Article citation info:
Ali MQ, Mohamad B. A review of the design and control using computational fluid dynamics of gasoline direct injection engines. Diagnostyka. 2022;23(3):2022306. https://doi.org/10.29354/diag/153373.

DIAGNOSTYKA, 2022, Vol. 23, No. 3

e-ISSN 2449-5220
DOI: 10.29354/diag/153373

A REVIEW OF THE DESIGN AND CONTROL USING COMPUTATIONAL FLUID DYNAMICS OF GASOLINE DIRECT INJECTION ENGINES

Mohammed Qasim ALI [1], Barhm MOHAMAD [2, *]

[1] Vocational Education Department, Ministry of Education, Babel, Iraq
[2] Department of Petroleum Technology, Koya Technical Institute, Erbil Polytechnic University, 44001 Erbil, Iraq
[*] Corresponding author, e-mail: mmm18926@gmail.com

Abstract

This paper explores the role of the computational fluid dynamics (CFD) modeling technique in the design, regulation, and production of the gasoline direct injection (GDI) engine combustion system through literature reviews. It begins with a brief analysis of injector technologies and the effect of spray characteristics on the optimization of the combustion system. The key challenges of optimizing a homogeneous-charge GDI combustion system are the enhancement of volumetric performance and homogeneity of fuel-air mixing with reduced wetting of surface fuel and the improvement of power output. Most of the calculations focused on dynamic mesh strategy to manage moving geometry varied from case to case. The techniques of the methods varied. During the opening event of a GDI gasoline-injector for automotive applications, the findings of the literature indicate the primary fuel atomization.

Keywords: computational fluid dynamics; engine emission; optimization; gasoline direct injection; combustion modelling; injector spray pattern

1. INTRODUCTION

As a relapse in the automotive industry, the worldwide issue about the environmental effects on systems of energy conversion is the enforce the government regulations stringent related to pollutant emissions and vehicle fuel-economy requirements. Currently, monitoring of the mixture formation and combustion processes are taking place inside the engine combustion chamber, a dynamic activity influenced by several variables, remains the preferred route for reducing both engine exhaust harm emissions and fuel consumption ratio. The multi-hole injector, slit injector, air-assisted injector, outward opening injector, and swirl injector are five main forms of direct injection (DI) injectors. Spark-ignition (SI) engine direct injection technology confirm the advantages in the matter of volumetric efficiency and its effect on thermal efficiency, enhanced engine response during load variations, during cold start and transient modes, decreased knock propensity and lower pollutant emissions. The ability to work in the stratified-charge mode also decreases partial load pumping losses, because the performance of the engine power can be regulated only by the variation of the mass of the injected fuel.

The next sections demonstrate the computer models developed by the authors to analyse gas exchange and fuel-air mixing in petrol engine, direct-injection engines, within commercial codes such as AVL Boost and Fire and GT Power etc. In particular, a comprehensive overview is given of algorithms, spray and liquid film models of moving mesh (topological changing grids in term of dynamic mesh strategy). Most of the simulations were carried out with typical models include the standard k-ε model for turbulence using the Reynolds-Averaged Navier-Stokes (RANS) method. In Lucchini et al. [1] gasoline was considered as a single-component fuel, with both liquid and vapor characteristics supposed to be the same as pure iso-octane. The gas step was handled like a perfect gas mixture. In Kuwahara et al. [2] the optical engine, used two-stage mixing it is possible to view the mixing and combustion phase in the cylindrical chamber through the quartz windows on the side walls of a pent-roof combustion chamber to eliminate the knock. Bozza et al. [3] were mapping the variable valve timing (VVT) engine in one dimensional (1D) simulation model, a different efficiency was considered at each camshaft position, as a consequence of the effect on the air flow exerted by the real position of the intake / exhaust camshaft specifics in fig. 1. The theoretical result reported is the correlation of engine efficiency parameters as a function of engine speed.

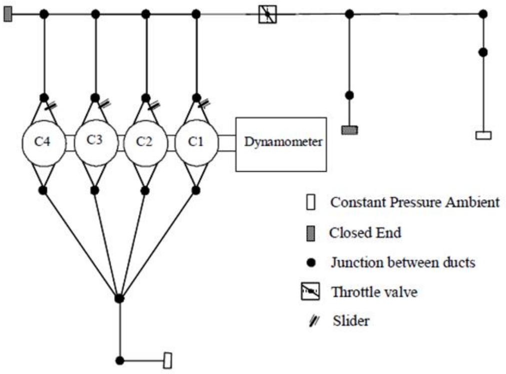

Fig. 1. 1D scheme of the VVT type engine [3]

In Montenegro et al. [4] CFD code was used to improve the performance of a Moto3 engine, the technique was based on the integration of a 1D code (Gasdyn) with a CFD code (OpenFOAM ®) to optimize the intake and exhaust systems. The wave motion was predicted using schematic in Fig. 2 The following indicates the one-dimensional used to match the measured data of the baseline configuration at the first step of the 1D model simulation process. In the second phase, the explanation of the fitting was justified by a deeper analysis conducted with the 3D model.

