

# Integrated 1D/2D/3D Simulation of Fuel Injection and Nozzle Cavitation

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## ABSTRACT

To promote advanced combustion strategies complying with stringent emission regulations of CI engines, computational models have to accurately predict the injector inner flow and cavitation development in the nozzle. This paper describes a coupled 1D/2D/3D modeling technique for the simulation of fuel flow and nozzle cavitation in diesel injection systems.

The new technique comprises 1D fuel flow, 2D multi-body dynamics and 3D modeling of nozzle inner flow using a multi-fluid method. The 1D/2D model of the common rail injector is created with AVL software Boost-Hydsim. The computational mesh including the nozzle sac with spray holes is generated with AVL meshing tool Fame. 3D multi-phase calculations are performed with AVL software FIRE. The co-simulation procedure is controlled by Boost-Hydsim. Initially Hydsim performs a standalone 1D simulation until the needle lift reaches a prescribed tolerance (typically 2 to 5  $\mu\text{m}$ ). From this time instant the 1D/2D/3D co-simulation with the FIRE multiphase solver is started. During the co-simulation process Boost-Hydsim transmits to FIRE the displacement vector of the needle tip and fuel pressure and temperature at the nozzle interface. Based on this data, FIRE moves the computational mesh, adjusts boundary conditions, computes the time step and sends back to Boost-Hydsim the hydraulic force vector acting on the needle tip, sac pressure and mass flow rate through the needle seat and nozzle holes.

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## INTRODUCTION

The basic 1D/3D nozzle flow simulation technique is already described in the previous works of the authors [1]. However, it was limited to 1D (longitudinal) needle motion both from 1D injector modeling in Boost-Hydsim and 3D nozzle flow calculation in FIRE. Moreover, only simple segment meshes with a single hole were considered. Now the co-simulation technique is extended in such a way that 2D motion of needle with 3 degrees-of-freedom can be simulated in Hydsim and corresponding mesh movement represented in FIRE. Using it the 1D and 2D (longitudinal and transverse) motion of the needle can be coupled with the 3D nozzle flow and cavitation model. In this way the new technique allows modeling of a non-uniform pressure distribution across the needle seat and nozzle holes.

Most of the cavitation models in fuel injection are based on the Eulerian or Lagrangian formulation or their combination [2]. Numerical and experimental investigation of cavitation in diesel nozzles has been carried out by Alajbegovic et al. [3], Arcoumanis et al. [4], Chen and Heister [5], Schmidt and Corradini [6], Sou and Kinugasa [7], Falcucci et al. [8] and other authors. A comprehensive survey of the cavitation models for diesel injection nozzles is provided by Giannadakis et al. [9]. Cavitating flow simulation in FIRE standalone using the standard multi-fluid method has been performed by Wang and Greif [10]. One-dimensional modeling of the injector needle and its effect on the nozzle cavitation has been studied by Čaika and Sampl [1] and Payri et al. [11].

## THEORETICAL BASIS

### Multi-Fluid Method in Nozzle Flow

Within the theory of the multi-phase flow, each phase is considered a continuum media and the conservation laws apply. An ensemble averaging is used to remove the microscopic interfaces. This results in macroscopic conservation equations analogous to their single-phase counterparts. The difference from single phase is the new variable (volume fraction) and new interfacial exchange terms. The averaged continuity and momentum equations can be derived from the work of Drew and Passman [12]:

$$\begin{aligned} \frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot \alpha_k \rho_k \mathbf{v}_k &= \Gamma_k, \\ \frac{\partial \alpha_k \rho_k \mathbf{v}_k}{\partial t} + \nabla \cdot \alpha_k \rho_k \mathbf{v}_k \mathbf{v}_k &= \\ -\alpha_k \nabla p + \nabla \cdot \alpha_k \boldsymbol{\tau}_k + \alpha_k \rho_k \mathbf{g} + \mathbf{M}_k + \mathbf{v}_{\text{int}} \Gamma_k, \end{aligned} \quad (1)$$

