Investigating injector angles to eliminate spray-wall impingement in a manifold port injection system of gasoline engines

Nguyen The Uy[1], Nguyen Duy Phu[1], Duong Quoc Cuong[2],
Phung Van Duoc[1], Nguyen Quoc Quan[1*], Pham Xuan Phuong[1]

[1]Faculty of Vehicle and Energy Engineering, Le Quy Don Technical University;
[2]Tran Dai Nghia University.
[*]Corresponding author: ngquanturbine@lqdtu.edu.vn

Received 24 Oct 2022; Revised 15 Dec 2022; Accepted 02 Feb 2023; Published 28 Feb 2023.
DOI: https://doi.org/10.54939/1859-1043.j.mst.85.2023.118-125

ABSTRACT

There has been an outstanding improvement in injection technology in the spark ignition (SI) engines' fuel supply systems, from traditional carburettors with throttle body injection (TBI), manifold port or multi-point injection (MPI) to direct injection (DI). This paper has developed an MPI intake manifold model and investigated fuel injector angles using a multiphase CFD package provided by FloEFD software. A wide range of injector angles from 22 to 30 degrees has been investigated in order to evaluate the influence of the injector angle on the wall-wetting issue, a critical problem of manifold injection systems in SI engines. The intake air pressure differential in the manifold was also evaluated. The results show that the fuel injector angle affects the multiphase flow in the MPI system. The manifold diameter meets the design specifications, and the pressure differential in the manifold is quite small. With an injector angle of 25 degrees, the wall-wetting issue is minimal. This model could be used for further studies on engine performance and emission formation.

Keywords: Injector angle; Wall wetting; Multi-point injection; Intake manifold.

1. INTRODUCTION

In the case of TBI, a central injection unit is used to replace the traditional carburettors [1]. A mixture of fuel vapor, drops, and the air is delivered to the cylinders through the intake manifold. In MPI systems, every cylinder is allocated its own injector, located prior to the intake valve, to inject an appropriate amount of fuel at a proper duration into the intake port. This avoids the problems associated with poor fuel distribution in carburetor and TBI systems. The MPI fuel injectors differ from others. MPI injectors produce the required jet shape. Injectors could be single-hole or multi-hole and could spray once or several times per engine cycle. Injectors must be suitable for the fuel type and intake manifold. Injectors are normally selected based on various parameters such as intake port geometry, injection position, injection timing (injection during closed or open intake valve operation), maximum intake air temperature, fuel quality (due to injector deposit formation), and minimum manifold air pressure (to prevent self-ignition) [2].

Evaluating the influence of injector parameters and intake manifold design on engine power and emissions can be found in [3, 4]. Li et al. [3] experimentally investigated the effect of different fuel injection parameters on the performance and emission characteristics of a thermoelectric pulse burner. It was shown that the fuel injector with a small top angle improves the pulse burner performance, and there is an optimal distance between the injector holes for maximizing burner efficiency.

Determining intake air mass flow rate and specific fuel consumption for different intake manifold shapes and lengths were reported in [5-7]. Numerous studies have been performed on the design of new intake manifolds in single- or multi-cylinder engines [8-14]. Spiral intake manifolds were designed to improve the engine volumetric efficiency and boost engine power [8].

Using computational fluid dynamics (CFD) to investigate the intake manifold characteristics, injector injection, and combustion chambers is relatively common in the literature [15-24]. Work done in [25-31] evaluated the impact of injector characteristics and intake manifold shape on engine efficiency, energy and emissions. In a numerical analysis conducted by Sevik et al.[25], the influence of injector location on the performance of natural gas direct-injection in a SI engine was provided. According to the results, delaying the injection start from 300° to 120° crank angle before the top dead center may reduce the early flame formation by about 15° crank angle.

Mahmood et al. [26] evaluated the influence of injector location on the performance of natural gas direct-injection in a spark ignition engine using CFD. The effect of injector characteristics and position on diesel engine performance was investigated in [28-31]. Currently, there is a lack of studies on the influence of injector location on the wall wetting issue in SI engines. The above studies have optimized intake manifold design. However, the impact of the injector angle on the air-fuel mixing quality and spray-wall impingement in the manifold is not available.

