

A 1d Model for the Prediction of Flash Atomization in Gdi Multi-Hole Injectors: Preliminary Results

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ABSTRACT

A flash evaporation model is being developed to capture the effects of bubble nucleation and growth inside multi-hole injector nozzles to investigate the flash evaporation in fuel injector sprays in Gasoline Direct Injection (GDI). The 1D flash evaporation model is a key tool for providing the 3D Eulerian-Eulerian or Lagrangian spray simulation model with the right droplet size in order to properly predict the effect of degree of superheating on mixture formation. Super heating conditions are likely to be found under partial load conditions in GDI applications or they might be deliberately induced to enhance fuel atomization and vaporization. A quasi-1D nozzle flow model has been developed to help quantifying the effects of main physical and geometrical parameters in promoting fuel flash evaporation. This model is based on an weakly compressible homogenous two-phase mixture assumption. A non-equilibrium model is used to predict the vapour formation rate along the nozzle. A fully explicit method based on a two-step Lax-Wendroff method is used together with a TVD scheme. An atomization model has been proposed to correlate the void fraction at nozzle exit to the most probable radius of the droplet generated from flashing atomization. An accurate two phase speed of sound is adopted allowing to predict the choked flow conditions once saturation has been reached. Metastable states are not considered in this first approach. A preliminary validation has been carried out based on an experimental nozzle flow configuration at two different values of superheating degree. A preliminary assessment of the model capability in capturing the effect of fuel conditions on droplet most probable diameter is presented.

INTRODUCTION

The *flash boiling* or *flash vaporization* is a thermodynamic instability of a liquid jet that occurs under superheated conditions. As the pressure of an accelerated liquid goes below its saturation value, a metastable state is reached and then a rapid boiling of the liquid might occur. It must be underlined that cavitation is a particular form of evaporation which differs from fuel flash boiling. The difference is that flashing is thermodynamically driven while cavitation is mechanically driven. In flashing the fuel enters a nozzle (or an orifice) already in superheated conditions with respect to discharge pressure. Furthermore, the vapour bubble density is much higher in flashing than in cavitation because of the larger pressure at which evaporation occurs. The evaporation rate during flashing can be in turn affected by cavitation since the latter makes available a liquid-vapour interface which greatly promotes the vapour bubble growth. Liquid jet flashing has been investigated extensively in nuclear engineering. This process can occur also during liquid fuel injection in internal combustion reciprocating engines. In both gasoline Port Fuel Injection (PFI) and Direct Injection (GDI) engines, the liquid fuel might be injected into a gaseous ambient (port or cylinder) whose pressure is below the saturation pressure of one of the fuel blending components at the local temperature. This results in *flash boiling* of the fuel. Figure 1 shows the saturation curve for a single component equivalent gasoline fuel while Figure 2 provides a zoom of such a curve for the range of pressure (temperature) of interest in spark ignition reciprocating engines. It can be easily noted that a liquid fuel injected at a temperature of 313 K will likely undergo flashing if the ambient (port or cylinder) pressure is below its saturation pressure, i.e., 40 kPa.

The superheated condition of liquid fuel is the result of the combination of: i) the fuel temperature increase in high pressure pump GDI system; ii) the heat exchange between injector and cylinder head; iii) a low discharge pressure. It has been recognized that flash boiling may greatly affect the fuel-air mixing process because it modifies:

- A. The initial liquid droplets SMD;
- B. The evaporation rate, mainly outside the nozzle;
- C. The liquid and vapour penetration;

Figure 3 shows experimental images of the influence of superheating degree on the spray shape in GDI multihole injectors [8]. In both type of gasoline injection systems (i.e., GDI and PFI), the spray targeting is a fundamental step to achieve the best engine efficiency in terms of minimization of fuel consumption, raw gas emission, and lubricant contamination with fuel. Thus, fuel flashing investigation and modelling are mandatory for achieving an optimised spray targeting. This paper will focus on the modelling topic. In particular, the emphasis is on the development of a 1D code able to provide basic information on nozzle flow condition of a superheated fuel and to provide correct initial condition for 3D CFD spray simulations for the prediction of the mixture formation. The latter calculations need the accurate initialisation of liquid spray otherwise they provide misinterpreting results. It must be noted that a 1D model can also provide information on the effect of different parameters (fluid type, injection pressure, superheating degree) on liquid characteristics at nozzle exit.

Before start developing a 1D flashing model an extensive literature survey has been carried out to identify the physics involved and status of modelling.