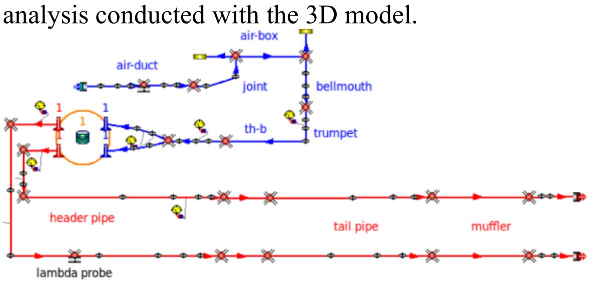

Fig. 2. 1D schematic of the engine GP30 under analysis by [4]

2. DESIGN METHODOLOGY

The injection mode has a direct effect on the degree of atomization and fuel penetration and diffusion. Gasoline Direct Injection (GDI) has been a useful solution for the automotive industry as it allows high air / fuel ratio flexibility, resulting in low fuel consumption and light load emissions (lean or stratified) and high-power output during instant acceleration and heavy loads (power mode). These various conditions relate not only to the quantity of fuel injected into the combustion chamber, but also to the injector's own geometry, as shown in Fig. 3.

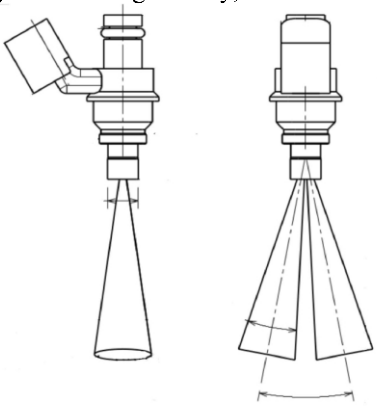

Fig. 3. Views of the fuel injector mounted on the engine (front and lateral). The spray cone's internal and external angles are differentiated by [4]

Different techniques were introduced to satisfy and retrofit a market motorcycle engine in most literature related to engine components designs. The characteristics of combustion include a high-swirl charge, fuel injection during the opening of the intake valve, and fuel type. By designing a new intake port with a controllable plate that can be switched to the stratified mode and homogeneous mode of GDI engines, the high-swirl charge is generated, as shown in fig. 4. Using CFD software, this design is achieved and verified. The results of the simulation suggest that the elevated swirl charge motion can be regenerated by the correct angle of fuel injection in stratified mode.

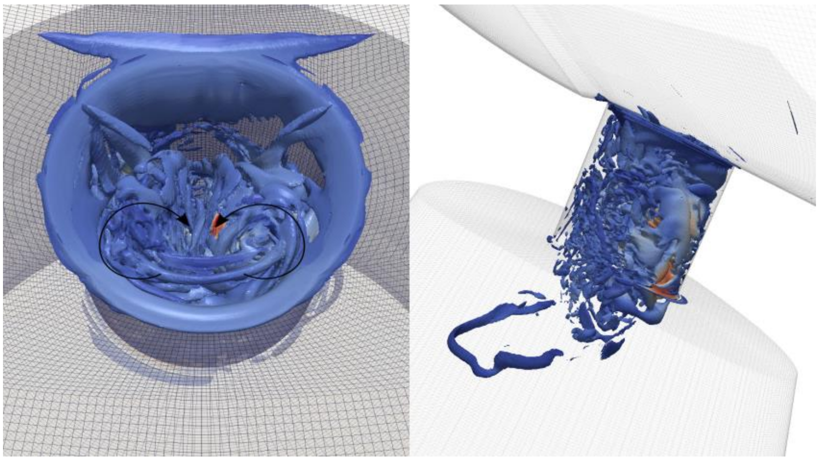

Fig. 4. Structure of the vortical inner nozzle on the left, the upper view, and on the right, the side view from at time 9.5×10^{-6} s, [5]

