Greif, R. Tatschl, P. Priesching, N. Duić, *3D CFD Calculation of Injector Nozzle Model Flow for Standard and Alternative Fuels* , HEAT 2008, Fifth International Conference on Transport Phenomena In Multiphase Systems June 30 - July 3, 2008, Bialystok, Poland .

[2] H-K Lee, M F Russell, C S Bae and H D Shin, *Development of cavitation and enhanced injector models for diesel fuel injection system simulation*, Proceedings of VAFSEP2004, 6-9 July 2004, Dublin, Ireland.

[3] H. K. Suh1, S. H. Park1,C. S. Lee, *Experimdental Investigation of Nozzle Cavitating Flow Characteristics for Diesel and Biodiesel Fuels*. International Journal of Automotive Technology, Vol. 9, No. 2, pp. 217-224 (2008), DOI 10.1007/s12239-008-0028-3



a) b) c)

Figure 1. (a) comparison of mass flow rate between simulation and measurement (b, c) Velocity profiles

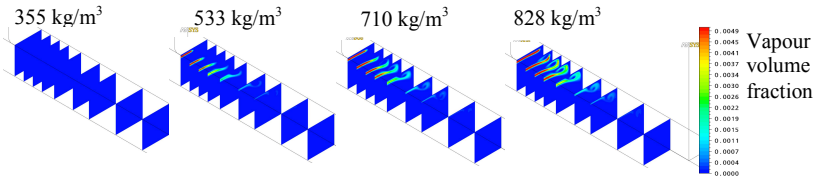


Figure 2. Effect of density on cavitation at p = 60 bar