In this work, a CFD model was developed for an MPI intake manifold to investigate the link between injector angle and spray-wall impingement. The engine investigated in this study is an MPI SI engine. The simulation model has been developed using Siemens FloEFD software. This study aims to evaluate the appropriate injector angle to achieve efficient air-fuel mixing and minimal fuel wetting on the intake manifold walls.

2. NUMERICAL MODEL DEVELOPMENT

2.1. Intake manifold design

The intake manifold must meet the following requirements: there are no sharp curves or complicated bends; the folds have a symmetrical shape so that the air-fuel mixture is uniformly distributed to every cylinder; and the injector position is close to the intake valve. Figure 1 shows examples of the intake manifold designed in this study. The 3D model is developed in Solidworks, and its inlet and outlet are fitted with the UMZ 420.10 engine head as a reference engine.

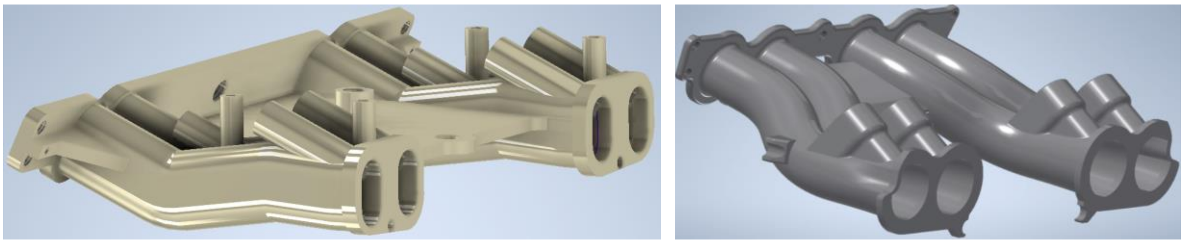


Figure 1. *Various geometries and injector angles of the intake manifold.*

Each intake manifold model has four folds, which correspond to 4 cylinders and 4 fuel injector holes. The dimensions of inlet and outlet holes are similar among the models, but pipe geometry, curvature, and injector angle are different. This is to evaluate the pressure differential and wall-weting propotion.

2.2. Simulation model

The simulation model developed in this study includes mechanical parts (an intake manifold, an injector and an engine head) and fluid flows (air and fuel). Atmospheric air enters the intake manifold, and fuel is injected from the injector.

To investigate the aerodynamic impact, simulations were conducted in the intake stroke with the assumption that four branches are inhaled simultaneously. The simulation conditions correspond to an engine regime with a maximum power of 84 kW and a speed of 4000 rpm. Based on the engine performance curves, pressure parameters at the end of the intake stroke, effective fuel consumption, and air mass flow rate are calculated. The simulation conditions are summarized in table 1.

Table 1. *Boundary conditions of the simulation model.*

Boundary	**Parameter**	**Fuel**	**Air**
Inlet	Volume (mass) flow rate	200 cm^3/s	0.036 kg/s
	Pressure	0.29 MPa	0.103 MPa
	Temperature	24 ^oC	24 ^oC
Outlet	Pressure (Intake manifold vacuum pressure)	0.0894 MPa	
	Temperature	24 ^oC	

The meshing model is separated into 3 zones with local element sizes (figure 2). The first zone is a large pipe with a little geometric variation. The second zone is a smaller pipe with rapid size changes. The third zone consists of a tiny injector hole, as shown in figure 2.

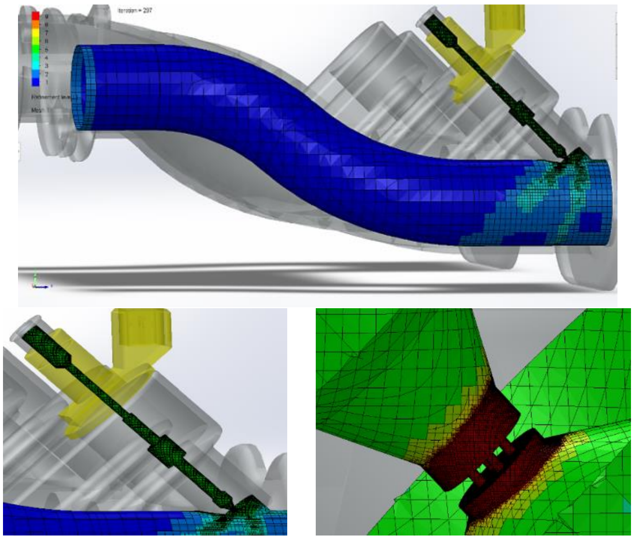


Figure 2. *Three zones of the meshing model.*

3. RESULTS AND DISCUSSION

3.1. Pipeline profile assessment

According to simulation results with various intake manifold models, it is necessary to avoid the gliding angle at the pipe inlet and outlet, as this will reduce the airflow cross-section. In addition, the folds must not have any sharp corners. Both the fold length and the deviation angle between the two flanges must satisfy the installation requirements. This could be accomplished by increasing the curvature radii of the bends and slowly changing the diameters.