REVIEW OF EXPERIMENTAL RESEARCH

The importance of the superheated liquid jet effects on the atomization process was investigated since the sixties by Brown and York [31], and Lienhard and Day [32], who have correlated fuel flashing with liquid jet breakup. Starting from the work of von Kuensberg Sarre et al. [7], the knowledge of the flash evaporation fundamental mechanisms has been drastically improved. This work changed the interpretation of the phenomenon given by Oza and Sinnamon [15]. By imposing fixed pressure boundary conditions, von Kuensberg Sarre et al. experimentally investigated the effect of the superheating degree on a water liquid jet. In their work they showed a decrease in the flow rate increasing the superheating degree and that newly droplets were formed from the unbroken liquid jet starting at nozzle exit, presumably from bubble growing inside the nozzle. As the superheating degree increased, the intact jet length and the drop size decreased. Basic experimental studies on flash boiling were performed by Yildiz et al. [21] who investigated the effect of fluid temperature, pressure and orifice dimension on liquid flashing evaporation and atomization.

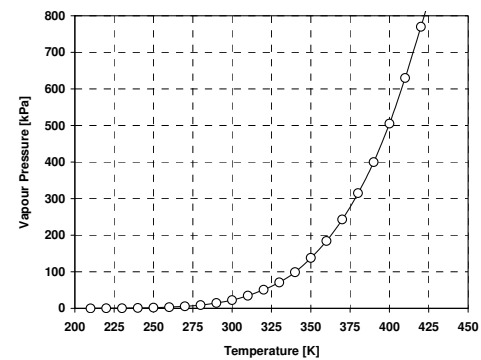


Figure 1: Gasoline (assumed as single-component) saturation pressure versus temperature (200-425 [K])

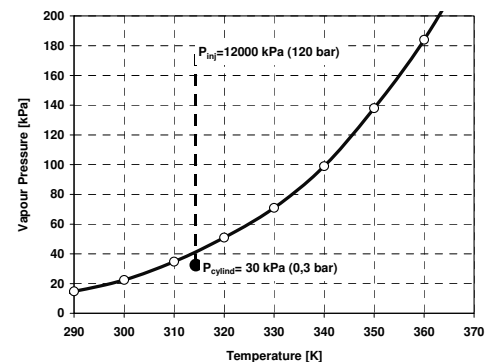


Figure 2: Gasoline (assumed as single-component) saturation pressure versus temperature (290-360 [K])

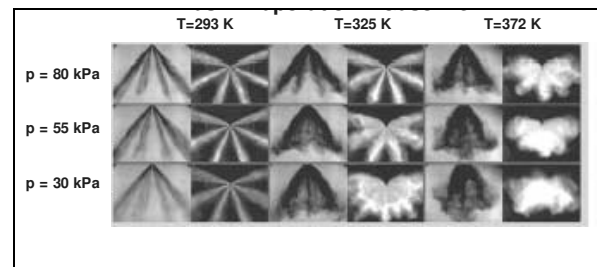


Figure 3: Effect of back-pressure and fuel temperature on flashing in GDI multi-hole spray [8]

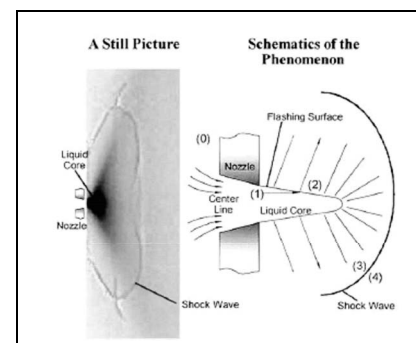


Figure 4: Fuel flashing in PFI spray – Low injection pressure [20]

