ABSTRACT

In this work multi phase flow and erosion analysis were done via simulations in AVL’s Workflow Manager with FIRE Solver CFD application, for standard diesel and two alternative biofuels, FAME and DME, inside different nozzle models and with various boundary conditions. Driving force for fluid flow is static pressure difference between inlet and outlet. Analysis criteria were: phase volume fraction distribution due to cavitation, mass flow rate, absolute velocity profile vs. nozzle model narrow channel height and erosion MDPR. Nozzle model consists of narrow channel with sharp (type I) or rounded (type Y) inlet section, with or without downstream placed target, so there was a total of four different model geometries. Simulation results showed that cavitation was present in almost all cases and that clear difference between three observed fuels can be seen. Mass flow in channel type I was lower than one in channel type Y. When comparing three observed fuels, it was noticed that DME fuel usually had highest velocity, but lowest mass flow rate. Contrary to DME, FAME fuel showed highest mass flow rate despite lowest velocity.

When designing fuel nozzles, cavitation and cavitation erosion should always be considered. Nozzles in which less cavitation occurred, achieved higher mass flow rates for same boundary conditions. When comparing simulation results and physical properties of observed fuels, it can be concluded that density is a leading term in determining mass flow rate. Also, erosion model predicts more intensive MDPR value near narrow channel exit.

INTRODUCTION

In this project it was planned to analyze multi phase cavitating flow for different kind of model nozzles, especially focusing on the type of fuel which is used. Standard diesel fuel was under investigation as well as different alternative fuels, DME and FAME. Since the physical properties of these biofuels differ significantly from the fuels used nowadays, it was necessary to analyze them on different nozzle models.

MATHEMATICAL MODEL

Mathematical model was set up for quasi-stationary, inner, non-compressible, viscous, turbulent and two-phase type of flow. Simulations were done using Multiphase module. In Multiphase module Multifluid model is used, which means that equations for all phases are calculated separately, with pressure as only coupled variable. Volume fraction of total must be equal to one. It consists of fundamental fluid dynamic
conservation equations, $k$-$\varepsilon$ turbulence model equations and interfacial models equations. For interfacial mass exchange Linear Cavitation Model was used and for interfacial momentum exchange Cavitation Drag Model was used. Both interfacial exchange models imply two additional transport equations: Bubble Number Density and Interfacial Area equation. These equations bring up additional closure coefficients of mathematical model. The erosion model follows the work of Berchiche et al., 2002, and Franc & Riondet, 2006, and provides two variables: Erosion Incubation Time and Mean Depth of Penetration Rate (MDPR).

Turbulent Kinematic Viscosity of Continuous Phase

As shown in Eq. (1) turbulence kinematic viscosity consists of bubble induced turbulence (BI) and shear induced turbulent viscosity (SI).

$$v_{ek} = v_{ek}^{SL} + v_{ek}^{BI}$$ (1)

Equation (2) is used for calculating bubble induced turbulence (Sato and Sekaguchi, 1975).

$$v_{ek}^{BI} = C_{Sat} D_{B} \left| v \right| \alpha_d$$ (2)

The relative velocity is defined as:

$$v_r = v_d - v_e$$ (3)

Linear Cavitation Model

Mass exchange can be derived to be equal to:

$$\Gamma = \frac{1}{C_{cr}} \text{sign}(\Delta p) 3.85 \frac{p_c}{p_e} \left( N^\frac{1}{3} \left( \alpha_d \right)^2 \left| \Delta p \right|^2 \right) - \Gamma_d$$ (4)

where the effective pressure difference equals:

$$\Delta p = p_{sat} - \left( p - C_{c} \frac{2}{3} \rho_e \kappa_e \right)$$ (5)

Cavitation Drag Model

Interfacial momentum source includes drag and turbulent dispersion forces, Eq (6).