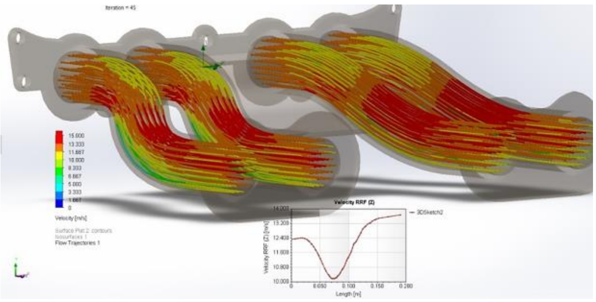


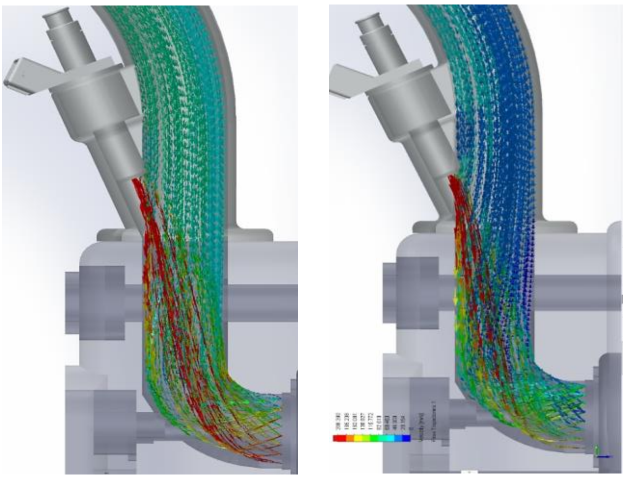
Figure 3. *Air velocity in the intake manifold and average velocity along a pipe.*

The air velocity simulation results (figure 3) qualitatively demonstrate that the air flows evenly into four branches and has no swirling regions. That contributes to a uniform air supply to each engine cylinder and a reduction of kinetic energy.

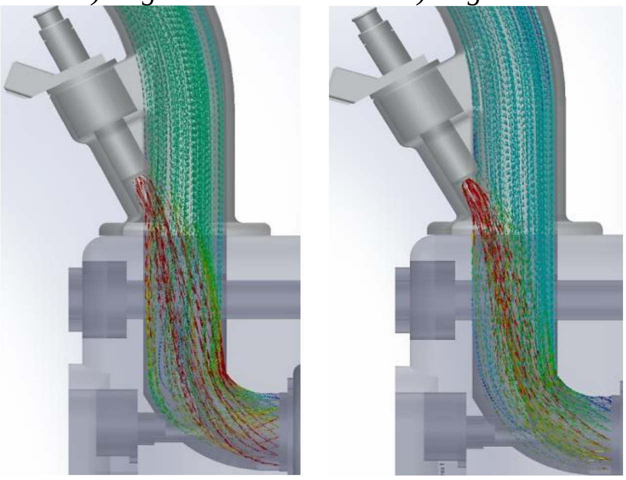
3.2. Evaluation of injector placement angle

To evaluate the injector position, four models of the intake manifold with injector angles of 22^o, 25^o, 27^o and 30^o were tested (figure 4). Observing the fuel spray trajectory to qualitatively evaluate the appropriate injector angle and quantitatively assess the wall wetting fraction.