For the time-transient phenomena and compressibility, the hard acceleration of the liquid phase within the injector nozzle is an important factor, the pressure can drop below the saturation value causing cavitation to begin, due to the presence of bubbles, Giussani et al. [5] will greatly alter the internal flow field. Internal Combustion Engine (ICE) thermodynamics and modeling of gas flows in cylinders has been a well-developed practice that has been thoroughly examined since the 1960s. One-dimensional models were only the prediction method of the steady-state and transient behavior of the engine air path system and were normally performed for their ability to diagnose the influence pressure wave propagation, that could impact on the engine volumetric efficiency (VE) by using detailed, frequently detected to as gas dynamic models or wave action models (WAM). By applying the mass, momentum and energy conservation equations for one-dimensional in condition of unsteady compressible flow, such models characterize the engine gas exchange mechanism from its physical foundations. For in-cylinder processes, the nature components of the intake and exhaust system are usually combined with zero-dimensional thermodynamic models, either based on single-zone or multi-zone combustion models. Today, WAMs are mainly used for production and research purposes by industry and academia alike. In the literature for engine system simulation for design and control applications, several models have been suggested, and well-running commercial tools are also in stock. Majority of the above models use methods of numerical solution based on various domain discretization rearrangements and referred to basic techniques of time-depended and space integration. In particular, explicit finite difference methods (FDMs) and finite-volume methods (FVMs) have traditionally been used for the solution of unsteady flow equations for mass, momentum and energy conservation. In most methods, second-order precision for time and space integration can also be implemented by FVMs to work on both collocated and staggered grid arrangements. Examples of one-dimensional FDMs and FVMs can be contained in Stockar et al. [6]. In certain matter, the applying of the FVM, based on an explicit time-depended staggered leapfrog system running on a staggered grid, was recently proposed Montenegro et al. [7]. The approach is non-monotonic as it is second-order precise, so it is combined with a novel flux limiting approach in term of the inclusion of an artificial viscous dissipation in the momentum equation solution. More details in fig. 5.

The state of the art in today's modeling for efficiency and fuel economy simulation of IC engine systems in term of simplified formulation of compressible fluids' conservation law equations, where a one-dimensional approximation is generally

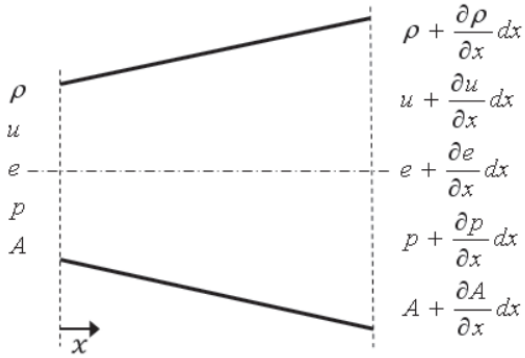

Fig. 5. One-dimensional scheme for the system [6]

approved. In an essential segment of a one-dimensional duct, consider a non-reacting unsteady flow, as shown in fig. 5. The conservation laws can be written as follows, under the assumptions of negligible friction and heat transfer and for non-reacting flows Winterbone and Pearson [8]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\rho u \, dA}{A \, dx} = 0$$

$$\frac{\partial \rho u}{\partial t} + \frac{\partial(P + \rho u^2)}{\partial x} + \frac{\rho u^2 \, dA}{A \, dx} + \rho G = 0$$

$$\frac{\partial \rho e_0}{\partial t} + \frac{\partial(\rho u h_0)}{\partial x} + \frac{\rho u h_0 \, dA}{A \, dx} - \rho \dot{q} = 0 \qquad (1)$$

This equation known as the nonlinear Euler equations, or as stated in literature, the strong or differential form.

The variables include ρ which indicates the density, u is the flow velocity vector, G represents body accelerations, P indicates the pressure, X is direction component and A refers to area. The intake port was changed by Yuh-Yih et al. [9] and it was called a switching technique that can turn the Semi Direct Injection (SDI) engine from stratified to homogeneous mode with the exception of idle or lower load and motor speed operation. In order to optimize fuel consumption and engine emissions while preserving engine-out NOx within a 1-1.5 g/kW-hr window, Pei Y et al. [10] explored and enhanced the gasoline compression ignition (GCI) combustion recipe (piston bowl geometry, injector spray pattern, in-cylinder swirl motion, and thermal boundary conditions).

In their analysis, the experimental design (DoE) approach techniques were created and carried out with the first step concentrating on optimizing the piston bowl form and the second phase addressing the refinement of the combustion recipe and the second (DoE) approach was applied to optimize fuel injection strategies. For the optimum performing piston bowl designs from the first (DoE) method, injector spray patterns, and in-cylinder swirl motion. From their findings, three piston designs showed that promising efficiency improvements were expected at B50 with up to 6.3 percent (condition for model design) and 5 percent for other designs. Costa [11] used 3D coupling computational fluid dynamics and a simplex algorithm to find the optimum synchronization of both injection and spark timing within the working cycle, then identified a complex system of single cylinder, four-valve, four-stroke gasoline direct injection. From Fig. 6 for injector, the tuning procedure scheme for the numerical spray sub-model constants was defined. The ModeFrontier software was used, as demonstrated in the tuning methodology. At each injection pressure (within a Microsoft Excel sheet), the log-normal distribution of the primary droplet size at the injector exit section is constructed from the value of (r) chosen in the DOE space and from the measured predicted value, according to this Eq. (2):

$$D_{th} = Cd\left(\frac{2\pi\tau_f}{\rho_g u^2 rel}\right)\lambda * \qquad (2)$$

