Turbulent cavitation in a microchannel

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Why cavitation in microchannel?

Cavitation may exist in injection nozzle, particularly for Direct Injection Engines where pressure of 1500 bars can be reached

Injection nozzles have diameter of a few hundreds of micrometer

Cavitation can have two negative effects - induced failure [1] – make the amount of fluid introduced incontrolable – and one positive effect: it can affect the atomization process [2], and improve mixing

Experiment done in decane

Modeling Engine Spray and Combustion Processes Gunnar Stiesch Springer

Channel in plexiglass done by micromachining 1mm deep

Square cross section 1 mm

Severe restriction

Fast expansion
Experimental set-up

double enveloppe tank

cavitation channel

high speed camera

controlling computer

gear pump

thermostated bath
Fluid used: 1 Methoxy HeptaFluoroPropane, commercial name NOVEC HFE 7000 from 3M

\[
\text{CH}_3\text{-O-O-CF}_2\text{-CF}_2\text{-CF}_3
\]

Molecular Weight: 200 g/mol
Liquid density: 1400 kg/m³
Viscosity at \(25°C\): \(0.32 \times 10^{-3}\) Pa.s
Surface tension: \(12.4 \times 10^{-3}\) N/m

Freezing point: \(-122°C\)
Boiling point at 1 atm: \(34°C\)
Critical density: \(553\) kg/m³
Critical pressure: \(28.4\) atm
Critical temperature: \(165°C\)

Specific heat: \(13.0\) kJ.kg\(^{-1}\)K\(^{-1}\)
Latent heat of vaporization: \(142\) kJ/kg
Thermal conductivity: \(0.075\) W.m\(^{-1}\)K\(^{-1}\)

Vapor pressure at \(25°C\): \(64.5\) kPa
Flow conditions in the restriction

<table>
<thead>
<tr>
<th>Flow rate [m³/s]</th>
<th>Pressure drop [Bar]</th>
<th>Velocity [m/s]</th>
<th>Reynolds</th>
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</table>

Onset of pocket cavitation in the divergence section

Onset of cavitation in the small channel
Pocket cavitation in the fast expansion divergence

Velocity in the small channel: 7 m/s, Reynolds 30 000
Flow field measurements by Particle Image Velocimetry (fluid: water, seedings particles 3.0 µm, volumetric flow rate 20 ml/min)
Images: 23000 fps (Phantom V710)

Film 1000x slower, T=20°C
Thermal effect of the cavitation?

\[ \Delta T^* = \frac{\rho_V L_V}{\rho_L C_{P,L}} \]

\( \rho_V \) density of the gas
\( \rho_L \) density of the liquid
\( L_V \) latent heat
\( C_{P,L} \) heat capacity of the liquid

Stepanoff number

\[ B = \frac{\Delta T}{\Delta T^*} = \frac{\alpha_V}{1 - \alpha_V} \approx 1 \]

\( \alpha_V \) vapor void fraction (volume fraction of vapour)

Mean thermal effect when \( \alpha_V = 0.5 \) (considering an infinite thermal diffusion) \( \Delta T = 0.5^\circ C \)
Experimental set-up for 2 colors flow induced fluorescence

Novec HFE 7000 + Pyrromethene 5x10^-5 mol/l
(2,6-di-tert-butyl-8-nonyl-1,3,5,7-tetramethylpyrromethene-BF$_2$ Complex)

532 nm filter
+ interference filter 615-625 nm

Photomultiplier 1

532 nm filter
+ interference filter 545-555 nm

Photomultiplier 2

Green continuous laser 532 nm


TWO COLOUR LIF: Fluorescence intensity in function of the wavelength

Fluorescence spectrum of Pyrromethene in Novec when excited by a 514.5 nm ion Argon laser. Two observed band: 545-555 nm and 615-625 nm
Temperature sensitivity coefficient : green dotted line, sensitivity different in both selected bands
Intensity of the light induced fluorescence

\[ I_f (\lambda) = K_{opt} (\lambda) K_{spec} (\lambda) V_c I_0 C e^{\frac{\beta(\lambda)}{T}} \]

\( \lambda \): wavelength
\( K_{opt} \): optical constant
\( K_{spec} \): constant depending only on the spectroscopic properties of the tracer
\( V_c \): concentration of the tracer
\( I_0 \): laser excitation intensity
\( C \): concentration of the tracer
\( \beta \): temperature sensitivity parameter
\( T \): temperature in °K
Two color LIF

\[ R_{12} = \frac{I_1}{I_2} = \frac{V_CI_0C \int_{545}^{555} K_{opt}(\lambda)K_{spec}(\lambda)e^{\frac{\beta(\lambda)}{T}} d\lambda}{V_CI_0C \int_{615}^{625} K_{opt}(\lambda)K_{spec}(\lambda)e^{\frac{\beta(\lambda)}{T}} d\lambda} \]

\[ R_{12} \approx \frac{K_{opt}(\lambda)K_{spec}(\lambda)e^{\frac{\beta(\lambda)}{T}} \times \Delta\lambda|_{\lambda=550}^{\lambda=555}}{K_{opt}(\lambda)K_{spec}(\lambda)e^{\frac{\beta(\lambda)}{T}} \times \Delta\lambda|_{\lambda=620}^{\lambda=615}} \approx Ae^{\frac{B}{T}} \]

This results in \( A = 21.67 \) and \( B = -885.37 \) K\(^{-1}\)

Void fraction (first rough approximation)

\[ \frac{I_1}{I_{1,\text{ref}}} \propto \alpha_L \propto (1 - \alpha_V) \quad \alpha_V \text{ vapor void fraction} \quad \alpha_L \text{ vapor void fraction} \]
Fluorescence calibration

\[ y = -885.37x + 3.076 \]
Temperature effect along the vertical axis (Z)

Local void fraction

Local temperature effect
Temperature effect along a cross section

Local void fraction

Local temperature effect
Conclusion

• Cavitation experiments have been conducted in a microchannel, in conditions (relatively) close to direct injection nozzles

• The 2 colors LIF is able to measure at least at some points the temperature decrease induced by the cavitation

• Locally, a cooling effect of a few Celsius is observed

• In the mushy area, where interfaces are numerous, it seems not to be possible to measure both the temperature and the void fraction, probably because of light scattering
Perspective

• Simulate numerically the experiment to test different models of cavitation

• Establishing the phase diagramme of the cavitation in fonction of the temperature and liquid flow rate

• Analyse quantitatively the cavitation in doing statistics on the void fraction, on the size of the cavitation bubbles,

• Study the presence or not of hysteresis in this cavitation, and if it can be observed on the pressure drop through the channel restriction
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Thanks for your attention