From the simulation, the fuel injected into the folds with an injector angle of 22^o will flow directly into the upper wall of the intake manifold. When the injector angles are 27^o or 30^o, fuel is sprayed into the lower wall. This will cause the fuel to accumulate and deposit on the wall. The deposited fuel is very hard to vaporize and mix with the intake air, and this is well-known as wall wetting problem. Consequently, this impairs the quality of mixing and combustion and increases emission concentrations.



a) Angle 22^o *b) Angle 25^o*



c) Angle 27^o *d) Angle 30^o*

***Figure 4.** Fuel injection into intake manifolds with various injector angles*.

With a 25° injector angle, the fuel is injected directly into the intake manifold. This helps fuel directly enter the engine and be uniformly distributed across the entire intake manifold, which eliminates the fuel-wetting issue, as mentioned.

3.3. The air-fuel mixture evaluation

The air-fuel mixture could be observed from the folding model shown in figure 5. The air-fuel ratio at the cross-section in front of the combustion chamber and the intake manifold wall at different injector angles are shown in figure 6.

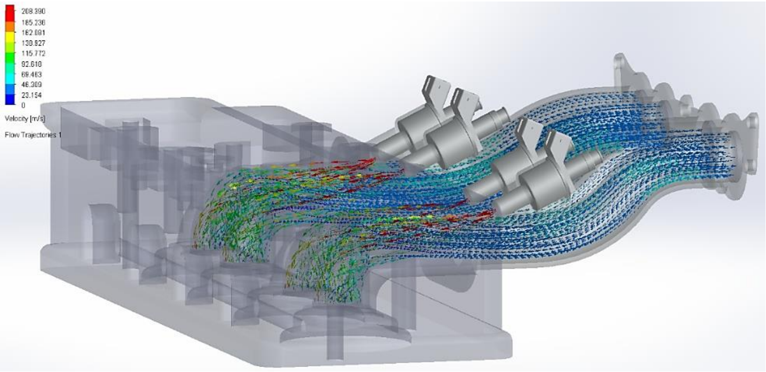


Figure 5. *Air-fuel mixture in the intake manifold.*

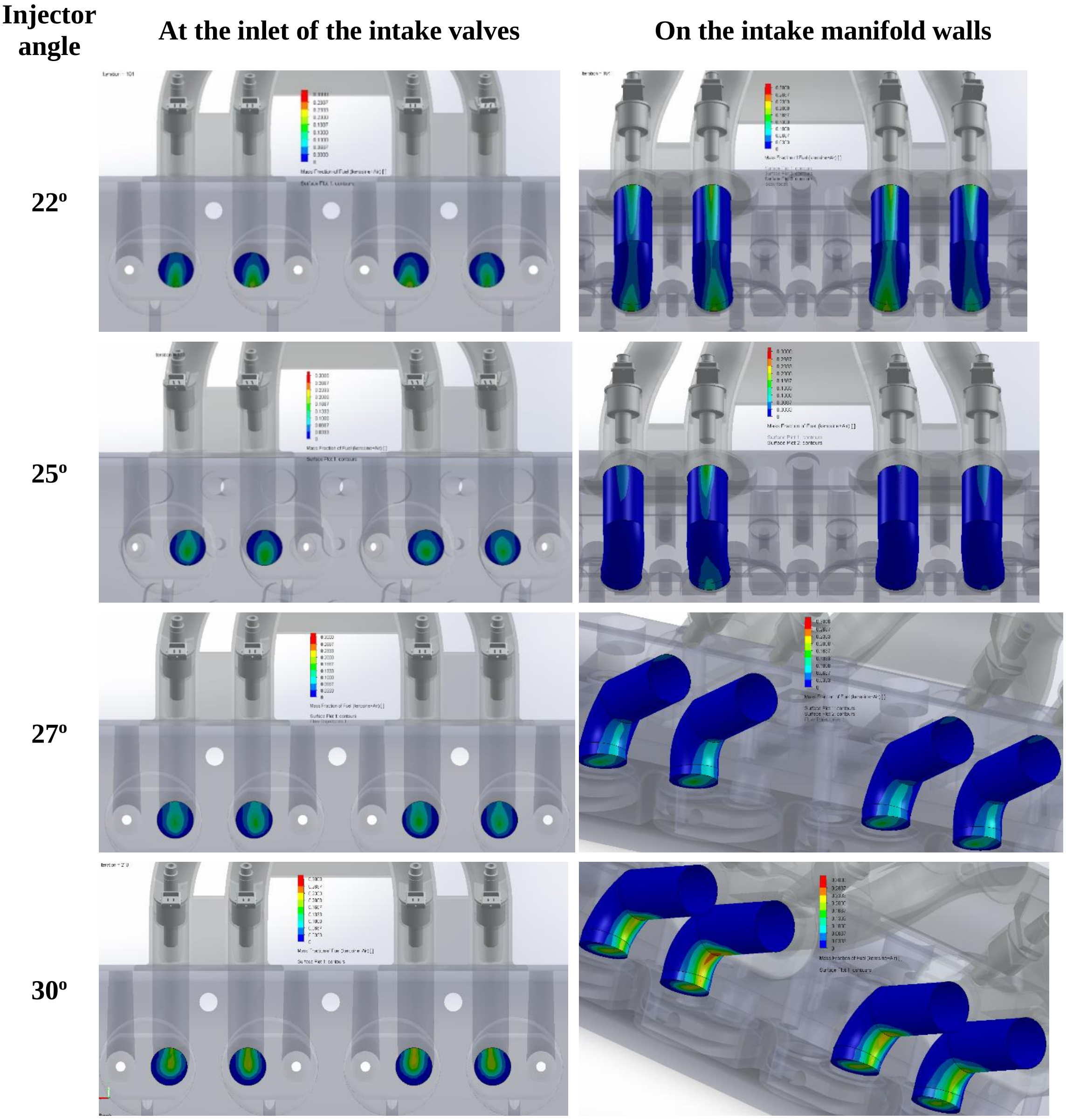


Figure 6. *Fuel-air mass ratio at various injector angles.*

The fuel-air ratio before supplying it to the combustion chamber with the injector angles (22^o, 27^o, and 30^o) is not uniformly distributed. Fuel is concentrated on one side of the pipe wall (areas with different colors), whereas the remaining wall contains little to no fuel (blue areas). At the 25° injector angle, the distribution is quite uniform. At the intake manifold inlets, fuel is concentrated in the middle of the cross-section and uniformly distributed, with less fuel sprayed onto the walls. In addition, the optimal fuel-air ratio (1/14.7) covers a wide area (blue area).