Where: τf the gasoline surface tension, u_{rel} the relative velocity between the fuel and the gas, ρg the surrounding gas density, Cd a constant of the order of the unity, and the parameter λ* Derived from the study of hydrodynamic stability and showing the dimensionless wavelength of the more unstable perturbation at the injector exit portion of the liquid-gas interface. The delivery profile is moved from the DOE space to the Fire Code spray model, which also receives the value of C1 as shown in figure 6.

A summary of the better output that is applicable to the case of double injection can be noted in Fig. 7. In the engine cylinder, where the burnt fuel mass fraction is represented, it passes through the maximum value of this vector at four different crank angles on a plane. Yi [12] showed how CFD modeling has been used in recent years to optimize the intake port design for enhanced flow capacity while providing adequate in-cylinder flow motion, and to improve the fuel injection and cam strategy for enhanced homogeneity of fuel-air mixture also to optimize the design of the combustion chamber to enhance high-speed and high-load mixing of fuel-air by alleviating the impact of intake chamber design to improve the uniformity between the intake flow movement and the spray configuration for stratified-charge activity, CFD modeling has been used to generate stable charge stratification over a large operation window with the least amount of engine emissions.

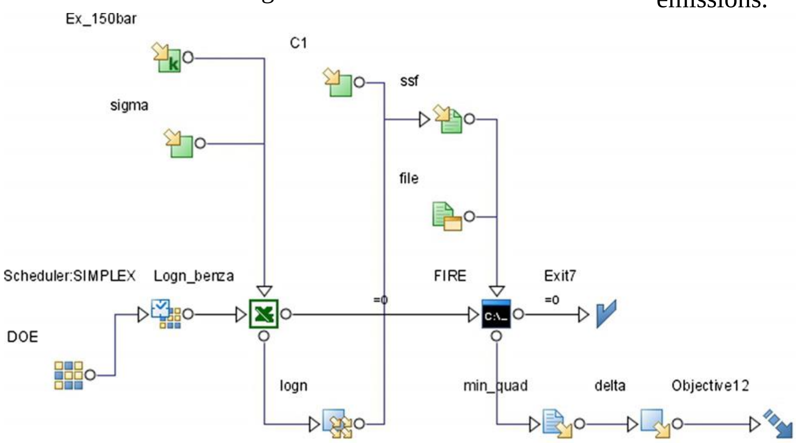

Fig. 6. The tuning procedure scheme for the constants of the numerical spray sub-model [11]

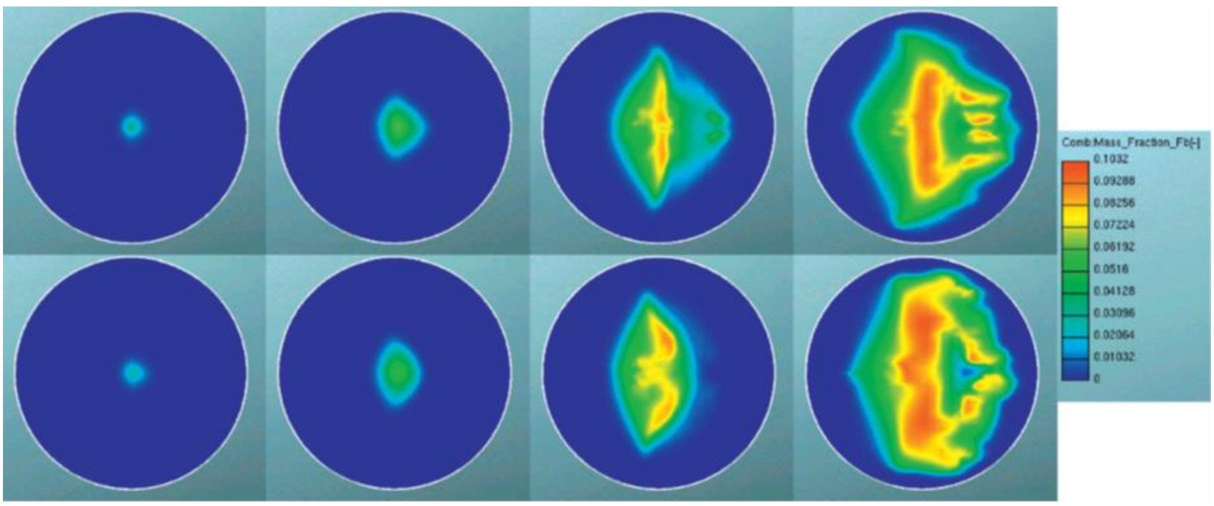

Fig. 7. In the optimum single injection case (top) and double injection case (bottom) at four Crank angles on a plane going through its maximum value, burnt fuel mass fraction [12]