Flash boiling was also observed in conventional PFI engines by Aquino et al. [16], Kim et al. [17], Kawano et al. [10] and Senda et al. [11], and in GDI engines by VanDerWege and Hochgreb [18], Leipertz et al. [14]. VanDerWege and Hochgreb [18] used a swirl atomizer in a GDI optical engine, and observed flash boiling during early injection conditions with sub-atmospheric pressure in the cylinder. Leipertz [14] studied the influence of the injector temperature on the spray distribution and on the fuel volatility of a high-pressure swirl injector of the type used in GDI engines, and, thus, a flash-boiling effect was investigated. The experiments were conducted at a chamber pressure of 50 kPa and a temperature of 323 K by varying the injector temperature at a constant rail pressure of 8 MPa. Three single-component fuels with different boiling points and multi-component fuel were chosen for the investigations. At low chamber pressure and at an injector temperature of 343 K fuel with the lowest boiling point changes the spray structure from a hollow-cone to a solid-cone distribution. By increasing the injector temperature the solid-cone structure can also be observed for fuels with higher boiling points. This transition was simultaneously detected on the camera for the liquid phase and on the camera for the vapour phase. The observed spray behaviour is caused by a flash-boiling effect, where a superheated liquid above its boiling temperature is disintegrated abruptly into a spray of small droplets. Simoes-Moreira and Sheperd [19] provided a further contribution by investigating the formation of evaporation waves in superheated dodecane. They performed a rapid decompression of saturated dodecane and considered initial temperature ranging from 180 to 300 °C. They showed that at low injection pressure evaporation waves starting from a liquid free surface appear above a given superheated degree threshold. At moderate superheated degrees, subsonic downstream states were observed while at larger superheated degrees the flow was choked corresponding to the Chapman-Jouguet condition. At the most extreme saturation degree, a 90% vapour fraction was estimated from measurements. Thus, these experiments showed that, at least at low injection pressure, a discontinuity (i.e. an evaporation wave) forms separating a pure liquid state and a two-phase liquid-vapour downstream state. More detailed conclusions have been recently achieved by Vieira and Simoes-Moreira [20], who considered the low-pressure flashing mechanism in iso-octane liquid jets. The study confirms previous results by showing the presence of a choked flow for high superheating degree. Moreover, they showed flashing takes place on the surface of a liquid core through an evaporation wave process. Downstream the evaporation discontinuity of the two-phase flow reaches a sonic condition corresponding to the maximum evaporation mass flow rate as shown in Figure 4.

According to experimental results it can be concluded that depending on fuel composition, superheating degree, cavitation intensity, hydrodynamic condition and injector shape, a liquid jet undergoing a sudden expansion quickly evaporates if the local pressure goes below the saturation pressure. As a result the mass flow rate remains choked for any

change in downstream pressure and an effervescent atomization might also occur. Depending on the combination of the above mentioned parameters, two main regimes can be identified:

1. external flashing with surface evaporation at nozzle exit
2. internal flashing with effervescent atomization at nozzle exit.

The first regime is likely occurring at low injection (i.e. below 4 MPa) pressure and/or in relatively very short nozzles or orifices. The second regime occurs at high injection pressure as those typical of GDI injection system.

Focusing the attention on GDI injection systems, the high turbulence levels in the nozzle flow perturbs strongly the vapour bubbles at their interface, thus contributing to an effervescent atomization just outside the nozzle according to experimental evidences [4,7]. It must be outlined that the effect of turbulence in atomising the liquid jet has been strongly enhanced by both the reach of a free-surface condition at liquid jet surface [25,26] and also by the presence of gaseous bubbles in the liquid core. The latter provide a free-surface interface which can be deformed by the turbulence energy at the corresponding scales. The newly atomised droplet will likely be in superheated conditions with respect to ambient pressure and contain vapour bubbles whose growth then causes the liquid droplet disintegration. Figure 5 would like to summarize the main processes governing the dynamics of a superheated liquid fuel with a focus on a cylindrical nozzle typical of GDI multi-hole injectors.

REVIEW OF 1D MODELING OF SUPERHEATED

Dealing with numerical modelling, it must be pointed out that the physics involved in the flash evaporation process is quite complex. The review of superheated fuel flow model can rely with several models and codes present over the last years: Kawano et al. [10], Senda et al. [11], Chang and Lee [22], Zeng and Lee [27], Zuo, Gomes and Rutland [23], only to cite the more important ones. In order to make a more comprehensive review as well as a comparison between the present work and the state of art of modelling, five key topics will now addressed.

1. Vapour generation

The first critical point is the choice of suitable a sub-model for evaluating the evaporation rate. This choice affects the overall structure of a 1D two-phase code. In literature, at least three different approaches can be mentioned:

- a. The *Multi-phase DEM method*. The more general, complex and accurate approach to model a liquid system which turns into a pure vapour or a liquid vapour mixture is based on DEM (discrete equations method) [24], recently proposed for internal combustion and multiphase mixtures.