$$\mathbf{M} = C_{D} \frac{1}{8} \rho_e A_r^2 v_e \mathbf{v} + C_{T} \rho_e k_v v_{a_d}^2 - \mathbf{M}_d$$ (6)

Drag coefficient $C_D$, Eq. (8), is a function of the bubble Reynolds number, Eq (7).

$$Re_b = \frac{V_d D_{B}}{V_e}$$ (7)

$$C_D = \begin{cases} 192 \left( 1 + 0.1 \Re_b^{0.75} \right) & \text{Re}_b \leq 1000 \\ 0.438 & \text{Re}_b > 1000 \end{cases}$$ (8)

Bubble Number Density and interfacial Area Equations

In order to account for the variable size nature of the bubble distribution, this model uses interfacial area , Eq. (9), and number density, Eq. (10), transport equations, derived from Moment method solution of Liouville’s theorem.

$$\frac{\partial N}{\partial t} + \nabla \cdot \left( N^\frac{1}{3} \mathbf{M} \right) = \sum R_j + R_{ph}$$ (9)

$$\frac{\partial A}{\partial t} + \nabla \cdot \left( A^\frac{1}{3} \Phi \right) = \sum \Phi_j + \Phi_{ph}$$ (10)

Source terms on right-hand side of the previous equations have been discussed by Ishii et al. (2003), Sun et al. (2004) for two-phase bubbly flows and by Yao et al. (2004) for gas-liquid boiling flows.

Equations (11) and (12) represent coalescence due to random collision

$$R_{cc} = 4.4 \times 10^3 C_{cc} \frac{1}{\alpha_{max}} \left( \frac{1}{\alpha_{max}} \right)^{\frac{1}{3}} - \exp \left( - \left( C_{cc} \frac{1}{\alpha_{max} - \alpha} \right)^{\frac{1}{3}} \right)$$ (11)

$$\Phi_{cc} = 0.17 C_{cc} \frac{1}{\alpha_{max} - \alpha} \left( \frac{1}{\alpha_{max} - \alpha} \right)^{\frac{1}{3}} - \exp \left( - \left( C_{cc} \frac{1}{\alpha_{max} - \alpha} \right)^{\frac{1}{3}} \right)$$ (12)

where $\alpha_{max}$ is the maximum volume fraction related to the packing limit, taken to be 0.62.

Equations (13) and (14) represent breakup due to turbulent impact

$$R_{ti} = 5.2 \times 10^7 C_{ti} (1-\alpha) \left( \frac{1}{\alpha} \right)^{\frac{1}{3}} \left( \frac{1}{\alpha} \right)^{\frac{11}{3}} \exp \left( - \left( \frac{We_{cr,ti}}{We} \right)^{\frac{1}{3}} \right)$$ (13)

$$\Phi_{ti} = 0.12 C_{ti} (1-\alpha) \left( \frac{1}{\alpha} \right)^{\frac{1}{3}} \left( \frac{1}{\alpha} \right)^{\frac{11}{3}} \exp \left( - \left( \frac{We_{crit,ti}}{We} \right)^{\frac{1}{3}} \right)$$ (14)

where $We_{crit}$ is the critical Webber number, taken to be 2.3.

Equations (15) and (16) represent bubble generation due to phase change.

$$R_{ph} = C_{ph} \frac{6Ph}{\rho D_{nuc}}$$ (15)

$$\Phi_{ph} = C_{ph} \frac{6Ph}{\rho D_{nuc}}$$ (16)
Following equation represents closure equation of interfacial mass and momentum transfer:

\[
\Phi_h = \text{sign}(\Delta p) \frac{\rho_d}{\sqrt{\rho_s}} \left( N^2 \right) \left( a_d \right)^2 \left| \Delta p \right| \tag{17}
\]

**Closure Coefficients and Empirical Factors**

In order to close mathematical model, AVL FIRE user interface enables user to enter values for closure coefficients and empirical factors. Model equations label, as well as GUI label with used value, are given in Table 1.

