Centre for Automotive Engineering

Vortex rings and related processes

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Modelling of two-phase vortex ring flow based on the fully Lagrangian Approach

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Outline

- Introduction
- Experimental observations
- FLA. Mathematical formulation
- Results and Discussion:
  - FLA + Analytical Solution
  - FLA + DNS
- Further work

Vortex ring flows

Classical publications:

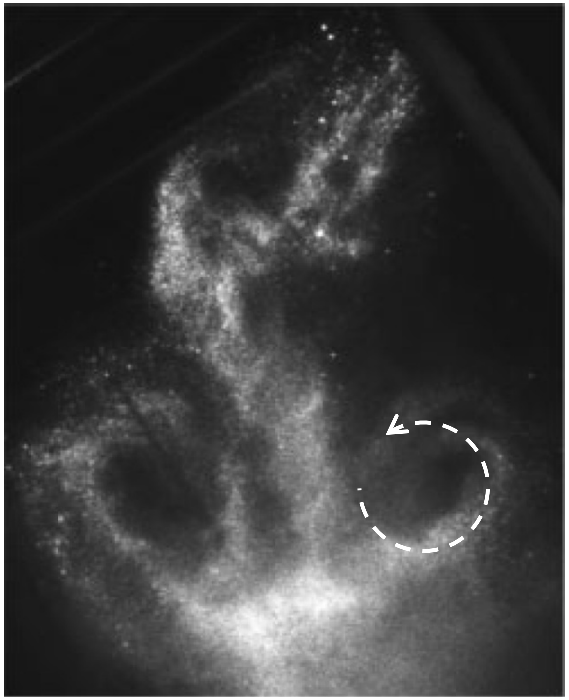
- Helmholtz 1858
- Lamb 1932
- Saffman 1992
- Shariff & Leonard 1992
- Mohseni & Gharib 1998

+ much more experimental and theoretical studies

Papers from the CAE (SHRL):

- Begg, S., Kaplanski, F., Sazhin, S., Hindle, M. & Heikal, M. 2009
- Kaplanski, F., Sazhin, S. S., Fukumoto, Y., Begg, S. & Heikal, M. 2009
- Kaplanski, F., Sazhin, S. S., Begg, S., Fukumoto, Y. & Heikal, M. 2010
- Kaplanski F., Fukumoto, Y. & Rudi, U. 2012
- Danaila, I., Kaplanski, F. & Sazhin, S. 2015

Motivation



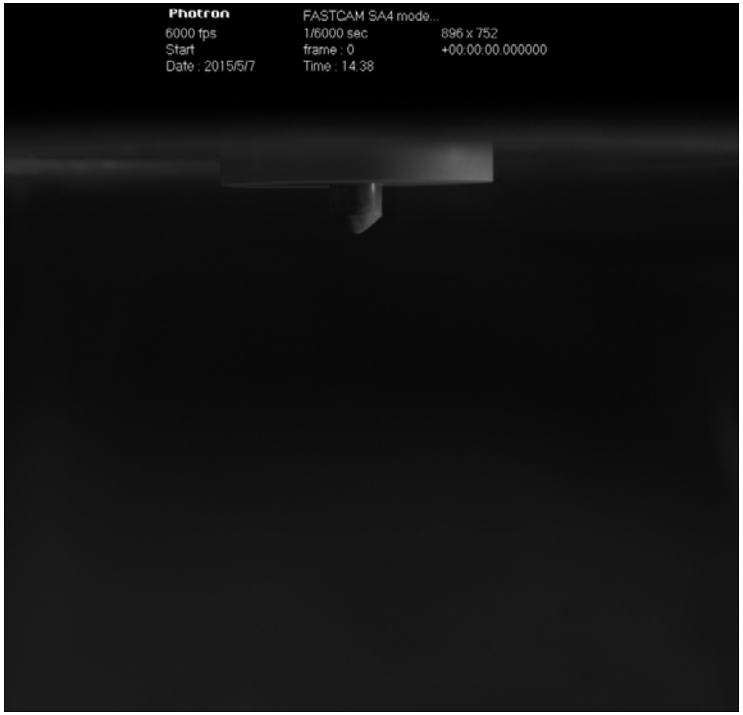
A typical high-speed photograph of a G-DI spray (Begg et al 2009)

EPSRC project "Investigation of vortex ring-like structures in internal combustion engines, taking into account thermal and confinement effects"

Extract from 'Aims and objectives':
"5. To investigate the applicability of the full Lagrangian approach to modelling sprays in the presence of swirl, thermal gradients, and the heating and evaporation of droplets."