Comparing injection trajectories reveals that the air-fuel mixture and fuel density on the manifold wall vary depending on injector angles. The average fuel-air mass ratio (figure 7) indicates that the minimum amount of fuel is injected into the manifold wall when the injector angle is set to 25°. By increasing the angle from the 25° angle, more fuel fraction is injected into the wall.

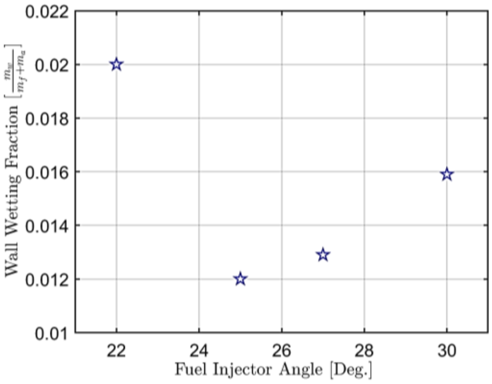


Figure 7. *Average fuel-air mass ratio on the manifold wall depending on injector angles (wall wetting fraction).*

4. CONCLUSIONS

In order to eliminate the wall wetting issue in MPI SI engines, the intake manifolds and injector angles should be carefully designed. In this study, a CFD model was developed to investigate the influence of injector angle on the wall wetting fraction.

The main outcomes are the following:

- The basic method for designing the intake manifold is to increase the curvature radius of the bends. Avoiding folds with complicated and fractured profiles and preventing burrs on fold walls could help to improve volume efficiency and, therefore, engine performance. It is suggested to gradually change the folded diameter to avoid sudden increases and decreases and to limit dead angles.

- For the specific reference engine investigated in this study, an appropriate injector angle (25^o) was achieved.

- The manifold diameter meets the requirements, and the pressure difference on the pipe is minimal, $\Delta p = 22$ Pa (0.024%).

REFERENCES

[1]. P. X. Pham, D. Q. Vo, and R. N. Jazar, *"Development of fuel metering techniques for spark ignition engines,"* Fuel, vol. 206, pp.701-715, (2017).

[2]. C. Baumgarten, *"Mixture Formation in Internal Combustion Engines"* (Heat and Mass Transfer). Springer, pp. 5-46, (2006).