In order to analyze the atomization of a hollow cone fuel spray produced by a high-pressure swirl injector of the simultaneous-fire port-fuel injection (PFI) engines, Rotondi and Bella [13] used numerical technique and validated by experiment to evaluate the atomization of a hollow cone fuel spray. In both stoichiometric and stratified activity modes, the mixture formation process was studied. The equivalence ratio of the three-dimensional distribution λ in a plane has been determined in several zones. Recent combustion advances made in petrol engines, particularly in direct-injection spark-ignition (DISI), have been revealed by Alkidas [14] for optimal efficiency, including reduction of engine emissions and fuel consumption in direct-injection spark-ignition (DISI) when operating under stratified conditions.

The combustion system for direct-injection spark ignition engines was categorized into three broad categories, see fig. 8, the mechanism of mixture formation covers: air-guided, wall-guided and spray-guided. The fuel spray is directed towards the spark plug through a well-defined interaction of the spray with the piston combustion cavity or in-cylinder air motion in the air-guided and wall-guided combustion systems, and the injector is mounted a long distance from the spark plug. The close arrangement of the spark plug and the injector gives a tight coupling between ignition and fuel preparation in the spray-guided combustion system.

In Drake and Haworth [16] optical diagnostics and CFD were reported in five gasoline-engine combustion systems: homogeneous spark-ignition direct-injection (DI), homogeneous-charge compression-ignition (HCCI), stratified spray-guided spark-ignition direct-injection (SG-SIDI) stratified wall-guided spark-ignition direct-injection (WG-SIDI) and homogeneous spark-ignition port-fuel-injection (PFI). The focuses were on the SG-SIDI, WG-SIDI and HCCI engines, the methods were successfully demonstrated engine improvement.

Hentschel [17] showed spray formation by double-pulse particle image velocimetry (PIV) in direct injection engine two-dimensional flow measurements. Other methods have also been used to calculate the fuel / air ratio within and outside of the spray, such as one-dimensional spontaneous Raman spectroscopy (SRS). Furthermore, laser-induced fluorescence (LIF) for fuel vapor analysis and spray uses an excimer laser. These methods have been implemented under homogeneous charge conditions in direct injection engines. The new optimization technique for mixture formation in direct injection into the gasoline engine was summarized by Chincholkar and Suryawanshi [18]. In order to build and optimize the intake system by eliminating secondary injectors, Mohamad et al. [19] used coupled method technique and applied new location for the primary injectors for the Formula race car engine, power output, torque, specific fuel consumption, along with three-dimensional air flow to the engine were monitored. Mohamad et al. [20] used CFD tools to conduct different design phases to test two major flow properties that are intake system velocity and pressure. The authors show that in the plenum zone and runner part, velocity is theoretically high, which can lead to air volume fluctuations in the combustion chamber at high engine speed. In contrast, Mohamad et al. [21] studied the effect of mixing fuel on the combustion and engine efficiency of the internal combustion engine, E40g60 (40% ethanol and 60% GF by volume) and M35g65 (35% methanol and 65% GF by volume) respectively. The ethanol-gasoline blend has a higher laminar flame propagation speed, according to their findings, which can complete the combustion process sooner and thus increase the thermal efficiency of the engine. Due to the lower peak of in-cylinder temperature by combustion retardation, the NOx emissions were reduced with ethanol blending.