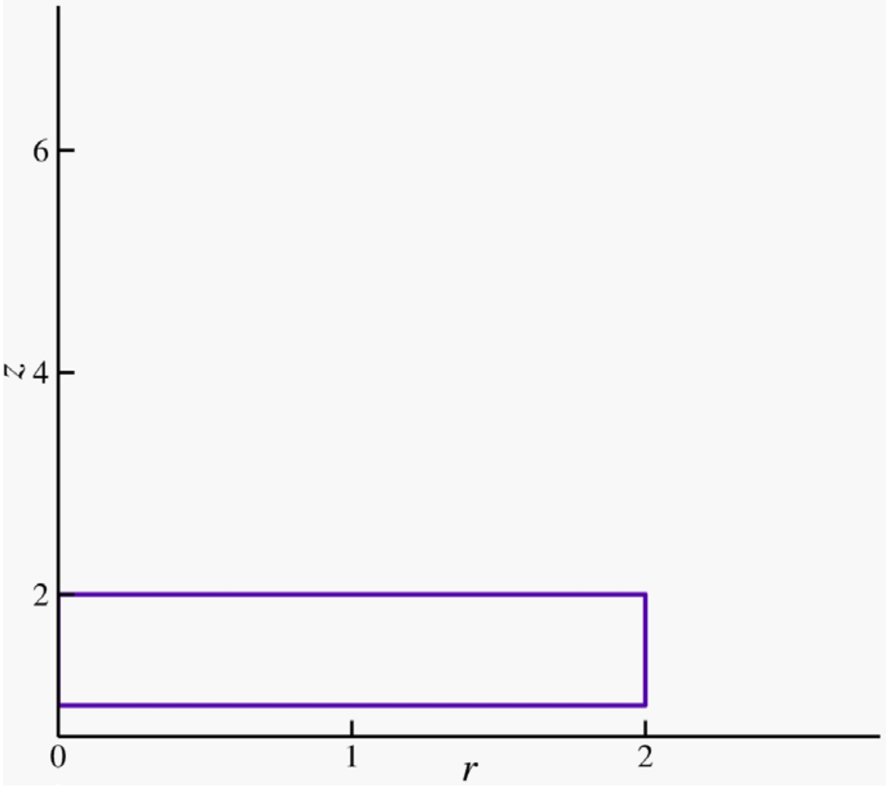
Experimental observations:

Injector 5: Bosch HDEV Hollow Cone, DI piezoelectric, 100-200 bar fuel pressure, high flow rate 42 mg/ms at 200 bar, multiple injection

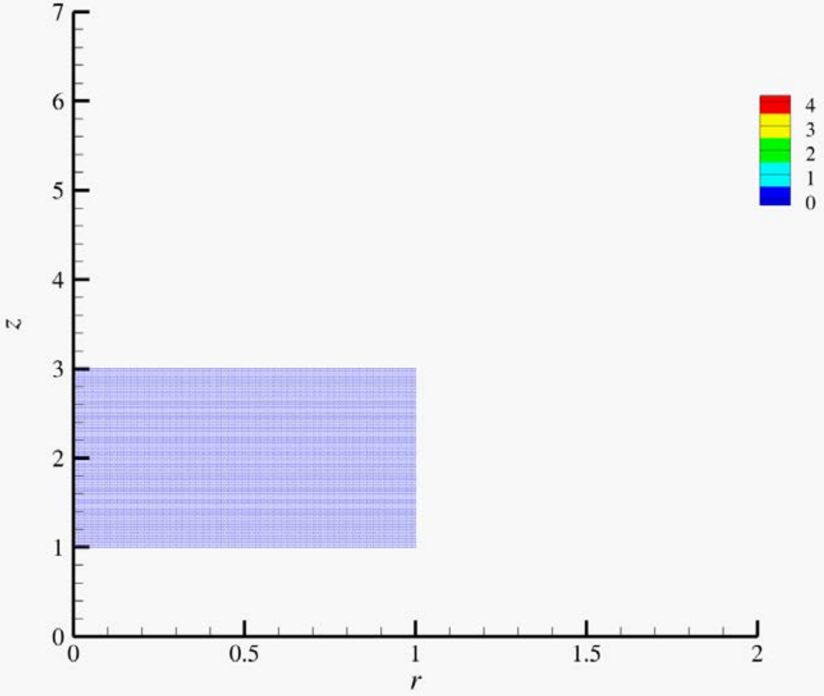


Vortex ring formation

Why FLA?