[3]. F. Li, M. Du, and L. Y. c, *"Effect of fuel injection parameters on performance characteristics and emissions of a thermoacoustic system,"* Aerospace Science and Technology, p. 10, (2021).

[4]. X. Wang, K. Li, and W. Su, *"Experimental and numerical investigations on internal flow characteristics of diesel nozzle under real fuel injection conditions,"* Experimental Thermal and Fluid

Science, vol. 42, pp. 204-211, (2012).

[5]. D. N. Malkhede and H. Khalane, *"Maximizing Volumetric Efficiency of IC Engine through Intake Manifold Tuning,"* presented at the SAE Technical Paper Series, (2015).

[6]. V. Harantová, Z. Otáhalová, and M. Kasanický, *"Estimation of fuel consumption based on data from opening fuel injector valve,"* 13th International Scientific Conference on Sustainable, Modern and Safe Transport, (2019).

[7]. F. Payri, V. Bermúdez, R. Payri, and F. J. Salvador, *"The influence of cavitation on the internal flow and the spray characteristics in diesel injection nozzles,"* Fuel, vol. 83, no. 4-5, pp. 419-431, (2004).

[8]. A. Manmadhachary, M. Santosh Kumar, and Y. Ravi Kumar, *"Design&manufacturing of spiral intake manifold to improve Volument efficiency of injection diesel engine byAM process,"* Materials Today: Proceedings, vol. 4, no. 2, pp. 1084-1090, (2017).

[9]. L. O. F. T. Alves, M. G. D. d. Santos, A. B. U. Junior, J. H. Guerrero, J. C. d. L. Júnior, and V. Abramchuk, *"Design of a new intake manifold of a single cylinder engine with three stages,"* SAE Technical Paper Series, (2017).

[10]. S. Ghodke and S. Bari, *"Effect of Integrating Variable Intake Runner Diameter and Variable Intake Valve Timing on an SI Engine's Performance,"* SAE Technical Paper Series, (2018).

[11]. P. Pogorevc and B. Kegl, *"Intake system design procedure for engines with special requirements,"* Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 220, no. 2, pp. 241-252, (2016).

[12]. M. A. Ceviz and M. Akın, *"Design of a new SI engine intake manifold with variable length plenum,"* Energy Conversion and Management, vol. 51, no. 11, pp. 2239-2244, (2010).

[13]. S. P. Singh, V. Kumar, D. Gupta, and N. Kumar, *"Influence of intake runner cross section design on the engine performance parameters of a four stroke, naturally aspirated carbureted SI engine,"* The International Journal of Advanced Culture Technology, vol. 3, no. 1, pp. 1-12, (2015).

[14]. H. Jagtap, C. Vinayak, and R. Koli, *"Intake System Design Approach for Turbocharged MPFI SI Engine,"* SAE international: Symposium on International Automotive Technology, (2011).

[15]. J. Kim, M. Yadav, and S. Kim, *"Characteristics of Secondary Flow Induced by 90-Degree Elbow in Turbulent Pipe Flow,"* Engineering Applications of Computational Fluid Mechanics, vol. 8, no. 2, pp. 229-239, (2014).

[16]. Q. H. Mazumder, *"CFD Analysis of Single and Multiphase Flow Characteristics in Elbow,"* Scientific Research, p. 5, (2012).

[17]. J.-S. Kim, W.-J. Lee, V. C. Pham, and J.-H. Choi, *"A Numerical Study on Fuel Injection Optimization for a ME-GI Dual-Fuel Marine Engine Based on CFD Analysis,"* Applied sciences, p. 26, (2022).

[18]. M. Guducu, *"CFD analysis of nozzle effect on jet formation,"* Aeronautical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden, 64, (2016).

[19]. X. Rangshu, *"CFD simulation calculation of inlet manifold modification designCFD simulation calculation of inlet manifold modification design,"* International Conference on Electric Information and Control Engineering, (2011).

[20]. V. Chintala and K. A. Subramanian, *"A CFD (computational fluid dynamics) study for optimization of gas injector orientation for performance improvement of a dual-fuel diesel engine,"* Energy, vol. 57, pp. 709-721, (2013).

[21]. S. Jafarmadar, S. Khalilarya, S. Shafee, and R. Barzegar, *"Modeling the effect of spray/wall impingement on combustion process and emission of DI diesel engine,"* Thermal Science, vol. 13, no. 3, pp. 23-33, (2009).