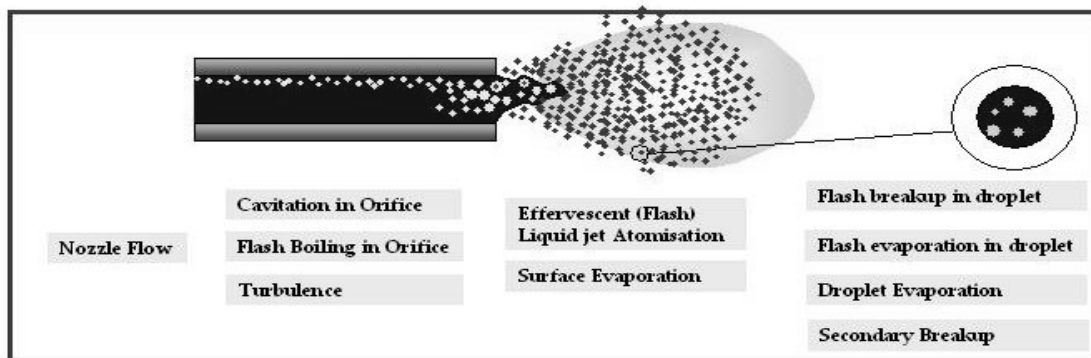


Figure 5: Schematic review of the physics involved in the flashing evaporation of a liquid issuing from nozzle

This method consists in connecting several systems of equations, each one being associated to a pure fluid. Interface problems between pure fluids are solved locally with the help of their own governing equations.

The Euler equations' solution, for each fluid resulting in interface problem (i.e., formation of evaporation waves), is obtained with conventional Riemann solvers. In order to consider sonic conditions, the phase transformation is assumed to occur at a finite rate. In particular, the evaporation wave is assumed to propagate at the maximum speed predicted by the Chapman-Jouguet condition. This method is quite complex but is the more general one and allows to deal with both total and partial evaporation fronts. Further detail can be found in [24].

b. Nucleation based models. Another approach accounts for the detailed physics of the nucleation process. The nucleation of the vapour bubble is classified into two modes: *homogeneous* and *heterogeneous*. The homogeneous nucleation occurs when the bubble appears in the liquid in absence of any bubble nuclei. The heterogeneous nucleation occurs when activated clusters of gaseous phase are present because of: crevices, incondensable gas, and fine solid particles. In such models, a defined density bubble number is assumed to be linked to the superheating degree. The effect of the different nucleation modes is thus included. The vapour bubble growth rate is then calculated according to a Rayleigh-Plesset equation [10, 11] or by using a transport equations of the mass of discrete classes of vapour bubble having the same size [22] where the interfacial heat transfer is included.

c. The Homogenous Relaxation Model (HRM). The HRM two-phase model, based on the adoption of an homogeneous mixture, is an extension of the Homogeneous Equilibrium Models (HEM). Contrary to HEM, which assumes that the vapour mass fraction adjusts instantly to its equilibrium value, in HRM an equation for evaluating the local and instantaneous rate at which the mass vapour fraction Y approaches its local equilibrium value Y_e is used [1,3, 28]. The HRM sub-model has been adopted in this work since it offers a very good compromise between accuracy and simplicity for industrial applications.

2. Cavitation modelling

It must be pointed out that in a 1D framework it is quite trivial to provide a model capable to deal with both cavitation and fuel flashing. One reason is that cavitation can be modelled assuming thermodynamic equilibrium between phases. This assumption can not be taken in the case of flash evaporation. Another reason is that cavitation is at least a 2D phenomenon, as shown in Figure 6-A, induced by flow separation, which can be retained in a 1D model with great uncertainty. Internal nozzle flashing can be assumed as a 1D phenomenon as shown in Figure 6-B where a still picture of a complete evaporation front is taken for three different superheating degree in [19]. No 1D model, able to deals with both cavitation and flashing evaporation, is available.

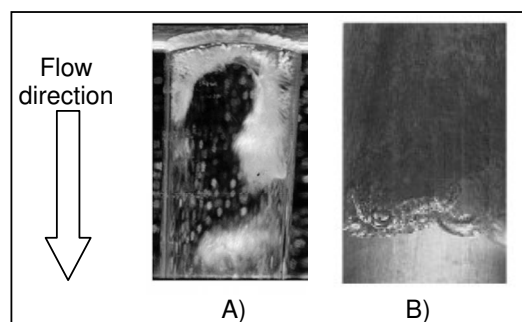


Figure 6: A) Cavitation – B) Complete evaporation front in fuel flashing [19]

3. Library of thermo-physical properties

In the view of the model application to fuel injectors, it must be pointed out that the thermofluid properties of the fluid, single-component or, more likely, multi-component, must be provided. Thermophysical properties of mono-component fuel are available, but it rarely happens that the precise composition of the real blended fuel is available. Moreover, an accurate evaluation should consider properties in the metastable state. An example of multi-component model for fuel flashing can be found in [10].