Lagrangian frame deformation



Number of folds

Mathematical formulation

One-way coupling

Carrier phase: viscous incompressible liquid
(DNS and Kaplanski-Rudi solution)

Dispersed phase: identical spherical particles/droplets, pressureless continuum

Force acting on a particle: aerodynamic drag force

Mathematical formulation

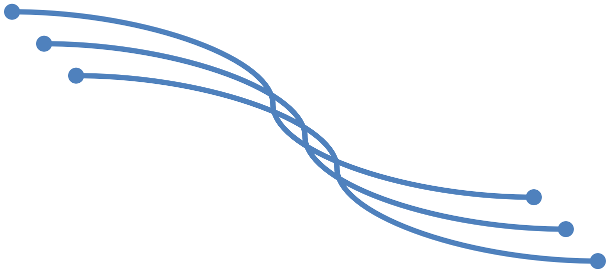
Fully Lagrangian approach:

Lagrangian variables:

Coordinates of trajectory origin

+

Time/parameter along a particle trajectory



$$n_s \left|J\right| = n_{s0} \left|J_0\right|$$

Mass conservation

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}_s$$

$$m\frac{d\mathbf{v}_s}{dt} = \mathbf{f}_s$$

Momentum balance

+ aux. equations for the Jacobian

$$J_{ij} = \frac{\partial x_i}{\partial x_{0\,j}}$$

Carrier phase: vortex ring

Incompressible viscous liquid

Cylindrical coordinates

- Kaplanski analytical solution

$$\Psi = -\frac{r\sqrt{\mathrm{Re}}}{4\sqrt{2t}} \int\limits_0^\infty F\left(x, \sqrt{\mathrm{Re}}\frac{z - z_{vc}}{\sqrt{2t}}\right) \mathrm{J}_1\left(\sqrt{\mathrm{Re}}\frac{x}{\sqrt{2t}}\right) \mathrm{J}_1\left(\sqrt{\mathrm{Re}}\frac{rx}{\sqrt{2t}}\right) dx.$$

- DNS (Second order finite difference)

Dispersed phase equations:

$$\boxed{\beta = \frac{6\pi\sigma\mu R_0^2}{m\Gamma_0}}$$

$$n_d r\left|J\right| = n_{d0} r_0$$

$$\frac{d\mathbf{r}_d}{dt} = \mathbf{v}_d$$

$$\frac{d\mathbf{v}_d}{dt} = \beta\left(\mathbf{v} - \mathbf{v}_d\right)$$

$$\frac{\partial J_{ij}}{\partial t} = q_{ij}$$

$$\frac{\partial q_{ij}}{\partial t} = \beta\left(\frac{\partial v_i}{\partial x_1} J_{1j} + \frac{\partial v_i}{\partial x_2} J_{2j} - q_{ij}\right)$$

$$J_{ij} = \frac{\partial x_{id}}{\partial x_{j0}} \qquad q_{ij} = \frac{\partial v_{id}}{\partial x_{j0}}$$

$1 - r$

$2 - z$

Initial conditions:

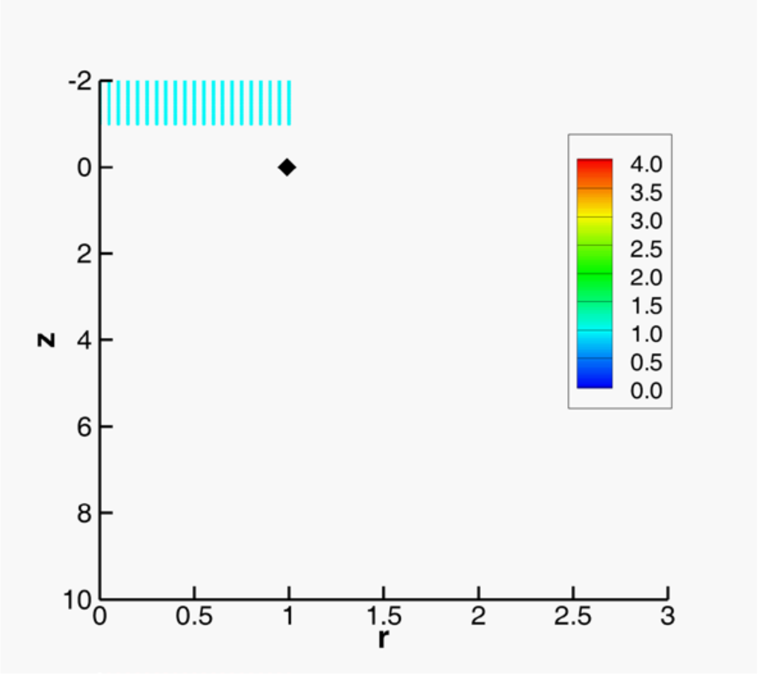
$$r_d = r_{d0},\ z_d = z_{d0},\ u_d = u_{d0},\ v_d = v_{d0},\ n_d = n_{d0}$$