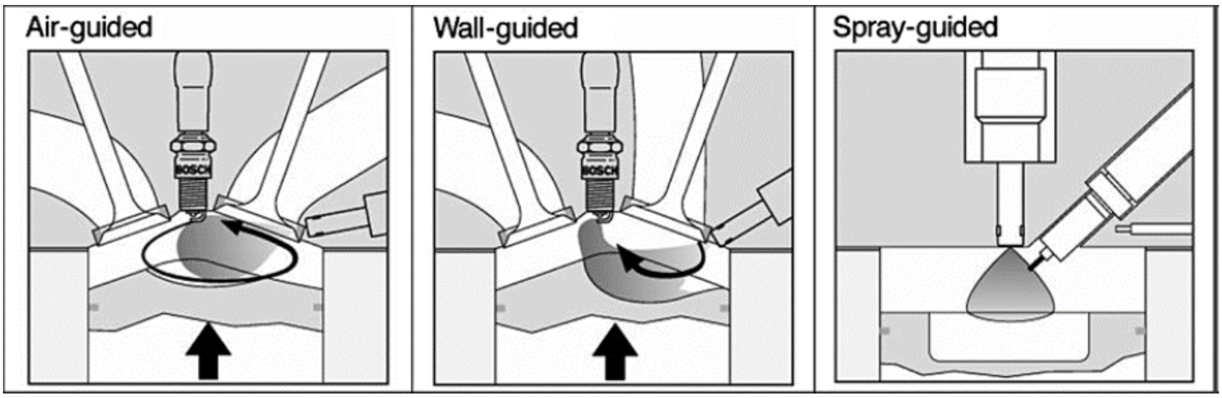

Fig. 8. DISI Combustion systems classifications Preussner et al. [15]

Table 1. Gasoline characteristics and additives for injection [21].

	Gasoline	**Methanol**	**Ethanol**
Molecular formula	-	CH_3OH	C_2H_5OH
Density kg/m^3	740	792	785
Oxygen content (%)	95-120	50	46
LHV MJ/kg	44.3	20	26.9
Auto-ignition temp. (°C)	228–470	465	425
Octane number	>90	111	108
Vapor pressure at 23.5 °C (kPa)	60–90	3.2	-
Latent heat kJ/kg	305	1103	840
Stoichiometric A/F (λ) ratio[kg/kg]	14.8	6.47	9.0

Cheolwoong et al. [22] discussed the effect of the spray-guided combustion system on the stratified lean combustion engine with a piezo-zero style gasoline direct injector, the tests were performed under different conditions on a single-cylinder engine, the result indicates that this method can decrease nitrogen oxide (NOx) and total tailed-hydrocarbons (THC) components. Even the back pressure was high and low atomization was controlled in the lean combustion area with a late injection strategy causing smoke emission. Computational fluid dynamics methodology used by Lucchini et al. [23] to model the formation of air-fuel and gas exchange mixtures in gasoline the multi-dimensional model approach for direct injection engines may be a better way to explain the soot formation from injected in homogeneities or impingement of liquid fuel on the cylinder walls. Two injection methods were implemented in this research, poor or unstable motion results from the complex interaction between the incoming gas jet and the flow produced by the spray momentum in 1st case when fuel is injected directly into the combustion chamber. If 2 fuel is directly injected with a wider gap, it could have a positive effect on the distribution of droplets within the cylinder in Fig. 9.

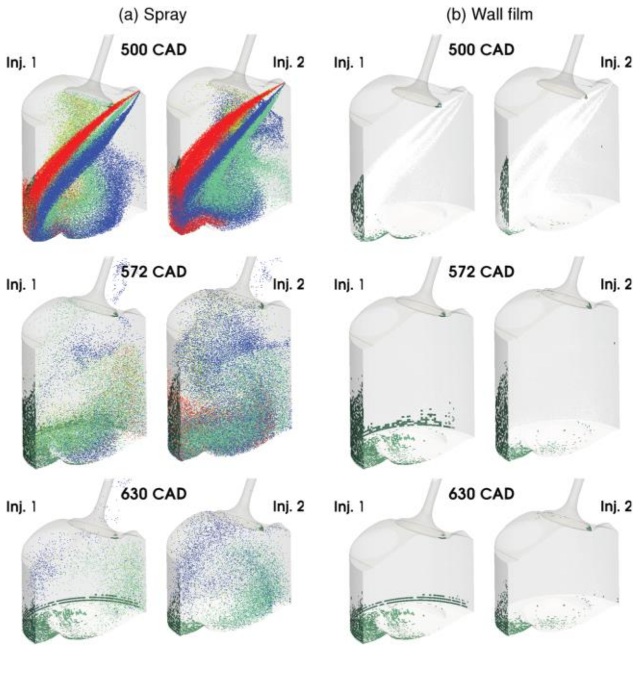

Fig. 9. Computed fuel spray and evolution of liquid film at different times after start of injection and initial point 1, 1500 r / min.: (a) distribution of fuel spray to distinguish the nozzle where each parcel is used so different colour, and (b) assessment of the formation of liquid film. Dark green indicates a liquid-coloured film [23]

Sens et al. [24] used the quantitative evaluation of droplet sizes and the schlieren method and their distribution, the impact of pre-heat of fuel spry on engine performance was studied to show that high fuel temperatures have a massive influence on spray behavior.