[22]. M. L. G. C. Y. J. a. Y. Ma, *"Numerical Simulation of Flows in Multi-cylinder Diesel Engine Inlet Manifold and its Application,"* SAE_NA Technical Paper Series, p. 8, (2001).

[23]. A. Sharma, A. Islam, and P. K. Singh, *"Performance Analysis of intake manifold for injection Systems of CNG Engine,"* European Journal of Molecular & Clinical Medicine, vol. 7, no. 4, p. 8, (2020).

[24]. C. d. L. R. Siqueira, M. P. Kessler, L. A. R. d. Araujo, and E. C. Rodrigues, *"Three-dimensional Transient Simulation of an Intake Manifold using CFD Techniques,"* SAE Technical Paper Series, (2006). https://www.sae.org/publications/technical-papers/content/2006-01-2633/?PC=DL2BUY

[25]. J. Sevik *et al.*, *"Influence of Injector Location on Part-Load Performance Characteristics of Natural Gas Direct-Injection in a Spark Ignition Engine,"* SAE International Journal of Engines, vol. 9, no. 4, pp. 2262-2271, (2016).

[26]. H. A. Mahmood, A. O. Al-Sulttani, O. H. Attia, and N. M. Adam, *"A numerical study to improve the position and angle of the producer gas injector inside the intake manifold to minimize emissions and efficiency enhancement of a bi engine,"* EUREKA: Physics and Engineering, no. 5, pp. 100-109, (2021).

[27]. J. Suresh Kumar, V. Ganesan, J. M. Mallikarjuna, and S. Govindarajan, *"Spray Characteristics of a Fuel Injector: A CFD Study,"* Proceedings of the FISITA 2012 World Automotive Congress, (2013).

[28]. Z.-Y. Sun, G.-X. Li, C. Chen, Y.-S. Yu, and G.-X. Gao, *"Numerical investigation on effects of nozzle's geometric parameters on the flow and the cavitation characteristics within injector's nozzle for a high-pressure common-rail DI diesel engine,"* Energy Conversion and Management, vol. 89, pp. 843-861, (2015).

[29]. H. Guo, S. Zhou, M. Shreka, and Y. Feng, *"Effect of Pre-Combustion Chamber Nozzle Parameters on the Performance of a Marine 2-Stroke Dual Fuel Engine,"* Processes, vol. 7, no. 12, (2019).

[30]. M. Sonachalam and V. Manieniyan, *"Optimization of critical angle, distance and flow rate of secondary fuel injection in DI diesel engine using computational fluid dynamics,"* SN Applied Sciences, vol. 3, no. 1, (2021).

[31]. K. B. Showry and A. V. S. R. Raju, *"Simulation of injection angles on combustion performance using multiple injection strategy in HSDI diesel engine by CFD,"* International Journal of Engineering and Technology, vol. 2, no. 4, p. 6, (2010).

TÓM TẮT

Nghiên cứu góc đặt vòi phun nhằm hạn chế hiện tượng nhiên liệu dính ướt thành ống nạp trên động cơ phun xăng đa điểm

Kỹ thuật phun nhiên liệu trên động cơ xăng đã có những bước phát triển đáng kể, từ bộ chế hòa khí truyền thống đến hệ thống phun xăng đơn điểm, đa điểm và phun trực tiếp. Bài báo xây dựng một mô hình 3D bằng phần mềm FloEFD cho hệ thống phun xăng đa điểm. Một giải góc đặt vòi phun từ 22 đến 30 độ đã được khảo sát nhằm đánh giá ảnh hưởng của góc đặt vòi phun đến hiện tượng dính ướt và mức độ giảm áp trên đường nạp. Các kết quả cho thấy góc phun 25^o giúp nhiên liệu phun thẳng vào họng nạp không va chạm vào thành đường ống, đồng thời giúp cho không khí và nhiên liệu được hòa trộn tốt hơn các trường hợp còn lại. Mô hình mô phỏng thiết lập trong bài báo giúp xác định góc phun hợp lý và có thể làm cơ sở cho các thử nghiệm trên động cơ thực tế, từ đó giúp nâng cao hiệu suất và giảm suất phát thải cho động cơ phun xăng đa điểm.

Từ khoá: Góc đặt vòi phun; Dính ướt; Phun đa điểm; Đường ống nạp.