**Table 1** Closure coefficients and empirical factors of mathematical model

<table>
<thead>
<tr>
<th>Label in model equations</th>
<th>GUI label</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_E )</td>
<td>Egler factor</td>
<td>1.2</td>
</tr>
<tr>
<td>( C_{CR} )</td>
<td>Condensation reduction factor</td>
<td>10</td>
</tr>
<tr>
<td>( C_{tt} )</td>
<td>CC1</td>
<td>1</td>
</tr>
<tr>
<td>( C_{ph} )</td>
<td>CB1</td>
<td>0.1</td>
</tr>
<tr>
<td>( D_{sato} )</td>
<td>CB4</td>
<td>1</td>
</tr>
<tr>
<td>( C_{sato} )</td>
<td>Sato’s coefficient</td>
<td>0.6</td>
</tr>
<tr>
<td>( C_{TD} )</td>
<td>Dispersion coefficient</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**COMPUTATIONAL DOMAIN**

**Nozzle Model Geometries With Corresponding Meshes**

We have a total of four different nozzle model geometries. In all models narrow channel represents fuel injector nozzle. There are narrow channel models with sharp (type I) and rounded (type Y) inlet, Fig. 1, without downstream placed target. Cases, where no target is present in model geometries were labeled as Channel cases.

Another nozzle models are those which have downstream placed target, Fig. 2, and which also have narrow channel type I or Y with same geometry as presented in Fig. 1. Cases with targets will be labelled as Target cases. Purpose of target is upstream influence on narrow channel flow, similar to influence of cylinder on flow inside real injector nozzle.

Depth of all models is 0.3 mm. Geometry of nozzle model is symmetrical regarding to x-y plane so computational domain consists from half of nozzle model geometry, regarding to x-y plane, Fig. 3. As a result of that, mesh thickness in all cases, determined with z coordinate, is equal to 0.15 mm.

**Table 2** Boundary conditions of static pressure

<table>
<thead>
<tr>
<th>Model case</th>
<th>Inlet (MPa)</th>
<th>Outlet (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>16</td>
</tr>
<tr>
<td>Target</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 3 Inlet and outlet boundary conditions

<table>
<thead>
<tr>
<th>Selection</th>
<th>Variables</th>
<th>Continuous phase</th>
<th>Dispersed phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>static pressure</td>
<td>depends on case</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>flow direction</td>
<td>$x=1$, $y=0$, $z=0$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>turbulent kinetic energy</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>turbulent length scale</td>
<td>2e-04</td>
<td>2e-04</td>
</tr>
<tr>
<td></td>
<td>turbulent dissipation rate</td>
<td>25</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>volume fraction</td>
<td>0.99999</td>
<td>1e-06</td>
</tr>
<tr>
<td>Outlet</td>
<td>static pressure</td>
<td>depends on case</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>turbulent parameters are not fixed</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>volume fraction</td>
<td>0.99999</td>
<td>1e-06</td>
</tr>
</tbody>
</table>

Table 4 Physical properties of observed fuels

<table>
<thead>
<tr>
<th>Phase</th>
<th>Density ($\rho$) kg/m$^3$</th>
<th>Dynamic viscosity ($\mu$) Pas</th>
<th>Saturation pressure ($p_{sat}$) Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>828</td>
<td>2.14E-03</td>
<td>892 (assumption)</td>
</tr>
<tr>
<td>Phase 2</td>
<td>661</td>
<td>1.558E-04</td>
<td>892 (assumption)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase</th>
<th>Density ($\rho$) kg/m$^3$</th>
<th>Dynamic viscosity ($\mu$) Pas</th>
<th>Saturation pressure ($p_{sat}$) Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>7</td>
<td>1E-05</td>
<td>892 (assumption)</td>
</tr>
<tr>
<td>Phase 2</td>
<td>11.23</td>
<td>1.028E-05</td>
<td>1E-05 (assumption)</td>
</tr>
</tbody>
</table>

Initial Conditions and Time Parameters

Initial conditions were: in every cell velocity was set to zero and static pressure was set to be equal to pressure on inlet selection. Since flow type was expected to be quasi-stationary, small variations of mass flow rates were expected. Simulation time step is 1e-08 s, and simulation end time is 4e-07 s.

