MODELLING OF CAVITATION FLOW IN A DIESEL INJECTION NOZZLE

S. Martynov¹, D. Mason², M. Heikal²

¹ Department of Mechanical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK
² Sir Harry Ricardo Laboratories, Internal Combustion Engines Group, University of Brighton, Brighton, BN2 4GJ, UK

The problem of modelling of scale effects on cavitation flow is considered. A single-fluid model of cavitation, which takes into account the liquid quality and viscous shear stress effects, is proposed. The model is implemented into the computational fluid dynamics code PHOENICS and validated using available experimental data on cavitation flows in nozzles.

Similarity of cavitation flows

<table>
<thead>
<tr>
<th>Similarity criteria</th>
<th>Reynolds number</th>
<th>Cavitation number</th>
<th>Structural number</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Re = \frac{pU}{\mu}</td>
<td>D/\pi )</td>
<td>( CN = \frac{p_l - p_v}{p_v}</td>
<td>\frac{p_l - p_v}{p_v} )</td>
</tr>
</tbody>
</table>

Scale effects

Cavitation bubble nuclei:

- Large Scale
- Small Scale

Radius and number density of cavitation bubbles give additional similarity criteria:

\( R_v/D, \frac{1}{S^2} \)

Viscous scale effect:

\( \frac{R_v}{D} = \frac{1}{S^2} \)

A model of hydrodynamic cavitation

Volume fraction equation

The liquid-vapour flow is described using the homogeneous mixture concept. The phase content and mixture properties are described by the vapour volume fraction \( \alpha \), governed by the transport equation:

\[
\frac{\partial \alpha}{\partial t} + \frac{\partial \alpha \mathbf{u}}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left( \alpha p \mu \frac{\partial \alpha}{\partial x_j} \right) + \frac{1}{\rho} \frac{\partial}{\partial x_j} \left( \alpha \frac{2}{3} \pi \alpha \left( \frac{\partial \alpha}{\partial x_j} \right)^2 \right)
\]

The model was implemented into the CFD code PHOENICS. Discretisation of the void fraction equation was performed using the "super-bee" convection scheme (Hirsch, 1990).

Model for the concentration of bubble nuclei

A model for the parameter \( n \) has been derived to meet the similarity criterion:

\[
C = \sqrt{\frac{n}{D}} = \text{idem}
\]

\[
\frac{p_v - p_{\text{min}}}{p_v} = \text{maximum tension in liquid, Pa;}
\]

\[
\frac{n}{n^*} = \text{adjustable liquid-specific number density parameter, } 1/m^3.
\]

Model for the cavitation pressure threshold

Cavitation onset in a static liquid: \( p < p_{cr} = p_v \)

In a flowing liquid cavitation onset depends on maximum tension (Joseph, 1995):

\[
-p + 2\mu \frac{\dot{S}_{ij}^{\max}}{\mu} = -p_v
\]

\[
p < p_{cr} = p_v + 2\mu \left( 1 + C_p \frac{\mu_t}{\mu} \right) \frac{\dot{S}_{ij}^{\max}}{\mu}
\]

\( S_{ij}^{\max} = \text{maximal rate of strain, } 1/s; \)

\( \mu = \text{dynamic viscosity of liquid, Pa s;} \)

\( \mu_t = \text{turbulent viscosity, Pa s;} \)

\( C_p = \text{adjustable coefficient.} \)

Results

Cavitation of a low viscosity fluid

Measured vapour-liquid field:

(Roosen et al., 1996)

Numerical predictions:

\( n = 4.4 \cdot 10^{-14} (m^3); \quad C_f = 10 \)

Cavitation of a high viscosity fluid

Measured vapour-liquid field:

(Winklhofer et al., 2001)

Numerical predictions:

\( n = 2 \cdot 10^{-15} (m^3); \quad C_f = 10 \)

Publications


Acknowledgements

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Conclusions

- A homogeneous-mixture model of cavitation flow, based on the theory of bubble dynamics, has been extended in order to describe the liquid quality and viscous shear stress effects on cavitation flow.
- Assuming hydrodynamic similarity of cavitation flows, an algebraic model for the number density of active cavitation nuclei is suggested.
- The influence of viscous shear stress on cavitation flow has been clarified, and described in the model for the cavitation pressure threshold.
- The model was adjusted to describe sub-cavitation and super-cavitation flows in real-scale models of diesel injectors.