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Research conducted at IFPEN has led to the development of an original approach to overcome persistent challenges in the field of injection processes, based on a combination of CFD and real-fluid thermodynamics.

Recent regulations governing vehicle emissions require further progress to be made concerning IC engine efficiency. A significant source of improvement can be found in the fuel injection process taking place in the combustion chamber, where numerous complex phenomena are still not fully understood.

While numerous CFD (Computational Fluid Dynamics) software solutions incorporate sophisticated injection process modeling, taking into account phase transition to simulate the cavitation phenomenon, for example, few CFD codes are capable of accurately simulating transcritical injection conditions<sup>a</sup> - i.e., from a temperature condition for which the fuel is in a subcritical liquid state, to a supercritical gas mixture in the combustion chamber. Thus most existing models can only simulate single-phase flows, potentially in supercritical conditions, or two-phase flows in subcritical conditions.

This lack of complete model, capable of the dynamic treatment of transcritical injection conditions, was addressed by IFPEN within the framework of post-doctoral research<sup>[1]</sup> and a thesis<sup>[2]</sup> funded by the European Union as part of the ITN IPPAD project<sup>[2,3]</sup>. In order to overcome the persistent

challenges associated with transcritical flows, **an original approach was developed, consisting in combining a compressible two-phase flow model**, based on a Eulerian-Eulerian approach<sup>b</sup>, **with a real-fluid thermodynamic model, incorporating liquid-vapor equilibrium.**

The proposed method involves **combining a phase equilibrium solver with a four-equation model, to handle liquid and gas balances in mechanical and thermal equilibrium.**

**This model was validated:**

- firstly, using a series of test scenarios based on a one-dimensional (1D) configuration, in particular via the simulation of evaporation and condensation phenomena, in subcritical, transcritical and supercritical conditions,
- and, secondly, by comparing three-dimensional (3D) results obtained with data in the literature.

**This new model has proved to be extremely accurate for the 3D simulation of cavitation phenomena in real-size injector nozzles.** The importance of taking into account the gases dissolved in liquid to describe bubble nucleation<sup>[2]</sup> has thus been demonstrated. Moreover, the consistency with experimental data proves that **the proposed solver is capable of managing the complex behavior of the phase transition, in subcritical, transcritical and supercritical conditions, making this new model unique.** Finally, **the capacity of the solver to handle transcritical injection at high pressures and temperatures was validated** by the successful modeling of the **Spray A injector, used as a reference by members of the Engine Combustion Network (ECN)** (see video)<sup>[3]</sup>.

### **3D transcritical injection simulation for the Spray A injector**

#### ***Operating conditions:***

- Fuel injected = n-dodecane / Injection pressure 150 MPa / Injection temperature 365 K
- Combustion chamber gas = nitrogen / Pressure 6 MPa / Temperature 900 K

a) *Every fluid has a critical point defined by its critical temperature and critical pressure ( $T_c$ ,  $P_c$ ). For a pure substance, it is said to be in a supercritical state when its pressure  $P > P_c$  or its temperature  $T > T_c$ . In the opposite case, the fluid is in a subcritical state. Transcritical conditions are said to exist when a fluid in a subcritical state is injected into a fluid in a supercritical state. Transcritical injection is common in direct injection compression ignition engines.*

b) *For two-phase flows (liquid and gas, for example), several methods can be used, including the Eulerian method and the Lagrangian method. The Eulerian-Eulerian approach refers to a problem that is solved using a Eulerian method for both the liquid and gas.*

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## Publications

[1] P. Yi, S. Yang, C. Habchi, and R. Lugo, ***A multicomponent real-fluid fully compressible four-equation model for two-phase flow with phase change***, Physics of Fluids 31, 026102 (2019) >> <https://doi.org/10.1063/1.5065781>

[2] S. Yang, [PhD thesis](#) at Paris-Saclay University (2019)

[3] S. Yang, P. Yi, C. Habchi, Int. Journal of Multiphase flow (2019) >> <https://doi.org/10.1016/j.ijmultiphaseflow.2019.103145>

An original modeling approach to help improve engine energy efficiency  
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