PHYSICAL PROPERTIES OF OBSERVED FUELS

Physical properties for all observed fuels are listed in Table 4. Properties for FAME are from a book ‘Biodiesel’ by M. Mittelbach.

Properties of FAME fuel are similar to mineral diesel, while properties of DME are similar to liquefied natural gas, Semelsberger et al. (2006).

RESULTS

Analysis Criteria and Result Representation

For all cases there is unique result presentation and analysis criteria.

Analysis criteria for volume fraction distribution due to cavitation are cavitation length and thickness. Cavitation distribution was taken from x-y symmetry plane, Fig. 3, around narrow channel area. Very important analysis criteria is mass flow rate achieved in narrow channel, which is critical zone for fluid flow. It was taken from inlet selection to avoid mass accumulation due to phase change. Continuous phase absolute velocity profiles vs. narrow channel height were taken near narrow channel exit along line that lies on x-y symmetry plane. Erosion MDPR was taken on erosion selections, which are located on narrow channel upper and lower wall, perpendicular to symmetry plane.

Nozzle Models Without Downstream Placed Target

In Fig. 6 continuous phase volume fraction distribution can be seen for three different pressure drops. Cavitation occurs in all Channel type I cases and it is longest and thickest in FAME fuel cases. In Channel type Y cases cavitation is negligible, except in 30-08 MPa pressure drop case.

Mass flow is presented in Figures 4 and 5 for all pressure drops. FAME fuel achieves highest mass flow rates in all cases. DME has lowest mass flow rates. Generally, mass flow rates in Channel Y cases are higher than ones in Channel I cases for same boundary conditions.
Fig. 5 Mass flow rates in Channel Y cases for all pressure drops

Velocity profile vs. channel height in Figures 7 and 8 shows that DME fuel achieved highest velocities in all cases, and that in Channel cases type I flow is rather undeveloped. In Channel Y cases flow velocity profiles are showing same trend regarding to fuel type, but flow is developed here, Fig. 9.

Fig. 7 Velocity profiles vs. narrow channel height in Channel I 10-04 MPa pressure drop case

Continuous phase, 10-04 MPa

- Standard Diesel
- DME
- FAME

Fig. 8 Velocity profiles vs. narrow channel height in Channel I 30-08 MPa pressure drop case

Continuous phase, 30-08 MPa

- Standard Diesel
- DME
- FAME

Fig. 9 Velocity profiles vs. narrow channel height in Channel Y 30-08 MPa pressure drop case

Continuous phase, 30-08 MPa

- Standard Diesel
- DME
- FAME

Erosion MDPR distribution, which is presented in Fig. 10, is also shown for three pressure drops. It can be noticed that for Channel cases type I MDPR is greater in near narrow channel exit. In Channel cases type Y greater values of MDPR are also present near rounded narrow channel inlet.

<table>
<thead>
<tr>
<th>CHANNEL CASE, TYPE I</th>
<th>CHANNEL CASE, TYPE Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-04 MPa</td>
<td>30-08 MPa</td>
</tr>
<tr>
<td>Standard diesel</td>
<td></td>
</tr>
<tr>
<td>FAME</td>
<td></td>
</tr>
<tr>
<td>DME</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6 Continuous phase volume fraction distribution in Channel cases
Nozzle Models With Downstream Placed Target

In Fig. 11 continuous phase volume fraction distribution for all Target cases is presented. Cavitation occurs in all cases along whole narrow channel, but cavitation streams are much more thinner in Target cases type Y.

Mass flow is presented in Fig. 12, and it shows same trend as in previous chapter. Again FAME fuel achieves highest and DME fuel lowest mass flow rates in all cases, and again mass flow rates in Target Y cases are higher than ones in Target I cases for same boundary conditions.