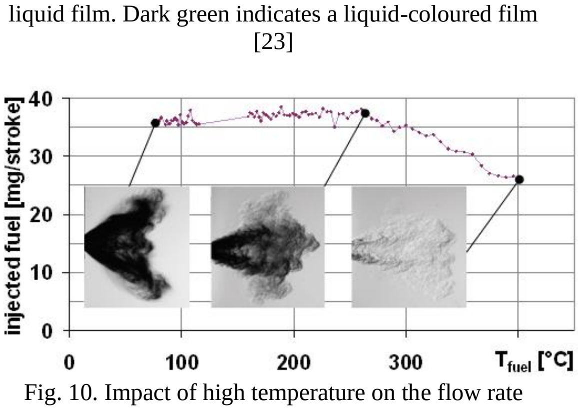

Fig. 10. Impact of high temperature on the flow rate of the fuel mass; T_{ch} = 25 °C, P_{ch} = 1 bar and P_{fuel}=85 bar, octane fuel No.95 [24]

3. CONCLUSIONS

The paper shows current developments carried out as stated by literature on dynamic simulation of multiphase flows of GDI injectors with particular emphasis on the coupling of an incompressible two-phase FVM solver. The dynamic mesh based on topological changes was selected and automatically managed in parallel by the cavitation model in a system. The commercial solvers were used for the simulation of a gasoline injector specifically designed for GDI engines by the authors. The topological adjustments are the primary state set up to model the early stages of gasoline injection, using both motion and static mesh, and applying them. The detailed properties of the flow structures were detected during the initial breakup, in this sense, to research the impact of the injector geometry on flow cavitation and the design process, the current approaches can be regarded as accurate and can therefore be implemented. In using the technique of calculating the diffusion distance as a function of time, the commercial CFD software has proved to be very robust, they must be maintained during the simulations even in the presence of topological changes, so that the process can be presumed to be totally conservative. Second-order precision has also been retained both in space and time, which is not neglected in the presence of complex grids that alter topologically. Some authors developed their own codes, and their papers introduced the methods.

Author contributions: *research concept and design, B.M.; Collection and/or assembly of data, B.M.; Data analysis and interpretation, B.M.; Writing the article, B.M., M.Q.A.; Critical revision of the article, B.M.; Final approval of the article, B.M.*

Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

REFERENCES

1. Lucchini T, Fiocco M, Onorati A, Montanaro A, Allocca L, Sementa P, Vaglieco BM, Catapano F. Full-cycle CFD modeling of air/fuel mixing process in an optically accessible GDI engine. SAE International Journal of Engines. 2013; 6(3):1610–1625, https://doi.org/10.4271/2013-24-0024.
2. Kuwahara K, Ueda K, Ando H. Mixing control strategy for engine performance improvement in a gasoline direct injection engine. SAE Paper. 1998: 980158. https://doi.org/10.4271/980158.
3. Bozza F, Torella E. The employment of a 1D simulation model for the A/F ratio control in a VVT Engine. SAE Trans J Eng. 2003;v3, https://doi.org/10.4271/2003-01-0027.
4. Montenegro G, Della Torre A, Cerri T, Onorati A, Nocivelli L, Fiocco M. 1D-3D coupled simulation of the fuel spray propagation inside the air-box of a moto3 motorbike: Analysis of spray targeting and injection timing. SAE Technical Paper-2017-01-0520. https://doi.org/10.4271/2017-01-0520.
5. Giussani F, Montorfano A, Piscaglia F, Onorati A, Hélie J, Aithal SM. Dynamic VOF modelling of the internal flow in GDI fuel injectors. Energy Procedia. 2016;101:574-581. https://doi.org/10.1016/j.egypro.2016.11.073.
6. Stockar S, Canova M, Guezennec Y, Torre A D, Montenegro G, Onorati A. Modeling wave action effects in internal combustion engine air path systems: Comparison of numerical and system dynamics approaches. International Journal of Engine Research, 2013;14(4):391–408. https://doi.org/10.1177/1468087412455747.
7. Montenegro G, Della Torre A, Onorati A, Fairbrother R, Dolinar A. Development and application of 3D generic cells to the acoustic modelling of exhaust systems. SAE technical paper. 2011.
8. Winterbone D, Pearson R. Theory of engine manifold design: wave action methods for IC engines. John Wiley & Sons Inc. 2005.
9. Yuh-Yih Wu, Bo-Chiuan Chen, Hsien-Chi Tsai, Anh-Trung Tran, Shou-Chih Hsiao. Design and control of semi-direct injection spark ignition engine fuelled by LPG. Energy Procedia. 2014;61:850–853, https://doi.org/10.1016/j.egypro.2014.11.980.
10. Pei Y, Pal P, Zhang Y, Traver M, Cleary D, Futterer C, Brenner M, Probst D, Som S. CFD-Guided Combustion System Optimization of a Gasoline Range Fuel in a Heavy-Duty Compression Ignition Engine Using Automatic Piston Geometry Generation and a Supercomputer. SAE Technical Paper, 2019-01-0001, https://doi.org/10.4271/2019-01-0001.
11. Costa M, Sorge U and Allocca L. CFD optimization for GDI spray model tuning and enhancement of engine performance. Advances in Engineering Software. 2019;49:43–53. https://doi.org/10.1016/j.advengsoft.2012.03.004.
12. Yi J. Design and optimization of gasoline direct injection engines using computational fluid dynamics. Advanced Direct Injection Combustion Engine Technologies and Development Gasoline and Gas Engines. 2014:166-198. https://doi.org/10.1533/9781845697327.166.
13. Rotondi R, Bella G. Gasoline direct injection spray simulation. International Journal of Thermal Sciences, 2006;45:168–179. https://doi.org/10.1016/j.ijthermalsci.2005.06.001.
14. Alkidas AC. Combustion advancements in gasoline engines. Energy Conversion and Management. 2007;48:2751–2761. https://doi.org/10.1016/j.enconman.2007.07.027.
15. Preussner C, Doring C, Fehler S. Kampmann S. GDI: Interaction between mixture preparation, combustion system and injector performance. SAE Paper NO. 980498. https://doi.org/10.4271/980498.
16. Drake, MC, Haworth DC. Advanced gasoline engine development using optical diagnostics and numerical modeling. Proceedings of the Combustion Institute. 2007;31:99–124. https://doi.org/10.1016/j.proci.2006.08.120.
17. Hentschel W. Optical diagnostics for combustion process development of direct-injection gasoline engines. Proceedings of the Combustion Institute. 2000;28:1119–1135. https://doi.org/10.1016/S0082-0784(00)80322-7.
18. Chincholkar SP. Suryawanshi JG. Gasoline Direct Injection, an Efficient Technology, 5th International Conference on Advances in Energy Research, ICAER 2015, Mumbai, India, Energy Procedia. 2015;90:666 – 672. https://doi.org/10.1016/j.egypro.2016.11.235.
19. Mohamad B, Karoly J, Zelentsov A. CFD modelling of formula student car intake system. Facta Universitatis Series: Mechanical Engineering. 2020; 18(1):153-163. https://doi.org/10.22190/FUME190509032M.
20. Mohamad B, Karoly J, Zelentsov A. Investigation and optimization of the acoustic performance of formula student race car intake system using coupled modelling techniques. Design of Machines and