where  $\alpha$ ,  $\rho$ ,  $\mathbf{v}$  and  $p$  are the averaged volume fraction, density, velocity and pressure, respectively, the subscript  $k$  denotes a phase indicator,  $\mathbf{v}_{\text{int}}$  is the interfacial velocity,  $\Gamma_k$  is the phase change rate and  $\mathbf{M}_k$  is the interfacial momentum transfer term. Essential term in the cavitation modeling is the vaporization rate, or the interfacial mass exchange  $\Gamma_k$ . In our cavitation model it is governed by the Rayleigh equation for the single bubble dynamics:

$$r\ddot{r} + \frac{3}{2}\dot{r}^2 = \frac{\Delta p}{\rho_l}, \quad (2)$$

where  $r$  is the bubble radius and  $\Delta p$  is the effective pressure difference. The mass change rate of a single bubble is:

$$\Gamma = 4\pi r^2 \rho_b \dot{r}. \quad (3)$$

For a population of bubbles with a distribution function  $f$ , defined as the number of bubbles within the radius span of  $(r, r+dr)$ , the total mass transfer rate is given by:

$$\Gamma_v = \int_0^\infty f(r) 4\pi r^2 \rho_b \dot{r} dr. \quad (4)$$

More details on the multi-phase flow application and bubble cavitation in injection nozzles can be found in [13].

### Modeling of Injector Flow and Motion of Mechanical Parts

Model of the injector flow (except nozzle) in Boost-Hydsim is based on the one-dimensional theory of weakly-compressible fluid mechanics [14]. Pressure wave propagation in lines is calculated using variable fluid density and velocity of sound. Two-dimensional needle motion with

3 degrees-of-freedom (translation along  $x$ ,  $y$  and  $z$  axes) and one-dimensional motion of other mechanical components (control valve body, pistons of hydraulic amplifier) is calculated by the classical theory of multi-body dynamics. Axial needle deformation due to varying pressure is considered by linear elasticity. For the leakage modeling in the clearance of the needle guide laminar flow theory is applied. Electric charge, mechanical strain and deformation of the piezoelectric stack actuator are obtained from the electro-mechanical lumped-parameter model:

$$\begin{aligned} q &= n \cdot x_n + C_n \cdot V_t, \\ V_t &= V_{\text{in}} - V_{rc}, \\ V_{rc} &= mrc(q), \\ F_t &= n \cdot V_t, \\ m_n \cdot \ddot{x}_n + b_n \cdot \dot{x}_n + k_n \cdot x_n &= F_t + F_{\text{ext}}, \end{aligned} \quad (5)$$

where  $q$  is the charge of the piezoelectric stack,  $n$  is the electromechanical transformer ratio,  $x_n$  is the endpoint displacement of the stack,  $C_n$  is the stack electrical capacitance,  $V_{\text{in}}$  is the input voltage applied on the stack,  $V_{rc}$  is the voltage loss due to hysteresis,  $V_t$  is the back electromotive force from the mechanical domain,  $F_t$  is the transduced force from the electrical domain,  $m_n$ ,  $b_n$  and  $k_n$  are the mass, damping and stiffness of the piezoelectric stack, respectively,  $N_L$  is the number of ceramic layers,  $F_{\text{ext}}$  is the force imposed from the external load and  $mrc()$  is the function relating the voltage across the resistive capacitor element to the charge in the ceramic layer. Further details on the modeling of the piezoelectric stack can be found in [15].

## INJECTOR MODEL

Injector in question is a piezo-controlled common rail injector CRI3 from Bosch [16]. Basic features of the CRI3 injector are sharp injector rate, small pilot injection quantity ( $0.5 \text{ mm}^3$ ), reduced tolerances for low emission standards, multiple injections (up to 7 per cycle), reduced static and dynamic forces, fail-safe-principle, low noise and compact design. The injector is designed for the rail pressure up to 180 MPa (CRI3.1) and 200 MPa (CRI3.2), respectively. Schematic of the injector is shown in Figure 1. The main components of the injector are piezoelectric stack actuator, hydraulic amplifier (coupler), control valve, throttle plate and nozzle. Nozzle design is shown in Figure 2. Hydsim models of the lower and upper injector parts are shown in Figure 3 and Figure 4.

The piezoelectric stack actuator consists of a dense pile of separately contacted layers (wafers) of electrically active ceramic material. The layers are assembled mechanically in series and connected electrically in parallel. With voltage applied, electric field across the ceramic layers induces a mechanical strain, which results in the stack elongation. Detailed description of the stack actuator is given in [15].



