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Multidimensional modelling of gaseous injection: Analysis of an impinging jet

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ABSTRACT

As a consequence of the increasing importance of environmental issues, natural gas has emerged as one of the most promising energy sources for internal combustion engines, in the short medium term, because its usage leads to cleaner combustion, lower CO_2 emissions, and energy source diversification. However, considering that automotive DI gas engines are rather new, only limited experience exists on the optimum configuration of the injection system and the related strategy. To facilitate the development of these applications, computer models are being developed.

In a previous paper, a phenomenological-3-D integrated approach to simulate gas injection has been presented and validated. This model has been implemented in a modified version of the KIVA 3V code. In this paper the model is used to perform the analysis of an impinging gas jet. The interaction between impinging jet and airflow plays a fundamental role in mixture formation and thus on the evolution of combustion process and pollutant formation. This is particularly true if considering stratified charge engine with late cycle injection. In this paper three wall jet treatments are considered: two different laws of the wall and a no-slip simulation in order to evaluate their feasibility in capturing the jet evolution. Numerical results are validated by comparison against experimental data found in literature.

1. Introduction

In this paper the computation of wall impinging turbulent jet is carried out in order to study its structure in particular in terms of jet tip penetration, jet diffusion and overall cloud shape. The first objective of this work is to evaluate the ability of some different approaches (two different law-of-the wall and no-slip) to correctly describe physical phenomena involved in fuel gas impingement process.

Wall impinging jets characterize many engineering applications such as cooling systems and direct injection internal combustion engines. The study of fuel diffusion of an impinging jet is of great interest in particular in this last application, where wall jet interaction greatly influences air fuel mixing inside the combustion chamber both in the case of liquid or gaseous fuels. In fact, this study is motivated by the aim of improving predictive capabilities of numerical models for direct injection gas fuelled internal combustion engines.

The impingement process is very important in particular in small direct injection engines as the fuel is likely to impinge on piston head. The impingement of the gas jet is expected to influence fuel distribution over the whole combustion chamber and also to affect the flow field. Accordingly it has a great influence on flame development and propagation. As a consequence a good understanding of injection and impingement process leads to a deeper understanding of the overall engine operation and pollutant formation.

Capturing the evolution of a three dimensional unsteady and turbulent gas jet is itself one of the most challenging computational fluid dynamics problem. These difficulties are even emphasized in internal combustion engine applications, where small injector dimensions (compared with engine dimension) cause unaffordable computational costs.

Several prior experimental, analytical and computational studies about the structure and the time-dependent evolution of round and plane impinging turbulent jets are present in literature. Experimental measurements made by Fujimoto et al. (1997) and Tomita et al. (1995) show motion and air-entrainment characteristics of round impinging gas jets, both in subsonic and sonic underexpanded cases. In these experiments, the radial penetration following impingement was also found to be approximately proportional to the half power of time, but smaller than that of the free jet. In their theoretical–analytical work (Phares et al., 2000) focused the attention on the wall shear stress produced by the jet-wall interaction, demonstrating that in the near-impact region a laminar boundary layer analysis could predict wall shear stress values much better than a fully developed turbulent boundary layer approach. These considerations have been confirmed by the numerical analysis reported by Bouainouche et al. (1997) where,

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Nomenclature

Subscripts

0	nozzle
0-D	phenomenological model
3-D	three dimensional model
a	environment
e	equivalent
inj	injected
m	jet axis
s	stagnation
$\|\|$	wall parallel component