Structures. 2019;9(1):13–23. https://doi.org/10.32972.dms.2019.002.
21. Mohamad B, Szepesi G, Bollo B. Combustion Optimization in Spark Ignition Engines, MultiScience - XXXI. microCAD International Multidisciplinary Scientific Conference, University of Miskolc, Hungary. 2017. https://doi.org/10.26649/musci.2017.065.
22. Cheolwoong P, Sungdae K, Hongsuk K, Moriyoshi Y. Stratified lean combustion characteristics of a spray-guided combustion system in a gasoline direct injection engine. Energy. 2012;4(1):401-407. https://doi.org/10.1016/j.energy.2012.02.060.
23. Lucchini T, Errico G D, Onorati A, Bonandrini G, Venturoli L, Gioia RD. Development and application of a computational fluid dynamics methodology to predict fuel–air mixing and sources of soot formation in gasoline direct injection engines. International Journal of Engine Research. 2013;15(5):581–596. https://doi.org/10.1177/1468087413500297.
24. Sens M, Maass J, Wirths S, Marohn R. Effects of highly-heated fuel and/or high injection pressures on the spray formation of gasoline direct injection injectors. Fuel Systems for IC Engines. 2012; 215-238. https://doi.org/10.1533/9780857096043.6.215.
25. Merkisz, J. Pielecha, I. Łegowik, A. The assessment of autoignition of modified jet fuels. Energies. 2021; 14:633. https://doi.org/10.3390/en14030633.

Received 2022-04-29
Accepted 2022-08-30
Available online 2022-09-01

Dr. **Barhm MOHAMAD**, Doctor of Mechanical Engineering and lecturer at the Department of Petroleum Technology, Koya Technical Institute, Erbil Polytechnic University, 44001 Erbil, Iraq. His research area is engine powertrain. Especially, he is interested in aerodynamic analysis of locomotives and vehicles using computational fluid dynamics. He has authored and co-authored more than 60 papers, mostly published in international journals or international conference proceedings and he is the coordinator of numerous projects funded by regional, national and EU grants.

Mohammed Qasim ALI, a researcher in vocational department in ministry of education, Iraq. His research area is machine design. Especially, he is interested in damage identification techniques in composite materials.