Velocity profiles vs. channel height are presented in Figures 13-16. Again DME achieved highest velocities in all cases. It is noticeable that flow is much more developed in Target I cases, than it is in Channel I cases.
Erosion MDPR, Fig. 17, shows that DME fuel has highest MDPR value close to the narrow channel exit. In Target Y cases it can be seen that erosion is more intense near rounded narrow channel inlet.

<table>
<thead>
<tr>
<th>TARGET CASE, TYPE I</th>
<th>TARGET CASE, TYPE Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-0.1 MPa</td>
<td>40-02 MPa</td>
</tr>
<tr>
<td>10-0.1 MPa</td>
<td>40-02 MPa</td>
</tr>
<tr>
<td>Standard Diesel</td>
<td>Standard Diesel</td>
</tr>
<tr>
<td>DME</td>
<td>FAME</td>
</tr>
<tr>
<td>FAME</td>
<td>DME</td>
</tr>
</tbody>
</table>

Fig. 17 Erosion MDPR distribution along narrow channel wall in Target cases

CONCLUSIONS

Most significant conclusion when comparing all fuels is regarded to their mass flow rates. When looking Figures 4, 5 and 12 and taking Table 4 into consideration, it can be noticed that fluid density is more significant property than viscosity. This is concluded upon a fact that in almost all cases DME fuel had highest velocity, which is generally related to viscosity, but lowest mass flow rate due to lowest density. FAME fuel Standard diesel and FAME had similar results due to their similar properties. Their mass flow rates were higher than DME’s which is related to their greater density.

When comparing Figures 4, 5 and 12 with Figures 6 and 11, following conclusion imposes. Nozzles in which less cavitation occurs inside narrow channel, which is critical region for nozzle mass flow rate, will achieve larger mass flow rates for same boundary conditions.

Based on simulation results, when designing fuel nozzles, cavitation should always be considered as well as resulting cavitation erosion. As presented in Figures 6 and 11, cavitation is significantly reduced with rounded narrow channel inlet. Also, when comparing Figures 10 and 17, it can be seen that downstream placed target reduces MDPR inside narrow channel wall. This means that condensation of dispersed phase occurs outside narrow channel region, probably on target.

NOMENCLATURE
A''''' interfacial area density 1/m
D_b bubble diameter m
D_{nuc} nucleate bubble size m
k specific kinetic energy m^2/s^2
M linear momentum kg/(m s)^2
MDPR Mean Depth of Penetration Rate m/s
N''''' bubble number density 1/m^3
p pressure (static) Pa
Ph term representing closure Eq. 17 kg/(m^3 s)
R_j number density source term not related to phase change 1/(m^3 s)
R_{ph} number density source term related to phase change 1/(m^3 s)
t time s
v velocity m/s
α volume fraction m^3/m^3
Γ interfacial mass exchange kg/(m^3 s)
ε turbulent dissipation rate m^2/s
ν kinematic viscosity m^2/s
ρ fluid density kg/m^3
Φ_{ph} interfacial area source term related to phase change 1/(m s)
Φ_{j} interfacial area source term not related to phase change 1/(m s)
C_{CR} condensation reduction factor -
C_{E} Egler coefficient -
C_{ph} closure coefficient -
C_{rc} closure coefficient -
C_{Sato} Sato’s coefficient -
C_{ui} closure coefficient -
Re Reynolds number (defined in Eq. 7) -
We Webber number -
W_{ec} Critical Webber number -

Subscripts

c continuous phase
d dispersed phase
D drag
i interfacial
j source terms not related to phase change
ph source terms regarding to phase change
r relative between dispersed and continuous
sat saturation
TD turbulent dispersion

Superscripts

BI bubble induced
SI shear induced
t turbulent

REFERENCES

AVL FIRE v.8 Manual, Multiphase flow, July 2007