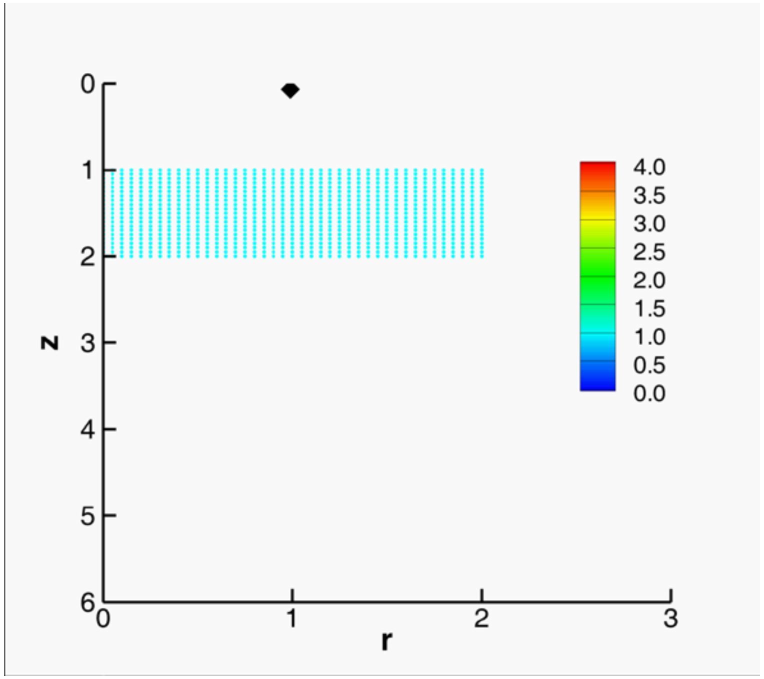
$$q_{ij} = 0, \quad J_{ij} = \delta_{ij}$$