Symbols and abbreviations

a	free jet model constant
A	area (m^2)
B	Launder and Spalding model constant
b	free jet model constant
C	free jet model constant
C_μ	Launder and Spalding model constant
d	diameter
h	free jet model constant
k	isentropic exponent
k_p	wall cell turbulent kinetic energy ($m^2\ s^{-2}$)
L	wall-injector distance (cm)
$\dot{m}$	mass flow ($kg\ s^{-1}$)
p	pressure (Pa)
r	radius (m)
R	jet radius (m)
Re	Reynolds number
Re_y	local Reynolds number referred to wall distance
$r_{1/2}$	half velocity radius (m)
T	temperature (K)
U	velocity ($m\ s^{-1}$)
u_τ	friction velocity ($m\ s^{-1}$)
U^+	nondimensional wall velocity
x	concentration
t	time (s)
y^+	nondimensional wall distance
y	wall distance (m)
C_d	discharge coefficient
z	jet penetration axis (m)
l_{core}	core region length (m)
z_0	apparent jet origin position (m)
α	$ln(2)$
β	Kiva 3V wall function model constant
δ	characteristic jet dimension (m)
μ	dynamic viscosity ($N\ s\ m^{-2}$)
τ_w	momentum flux at the wall (Pa)
ξ	nondimensional velocity profile
ρ	density ($kg\ m^{-3}$)

some numerical computations are performed on a plane turbulent jet impinging on a flat wall, with the aim to investigate the trend of the wall shear stress in both the near-impact and in the far-impact regions. The analysis was performed employing turbulent wall functions, based on Launder and Spalding assumptions (Launder and Spalding, 1974), showing that this surface boundary condition underpredicts the mean shear stress in the impingement region. A numerical axi-symmetric approach was also proposed by Abraham and Song (2003) to study the structure and the penetration characteristics of round turbulent impinging jets. Turbulent wall functions, based on Launder and Spalding proposal, were employed to model momentum at the walls, finding significant errors in predicting jet tip radial penetration, demonstrating not to be the best choice to capture the main properties of the physical phenomena.

In this paper, the free jet is simulated through an original methodology, developed by Andreassi et al. (2009a,b) and based on the integration of a phenomenological model with the three dimensional simulation. This model allows holding down grid requirements while keeping a good description of injection phenomena. For what concerns wall interaction two different wall functions have been tested to model momentum flux at the wall. The resolution of the boundary layer, with a no-slip condition has also been considered.

2. Computational tools

Simulations have been performed with a modified version of KIVA 3V code (Andreassi et al., 1999; Pontoppidan et al., 1999; Bella et al., 2002), which solves the fluid dynamics equations with a finite volume approach over a structured multi-block grid. Temporal and spatial differencing is performed with the Arbitrary Lagrangian Eulerian (ALE) technique which is a semi-implicit quasi second order upwind approach. This code is still one of the most effective on investigating in-cylinder processes, as it is particularly suitable for moving grids (i.e. piston and valves).

2.1. Free-jet model

Many experimental evidences show that a transient gas jet can be described as composed of two different regions (Ouelette and Hill, 1992; Fujimoto et al., 1997):

1. a semi spherical shaped vorticose region, on the tip of the jet;
2. a quasi steady conical region feeding the vortex structure in terms of mass, momentum and energy.

As the aim of the zero-dimensional model is capturing the evolution of the first part of the jet, the interest is focused on the description of the conical and quasi steady region. The evolution of the vortex structure and thus the estimation of the jet tip penetration is left to the 3-D detailed simulation.

Making the hypothesis that the jet evolves into a constant pressure environment and considering that outside the injector there is no length scale imposed, it is possible to state that velocity and concentration profiles are self-similar (Ouelette and Hill, 1992). It means that nondimensional fields do not depend on the distance form the orifice. This condition, using nomenclature in Fig. 1, can be expressed as:

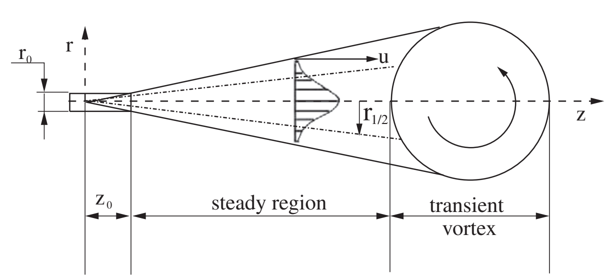

Fig. 1. Scheme of the free jet.