4. Equation of State

The Equation Of State (EOS) used in two-phase flow links the pressure variation to the density variation via the speed of sound through a proper thermodynamic path. The latter is non trivial to be defined in a two phase flow where the void fraction is not fixed but continuously varying in space and time. It must be underlined that many authors use the relation proposed by Wallis [5] which theoretically holds only for a mixture with a given vapour mass fraction. The latter is not the case of a vaporizing liquid fluid, as also demonstrated in [4] and in [24]. In the present work, a derivation of the exact speed of sound for a vaporizing two-phase mixture is proposed.

5. Atomization process

Focusing on fuel flashing under the operating condition of high pressure GDI injectors, it is expected that an effervescent atomization will occur outside the nozzle, together with a fast surface evaporation. Thus, in order to fulfil the task of the present model, an atomization model must be introduced. The literature review shows that there are three main models available and proposed for engine injector flows. The model proposed by Senda et al. [11] and Kawano et al. [10] was developed to describe PFI pintle injector sprays assuming that the limit of vapour bubble growth inside the liquid film sheet was provided by a critical void fraction α . Above a valued threshold of void fraction (i.e., $\alpha > 0.55$ in [10,11]), the fuel film was assumed to brake into small droplets. The idea of this atomization model was to relate the bubble diameter to the void fraction and the superheating degree. The weak point of the model is that the effect of the turbulence is not accounted for. If this assumption correctly holds for PFI applications which operate at low injection pressure, as those considered by Senda et al. and by Kawano et al. [10], it can not be considered accurate enough for high pressure injector nozzle flow where the turbulence has been demonstrated to play a fundamental role in atomization [25,26]. Zeng and Lee [27] developed an interesting atomization model based on the classical blob injection concept. The atomization was represented as the result of two competing mechanisms: aerodynamic force and bubble growth. The model was successfully applied to predict the atomization of a hollow-cone spray from a pintle injector under flash boiling conditions. Also in this model the turbulence effect of liquid jet atomization is not considered. Zuo, Gomes and Rutland [23] presented a comprehensive superheat fuel spray and vaporization model. In the model, it was assumed that, under superheated conditions, a hollow cone spray sheet still forms from a pressure-swirl atomizer. The sheet flash boiling was considered to be constrained by the transient heat conduction process inside the sheet with an effective thermal conductivity. Hydrodynamic instability, cavitation and bubble growth inside the sheet eventually breakup the sheet to form droplets. Models of the subsequent droplet vaporization account for heat transfer under both flash boiling and sub-boiling conditions.

Starting from previous point, with focus on high-pressure GDI engines, the present work would like to pursue a first attempt to include also the effect of turbulence in the atomization of rounded jet as those issuing from multi-hole injectors.

CONTRIBUTION OF THE WORK

A compressible homogeneous mixture 1D model has been developed at University of Bologna in the code 4-Flash in order to predict the flash evaporation of a superheated liquid fluid undergoing an expansion through a cylindrical nozzle. The code assumes no-slip between phases and an adiabatic flow condition through the injector nozzle. An accurate derivation of the speed of sound as a function of the evaporation rate is proposed. A homogeneous relaxation model (HRM) has been used to predict the evaporation rate. An atomization sub-model able to capture the effect of both superheating and turbulence has been introduced. At the present state of the code a sub-model for fuel flashing surface evaporation is not included as well as a library for considering the transition though a metastable state. The main difference with respect previous work in ICE field are related to the overall modelling framework. The latter allows to consider the whole dynamics of the fuel from the nozzle to gas ambient relating the nozzle flow characteristics to atomization. The model, thus, can provide initial conditions to secondary breakup models used in 3D CFD calculation of mixture formation. The 1D model can provide also the mass fraction vaporized along the nozzle. It must be pointed out that because of the high liquid-to-vapour densities ratio (of the order of 10^3), the vapour mass fraction is usually small compared to the volume vapour fraction. The latter greatly contributes to the mechanism of effervescent atomization, as will be discussed later.

1-D TWO PHASE MODEL FRAMEWORK

GOVERNING EQUATIONS

The 4-Flash code governing equations, written in conservative form for a constant-area cross section, are for a 1D compressible homogeneous adiabatic two-phase flow:

1. Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0$$

The mixture density time derivative is more conveniently replaced by the pressure time-derivative:

$$\frac{1}{a^2} \frac{\partial p}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0 \quad (1)$$

2. Momentum transport equation

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial p}{\partial x} = M$$

assuming no-slip between the two phases.