Two-phase flow, number density

Simulations based on Kaplanski solution,

Re = 100





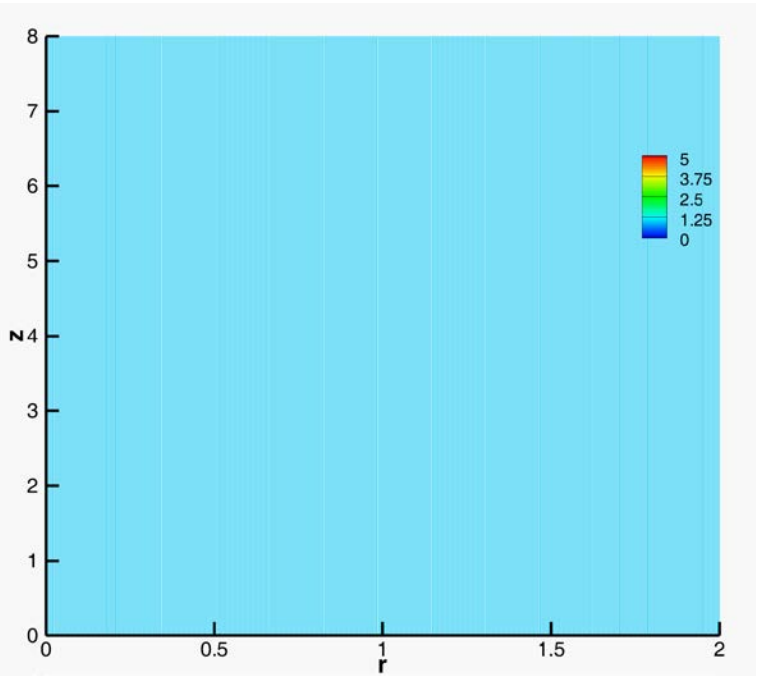
Two-phase jet

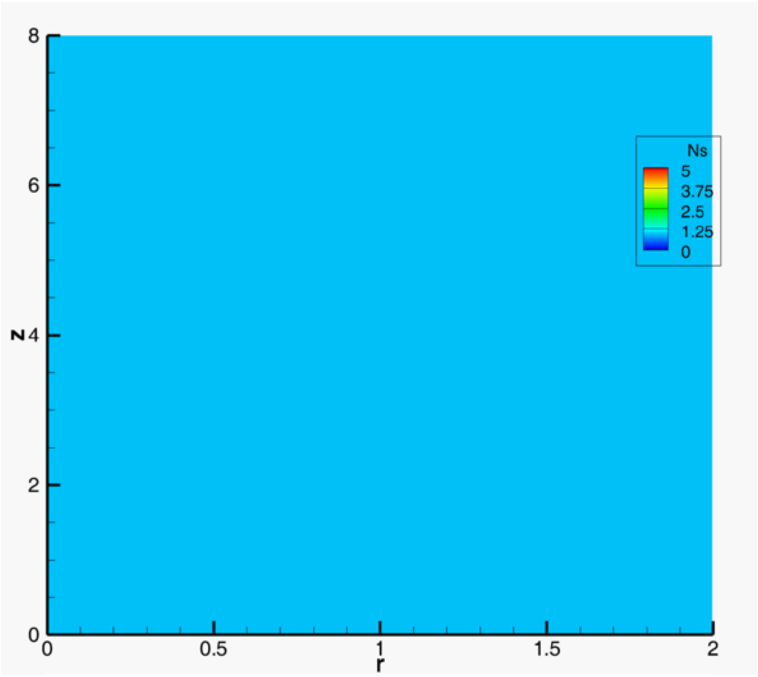
Cloud of particles ahead of the vortex ring

Two-phase flow, number density

Simulations based on DNS

Re = 20 000



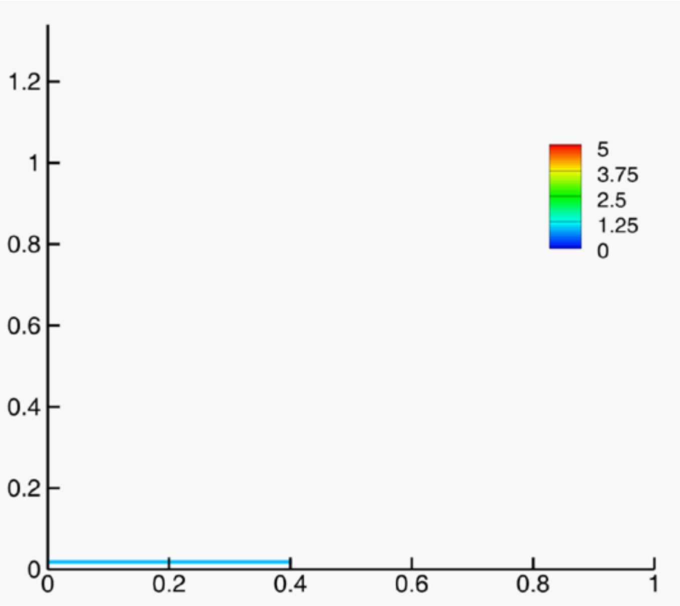


Propagation of vortex ring in a cloud of particles

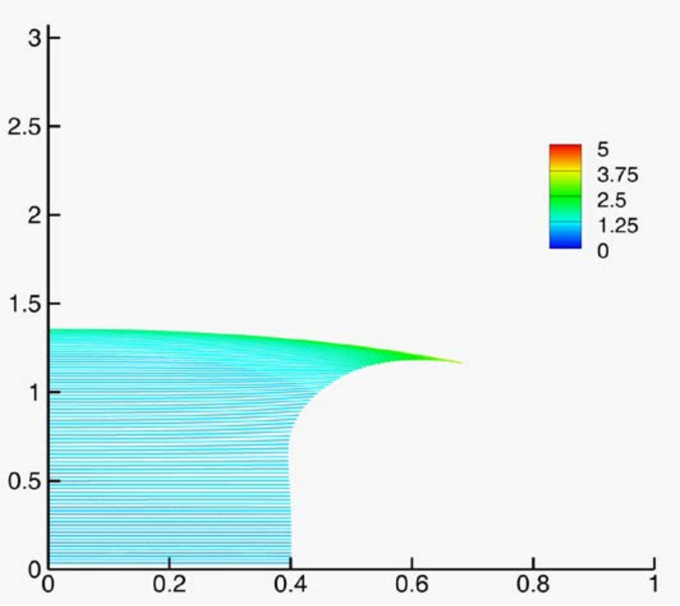
Two-phase jet, number density

Simulations based on DNS

Re = 20 000



Injection



Flow

Further work

- Two-phase jet, injection: more detailed study
- Comparison between DNS+FLA and Kaplanski+FLA
- Evolution of droplet number density in confined vortex rings